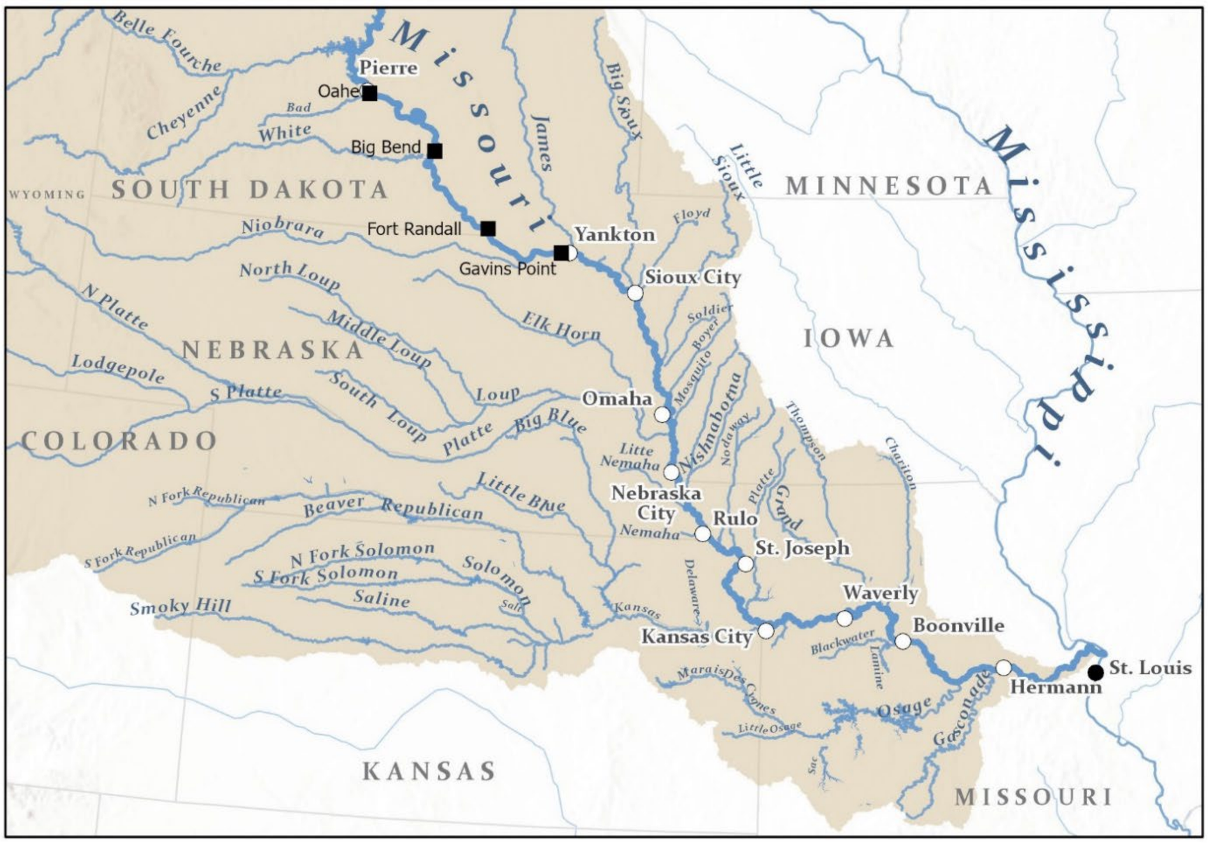
Missouri River Flow Frequency Study

Yankton, South Dakota to Hermann, Missouri

Appendix I: Updates to Tributary ResSim Models



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

June 2023

ATR Report: February 2022
USACE Kansas City District

Kansas River Reservoirs Flood and Sediment Study HEC-ResSim Documentation

Model Data Review and Documentation

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Executive Summary

The following work is included as part of the Kansas River Reservoirs Flood and Sediment Study (KRRFSS). This ongoing study investigates water and related land resource issues and opportunities in the Kansas River Basin to recommend comprehensive, long-term, and sustainable water resource solutions and management based on a Shared Vision for the basin. The modeling was also used to support the Missouri River Flow Frequency Study, which used a period of record of 1930-2019.

An existing HEC-ResSim model was updated to evaluate the impacts of the current operation of the lower seven flood control reservoirs on the Kansas River basin. The reservoir operation sets are based on the current Water Control Manuals for each reservoir. With and without navigation scenarios were run for the existing conditions. Existing data sets were extended to cover the period of January 1, 1920 to December 31, 2019. Reservoir routing parameters were verified and changed as necessary. Updated local flows were created using the extended data set for use in the updated model simulation.

Necessary output from the model includes a complete regulated set of flows at several key stream gage locations on the Kansas River and the pool elevations and releases for each reservoir. Model output is available for use by other disciplines within the study

1. Introduction

This document provides the methodology used to simulate regulated flow on the Kansas River from January 1920 through December 2019. Reservoir modeling was conducted using Hydrologic Engineering Center Reservoir System Simulation (HEC-ResSim) version 3.5. Several data sets needed to be extended beyond their existing period of record. These included USGS gauging stations, inflow points, and local flow between gages. The flood control reservoirs included in this study are the lower seven reservoirs all on tributaries of the Kansas River: Kanopolis, Wilson, Waconda, Milford, Tuttle Creek, Perry, and Clinton.

All analysis is conducted as part of the Kansas River Reservoirs Flood and Sediment Study (KRRFSS). The existing conditions simulation will be used as a baseline for future without project simulations that evaluate changes as sediment accumulates over the next 100 years of the project study evaluation. Several alternatives will also be evaluated including changes to reservoir operations. The existing condition flows on the Kansas River will be used to evaluated flood risk reduction measures and will develop updated flow frequency relationships for unregulated and regulated basin conditions. Simulated reservoir pool elevations and outflows will be utilized for evaluation of recreation, water supply, and water quality needs within the basin.

2. Basin Description

The Kansas River is formed by the confluence of Smoky Hill and Republican Rivers near Junction City, Kansas. It flows approximately 148 miles generally eastward where it joins the Missouri River near Kansas City. There are seven U.S. Army Corps of Engineers (USACE) and eleven U.S Bureau of Reclamation (USBR) reservoirs which are authorized for flood control in the basin. The lower seven reservoirs are included in this study since they are the major contributors to Kansas River Basin flood storage.

These seven reservoirs include three which are in the Smoky Hill River Basin: Kanopolis Reservoir on the Smoky Hill River, Wilson Reservoir on the Saline River, and Waconda Reservoir on the Solomon River. The Smoky Hill River Basin reservoirs and the corresponding control point gages are shown in Figure 2-1. The rest of the seven reservoirs are on tributaries to the lower Kansas River and are Milford Reservoir on the Republican River, Tuttle Creek Reservoir on the Big Blue River, Perry Reservoir on the Delaware River, and Clinton Reservoir on the Wakarusa River. The Kansas River Basin reservoirs and the corresponding control point gages for flood control operations are shown in Figure 2-2.

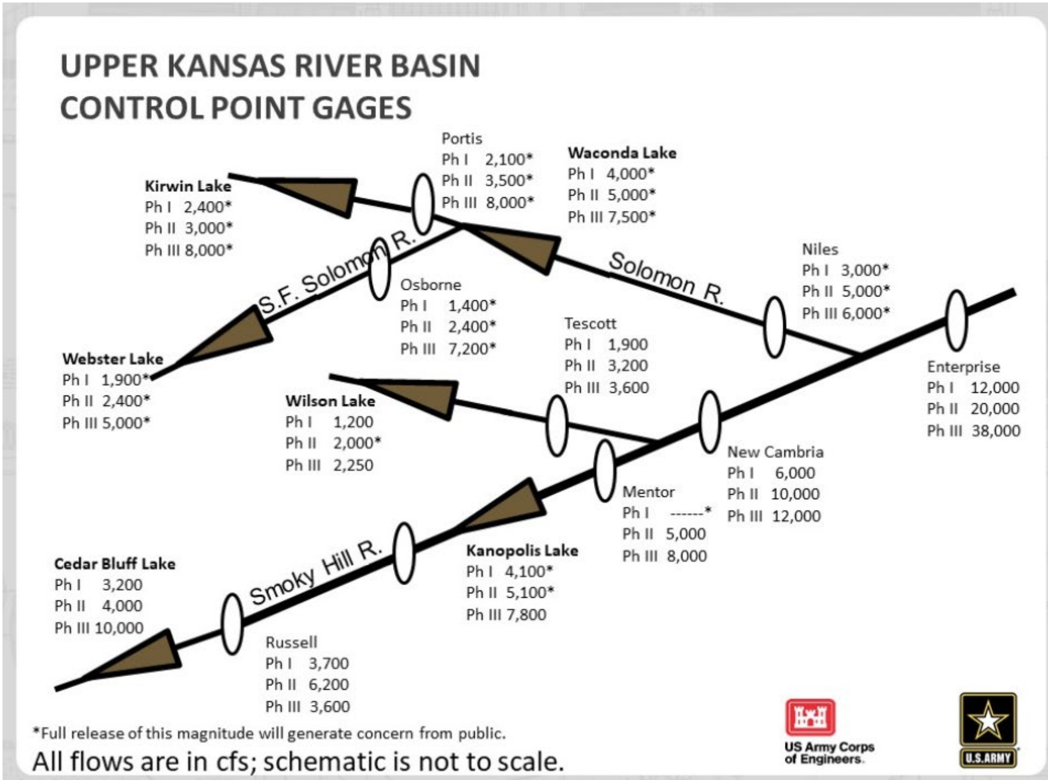


Figure 2-1. Schematic of the Smoky Hill River Basin reservoirs and control points.

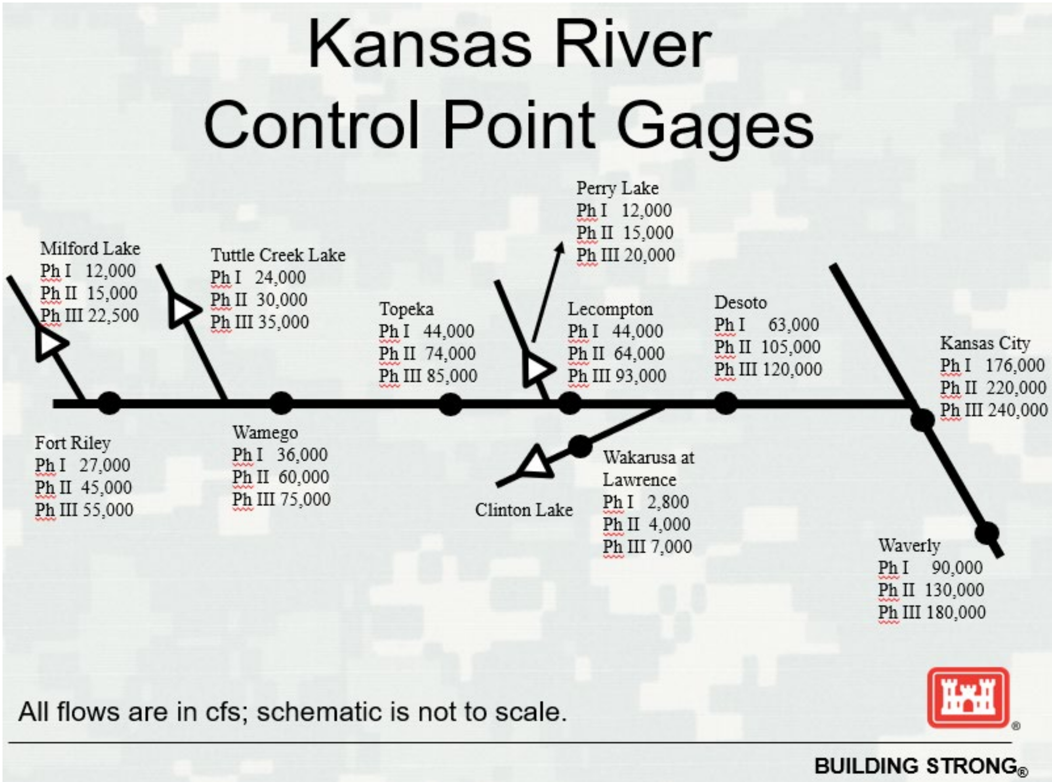
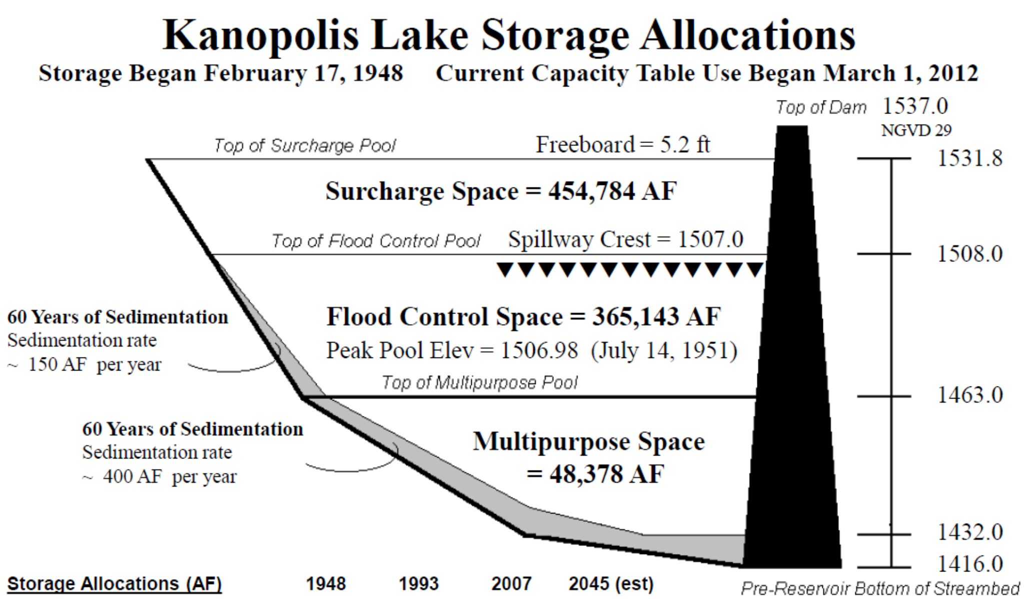


Figure 2-2. Schematic of the Kansas River Basin reservoirs and control points.

These seven reservoirs vary widely in storage and release capacity. Table 2-1 details pertinent information for each reservoir. Generally, the size of the flood storage and the discharge capacity is indicative of how much the reservoir impacts downstream flows. The larger reservoirs also tend to be authorized for more release capacity. Figure 2-3 through Figure 2-9 depict the current reservoir allocation zones and storage capacity of each zone to include the multipurpose or conservation pool.

Table 2-1. Pertinent data for the lower seven reservoirs in the Kansas River Basin

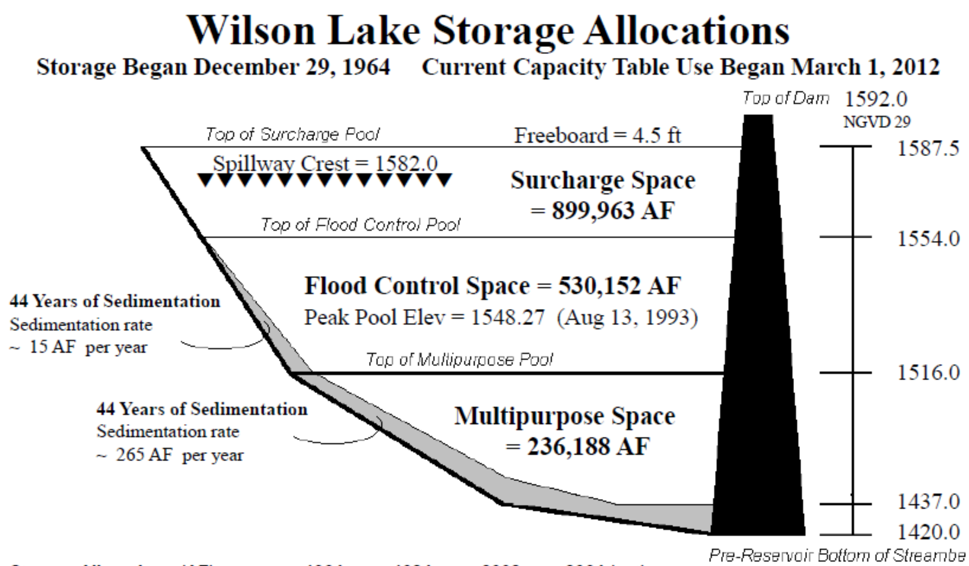
Reservoir	Owner	Date of Closure	Date Multi-purpose Filled	Flood Control Storage (ac-ft)	Outlet Discharge Capacity Top of Flood Pool (cfs)	Surcharge Storage (ac-ft)	Spillway Discharge Capacity Top of Surcharge Pool (cfs)
Kanopolis	USACE	26Jul1946	19July1948	365,143	6,400	484,912	172,000
Wilson	USACE	3Sep1963	12Mar1973	530,152	6,500	899,749	15,700
Waconda	USBR	18Oct1967	16May1973	722,986	5,200	166,572	278,000
Milford	USACE	24Aug1964	14Jul1967	757,874	23,100	1,475,913	560,000
Tuttle Creek	USACE	20Jul1959	29Apr1963	1,884,312	45,900	959,939	579,000
Perry	USACE	2Aug1966	3Jun1970	515,520	27,500	695,362	65,000
Clinton	USACE	23Aug1975	3Apr1980	292,496	7,570	286,875	44,200



Storage Allocations (AF)	1948	1993	2007	2045 (est)
Total Flood Control Pool	**373,891**	**368,114**	**365,143**	**362,254**
Projected Flood Control	373,891	368,114	362,254	362,254
FP Sediment Reserve	0	0	2,889	0
Total Multipurpose Pool (1463)	**73,200**	**50,273**	**48,378**	**26,833**
Water Supply	0	0	12,500	12,500
Multipurpose Uses	15,041	11,890	14,333	14,333
MP Sediment Reserve	58,159	38,383	21,545	0

MP pool elev raised from 1459.0 to 1463.0 in 1968. MP pool reallocated in 2002 to add water supply allocation, with the remaining portion for operating MP uses, mainly minimum releases. Sediment reserve also added to FP. The State of Kansas (KWO) contracted for all water supply space in 2002. All in service.

Figure 2-3. Kanopolis Reservoir Storage Allocations



Storage Allocations (AF)	1964	1984	2008	2064 (est)
Total Flood Control Pool	**530,710**	**530,204**	**530,152**	**510,000**
Exclusive Flood Control	510,000	510,000	510,000	510,000
FP Sediment Reserve	20,710	20,204	20,152	0
Total Multipurpose Pool	**247,835**	**242,528**	**236,188**	**225,000**
Multipurpose (all purposes)	225,000	225,000	225,000	225,000
MP Sediment Reserve	22,835	17,528	11,188	0

The tables resulting from the 2008 survey have been used for operations since Mar 2012. The State of Kansas (KWO) has requested a reallocation study of Wilson Lake to make water supply space available, but the study has been put on hold.

Figure 2-4. Wilson Reservoir Storage Allocations

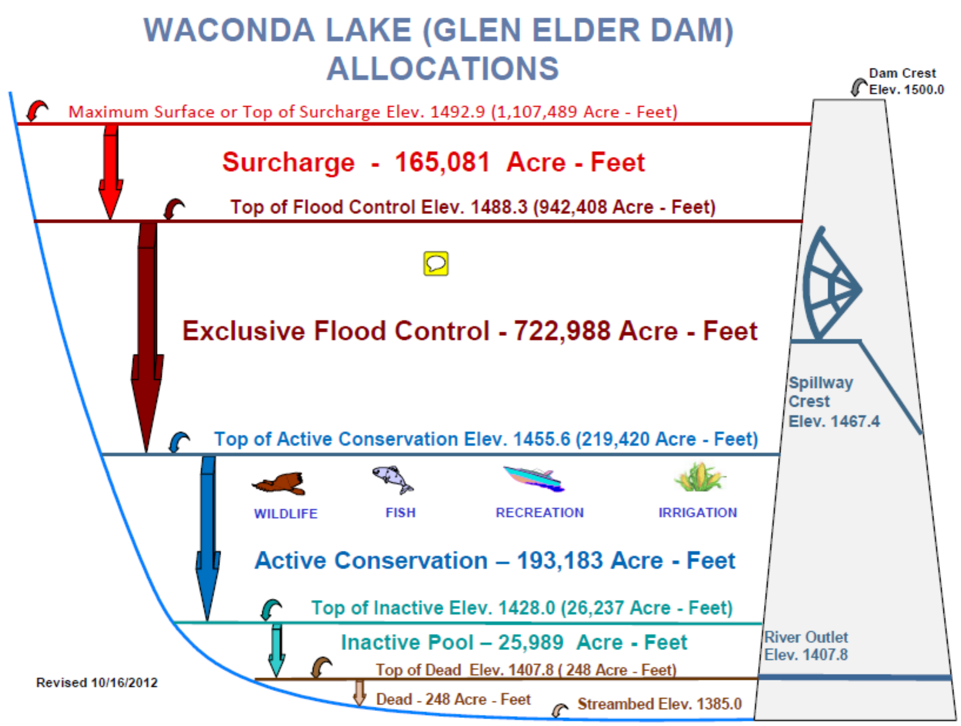
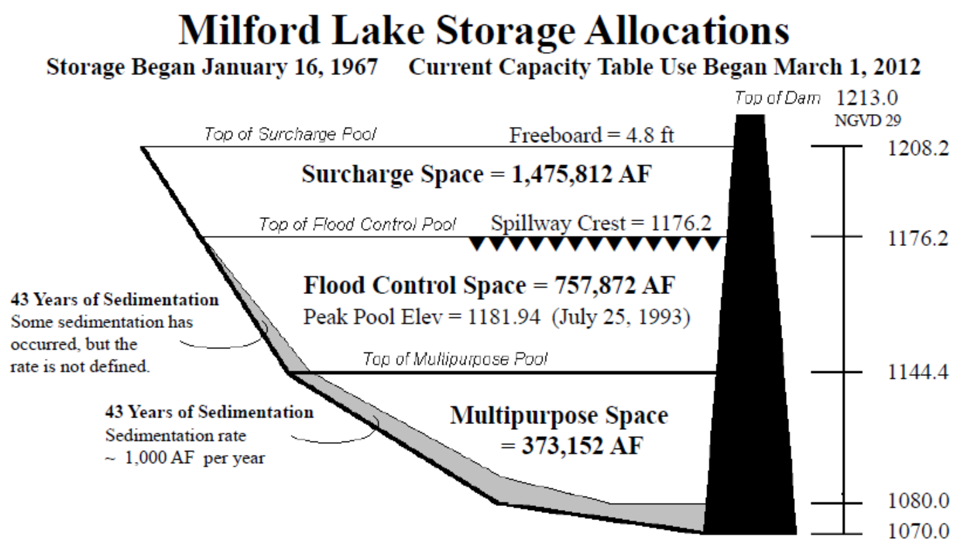


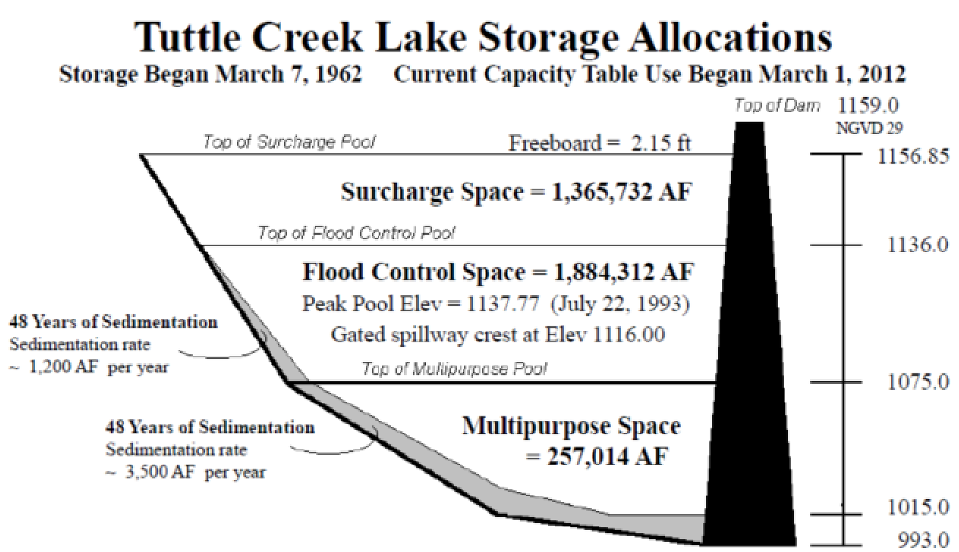
Figure 2-5. Waconda Reservoir Storage Allocations



Storage Allocations (AF)	1967	1980	2009	2067 (est)
Total Flood Control Pool	**757,746**	**756,601**	**757,872**	**700,000**
Exclusive Flood Control	700,000	700,000	700,000	700,000
FP Sediment Reserve	57,746	56,601	57,872	0
Total Multipurpose Pool	**415,352**	**388,608**	**373,152**	**300,000**
In-Service Water Supply	0	101,650	101,650	300,000
Future Use Water Supply	300,000	198,350	198,350	0
MP Sediment Reserve	115,352	88,608	73,152	0

2009 tables now used for lake ops. State of Kansas (KWO) contracted for water supply allocation in 1974. The initial in-service increment of 101,650 AF is subcontracted to the Kansas River Water Assurance District and KP&L. Until called into service, the future use space is operated for other MP uses.

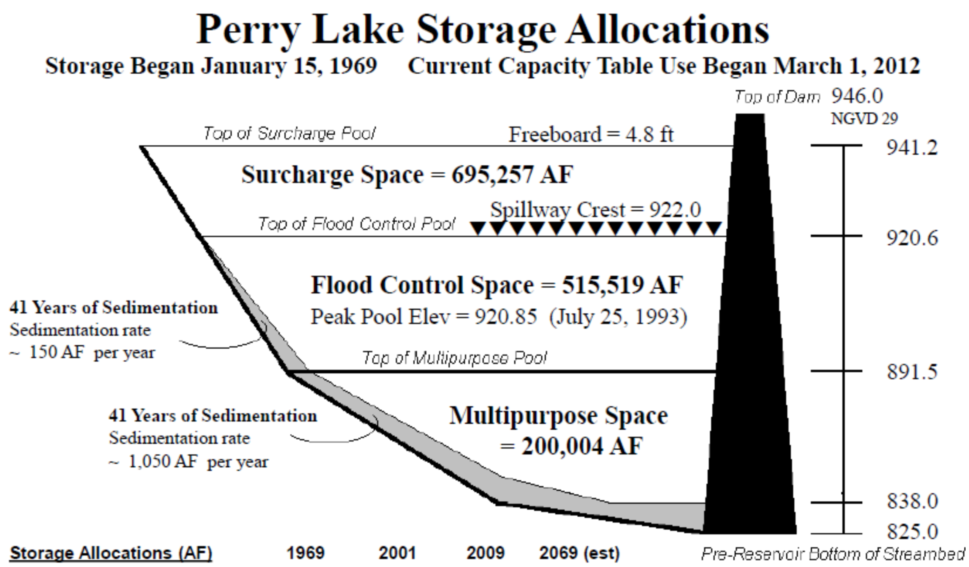
Figure 2-6. Milford Reservoir Storage Allocations



Storage Allocations (AF)	1962	1989	2009	2035 (est)
Total Flood Control Pool	**1,941,705**	**1,922,085**	**1,884,312**	**1,879,000**
Projected Flood Control	1,941,705	1,879,000	1,879,000	1,879,000
Nominal Sediment Reserve	0	43,085	5,312	0
Total Multipurpose Pool	**425,312**	**335,100**	**257,014**	**122,000**
Water Supply (all in-service)	0	50,000	50,000	50,000
WQ, Nav, Other Purposes	185,000	72,000	72,000	72,000
MP Sediment Reserve	240,312	213,100	135,014	0

The 1989 Reallocation added a water supply allocation and added space to the sediment reserve to extend its design life from 2012 to 2035. The State (KWO) contracted for the water supply, all of which is in service.

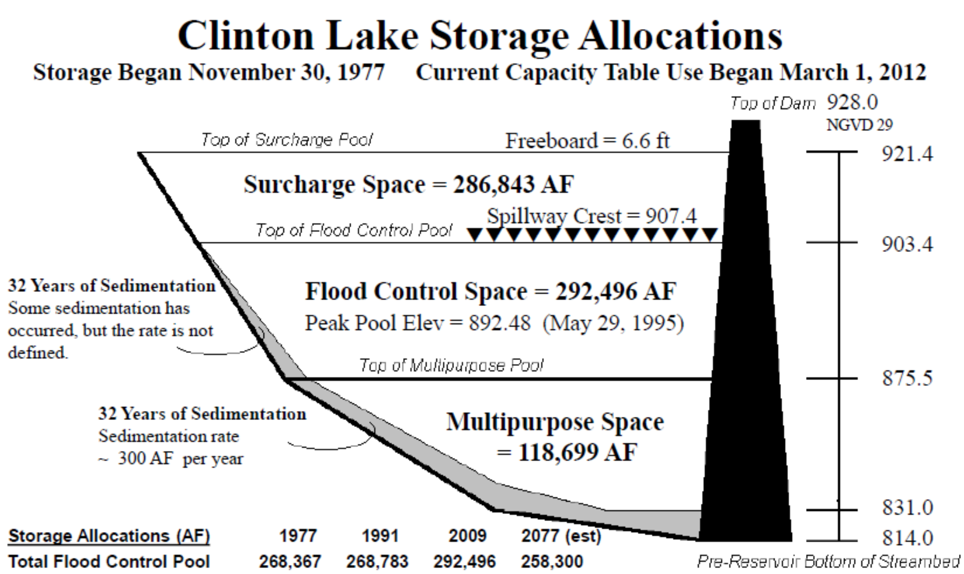
Figure 2-7. Tuttle Creek Reservoir Storage Allocations



Storage Allocations (AF)	1969	2001	2009	2069 (est)
Total Flood Control Pool	**521,880**	**515,397**	**515,519**	**480,000**
Exclusive Flood Control	480,000	480,000	480,000	480,000
FP Sediment Reserve	41,880	35,397	35,519	0
Total Multipurpose Pool	**243,220**	**206,682**	**200,004**	**150,000**
In-Service Water Supply	0	25,000	25,000	150,000
Future Use Water Supply	150,000	125,000	125,000	0
MP Sediment Reserve	93,220	56,582	50,004	0

2009 tables now used for operations. The State of Kansas (KWO) contracted for the water supply allocation in 1977. The initial 25,000 AF increment is contracted to the Kansas River Water Assurance District. Valley Falls has a separate water withdrawal contract.

Figure 2-8. Perry Reservoir Storage Allocations



Storage Allocations (AF)	1977	1991	2009	2077 (est)
Total Flood Control Pool	**268,367**	**268,783**	**292,496**	**258,300**
Exclusive Flood Control	258,300	258,300	258,300	258,300
FP Sediment Reserve	10,067	10,483	34,196	0
Total Multipurpose Pool	**129,171**	**125,334**	**118,699**	**110,400**
In-Service Water Supply	53,520	53,520	53,520	89,200
Future Use Water Supply	35,680	35,680	35,680	0
Water Quality	21,200	21,200	21,200	21,200
MP Sediment Reserve	18,771	14,934	8,299	0

2012 tables based on 2009 lake survey. Water supply allocation contracted to the State of Kansas (KWO) in 1977, with an initial in-service increment of 53,500 AF; the available water is subcontracted to the cities of Lawrence, Baldwin City, and six Douglas County rural water districts.

Figure 2-9. Clinton Reservoir Storage Allocations

Reservoirs upstream of Kanopolis, Waconda, and Milford have not been included in this study; however, these reservoirs do impact the inflow records of the downstream reservoirs after their respective closure dates since observed inflows are relied upon in the performance of this study. These upstream reservoirs and their dam closure dates are show in Table 2-2.

Table 2-2. Reservoirs upstream of the study area.

Downstream Lake	Upstream Lake(s)	Closure Date	Initial Fill Date
Kanopolis	Cedar Bluff	Sep 10, 1950	Jun 21, 1951
Waconda	Webster	May 3, 1956	Jun 18, 1957
	Kirwin	Mar 7, 1955	Jul 2, 1957
Milford	Lovewell	May 29, 1957	May 20, 1958
	Harlan County	July 22, 1951	Nov 14, 1952
	Norton	Jan 8, 1964	Jun 21, 1967
	Harry Strunk	Aug 8, 1949	Apr 2, 1951
	Hugh Butler	Sep 5, 1961	May 22, 1961
	Swanson	May 4, 1953	May 15, 1957
	Bonny	Jul 6, 1950	Mar 29, 1954
	Enders	Oct 23, 1950	January 1952

3. Methodology

HEC-ResSim version 3.5 was used to simulate reservoir operations and route water through the basin. HEC-ResSim is a reservoir simulation model which incorporates user-defined rules and data sets to determine reservoir outflows, resulting pool elevations and flow at downstream locations. The model routes reservoir outflows using hydrologic routing methods defined by the user. A depiction of the model junctions and reaches in the basin is shown in Figure 3-1 below. Note that the model schematic shows some portions of the Republican River above Milford Reservoir as being included in this study; however, this model reach was not set up due to time constraints and the majority of the KRRFSS alternatives being focused on other portions of the basin. Active modeling along the Republican River begins at Clay Center which is the inflow gage to Milford Reservoir. In addition to the Kansas River Basin, the Missouri River is modeled from St. Joseph to Waverly to allow the Missouri River control point of Waverly, Missouri to be modeled properly.

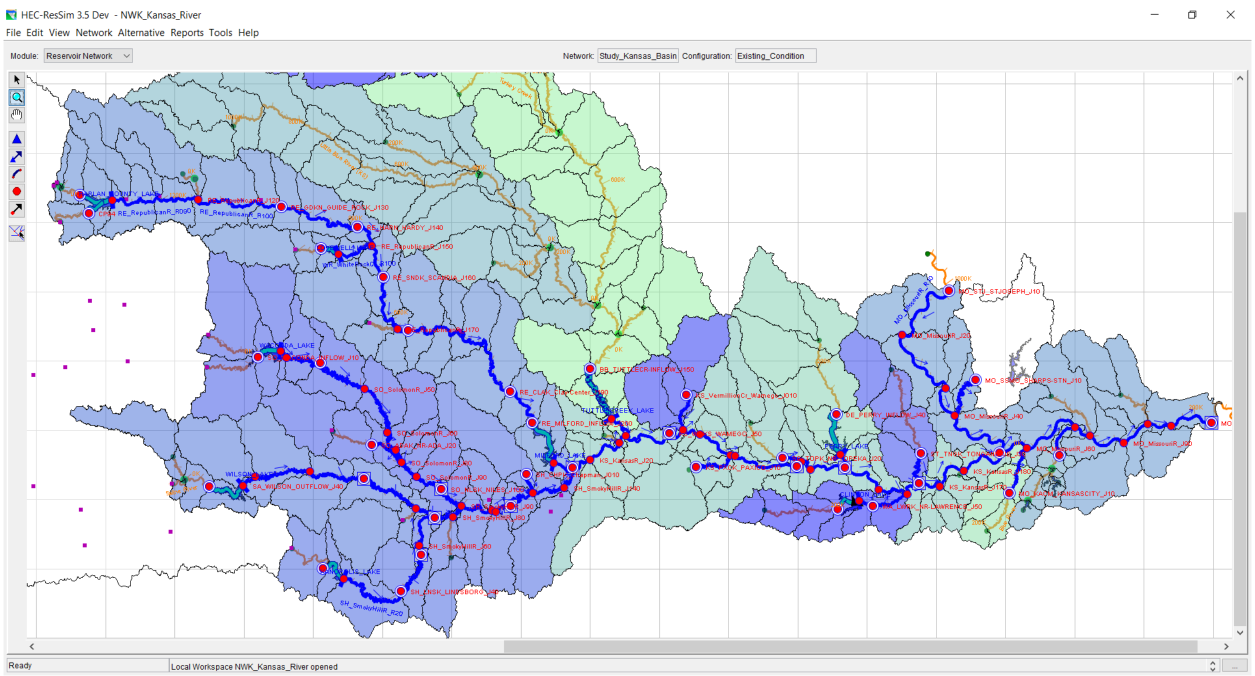


Figure 3-1. HEC-ResSim Kansas River network

An existing Kansas River basin HEC-ResSim model was utilized to begin this study. The existing model was completed in April 2017 through support of the Modeling, Mapping, and Consequence (MMC) Production Center. This model was primarily developed to operate as part of the CWMS modeling package using inputs from HEC-HMS and feeding output data into HEC-RAS. It was setup to run in an hourly time step and primarily used for real-time forecasting. The KRRFSS model modified the existing reservoir network to be used for long-term daily modeling. Over the course of this project, hydrologic routing parameters, local flow junctions, and the reservoir operation rule set were re-evaluated and updated where necessary to better suit the purposes of the KRRFSS.

3.1 Reservoir Data Extension

To utilize the model, a complete period of analysis data set for a number of inputs is required. Data sets were collected from observed records (period of record data) and extended, filling in missing and historical data by a variety of methods. Observed records were obtained from the U.S. Geological Study (USGS), comprising official daily streamflow records, as well as record inflow, release, and elevation data from the Corps Water Management System (CWMS) database. The period of analysis for the model input data was December 1, 1919 through January 2, 2020 with the first month used as a model lookback period. The functional data output is from 1920 through 2019. The model utilizes a daily time step in simulations.

Inflow from the Kansas City District CWMS database was used for the period after all lakes were constructed through 2019. CWMS lake inflow is mean daily as averaged over the 24-hour period extending from 1200 hours UTC of the previous day to 1200 hours UTC of the current day. As the Model operates on a midnight to midnight (UTC) basis, the inflow data from the database is time shifted from the model timestep. To account for this effect, the data has been shifted backward 12 hours. No averaging between days was attempted because that would further diminish peak inflow magnitudes. This data was all simply shifted backwards 12 hours. All USGS data is provided as a daily average value at midnight UTC and no shift is necessary for this data. Once the inflow values are shifted back 12 hours the data from the CWMS database begin for each lake on the dates listed in Table 3-1.

Table 3-1. Beginning of calculated daily average inflows

Lake	Initial Database Date
Kanopolis Lake	February 16, 1948
Wilson Lake	September 3, 1963
Waconda Lake	October 17, 1967
Milford Lake	August 23, 1964
Tuttle Creek Lake	July 20, 1959
Perry Lake	July 31, 1966
Clinton Lake	November 30, 1977

The CWMS database inflow is calculated by adding the following parameters: daily change in storage, reservoir releases, and evaporation. Precipitation on the pool of the lake accounts for some of the change in storage on rainy days. The data developed for the period prior to the CWMS data does not include the rain on pool component, but only includes runoff from the upstream basin as seen in the available gages at the time. This may result in a discrepancy inherent in the pre-dam data as rain on the reservoir water surface would provide some additional inflow that otherwise may have not reached the lake if infiltration occurred. This was assumed to be a small discrepancy.

For the timeframe that precedes the period of record database entries, the lake inflow was determined by evaluating the upstream gages, using standard hydrologic methods and statistical analysis. All gage data was obtained from the USGS website; daily, period-average flow records were obtained in all cases. A ratio of flow based on a direct comparison of the drainage basin area ratios was used only occasionally, due to the very large areas involved and the high variability in the amount of contribution. Hydrologic conditions in the basin tend to result in a much lower runoff contribution from the western drainage areas. The following sections describe the specific methods used for each lake.

3.2 Kanopolis Lake

Kanopolis Dam is located at river mile 183.7 of the Smoky Hill River and controls about 7,857 square miles of drainage area. The dam started impounding water on 17 Feb 1948; however, the downstream gages appear to be impacted by dam construction at the date of closure on 26 Jul 1946. The observed Corps of Engineers reservoir elevation, inflow, and outflow records extend from 17 Feb 1948 through the present. As the stored data is 1200 UTC of the day before to 1200 UTC of the current day, the values have been shifted backward 12 hours to make them representative of midnight-to-midnight flows. With the time shift, the observed inflow is used from 16 Feb 1948 through 31 Jan 2019. Table 3-2 provides a list of available gage information. The Ellsworth gage is upstream of the reservoir; the Langley gage is 0.8 miles downstream of the dam; the Lindsborg gage is about one day travel time downstream of the dam; and the Mentor gage is about two days travel time downstream of the dam.

Table 3-2. Pertinent Kanopolis Lake Gages

Gage	Drainage Area (mi^2)	Record
Smoky Hill River at Ellsworth	7,580	1Jan1900 to 31Oct 1905, 23Jul1918 to 04 July1925, Aug 1, 1928 to Present
Smoky Hill River at Langley	7,857	Oct 1, 1940 to Present
Smoky Hill River at Lindsborg	8,110	Partial years 1905 to 1923, 01Feb1930 to 29Sep1965, 31July2014 to Present
Smoky Hill River at Mentor	8,341	01Dec1923 to 01Nov1930, 22May1931 to 30Jun1932, 01Oct1947 to Present

Before the dam was constructed, inflow records are approximated using several different methods depending on the data available in the period of record beginning in 1920. Where possible the data was extended using linear and multi-linear regression as outlined in chapter 9 of EM 1110-2-1415, Hydrologic Frequency Analysis. The various approaches are outlined in Table 3-3. Comparing the simulated data to the portion of overlapping observed data for each computation method reveals the degree of correlation that was achieved. Pre-dam Langley and the Kanopolis computed inflow record were used as the observed data. HEC-DSS and Microsoft Excel were utilized to develop linear and multi-linear regressions between gages to approximate flow at the dam when no data was available. The equations were generally calculated in DSS and the plots in Excel. Occasionally, the coefficients were slightly different between the two methods. Each equation is explained in more detail in the following sections.

Table 3-3. Methods used to extend daily Kanopolis inflow records from 1920 to present

Date Range	Equation Used	Comment
23July1918 to 30Dec1918	KANS = 51.308+0.995*Ellsworth	Based on linear regression with Ellsworth data
31Dec1918 to 30July1919	KANS = -11.681+0.513*Ellsworth +0.507*Lindsborg	Based on multi-linear regression with Ellsworth and Lindsborg minus 1 day
31July1919 to 28Feb1920	KANS = 51.308+0.995*Ellsworth	Based on linear regression with Ellsworth data
29Feb1920 to 29Sep1920	KANS = -11.681+0.513*Ellsworth +0.507*Lindsborg	Based on multi-linear regression with Ellsworth and Lindsborg minus 1 day
30Sep1920 to 27Feb1921	KANS = 51.308+0.995*Ellsworth	Based on linear regression with Ellsworth data
28Feb1921 to 29Sep1921	KANS = -11.681+0.513*Ellsworth +0.507*Lindsborg	Based on multi-linear regression with Ellsworth and Lindsborg minus 1 day
30Sep1921 to 27Feb1922	KANS = 51.308+0.995*Ellsworth	Based on linear regression with Ellsworth data
28Feb1922 to 29Sep1922	KANS = -11.681+0.513*Ellsworth +0.507*Lindsborg	Based on multi-linear regression with Ellsworth and Lindsborg minus 1 day
30Sep1922 to 27Feb1923	KANS = 51.308+0.995*Ellsworth	Based on linear regression with Ellsworth data
28Feb1923 to 28Sep1923	KANS = -11.681+0.513*Ellsworth +0.507*Lindsborg	Based on multi-linear regression with Ellsworth and Lindsborg minus 1 day
29Sep1923 to 4July1925	KANS = 51.308+0.995*Ellsworth	Based on linear regression with Ellsworth data
5Jul1925 to 31July1928	KANS = Mentor/1.0616	Mentor reduced to account for gain in watershed between Kanopolis and Mentor.
01Aug1928 to 30Jan1930	KANS = 51.308+0.995*Ellsworth	Based on linear regression with Ellsworth data
31Jan1930 to 22Oct1940	KANS = -11.681+0.513*Ellsworth +0.507*Lindsborg	Based on multi-linear regression with Ellsworth and Lindsborg minus 1 day
23Oct1940 to 26Jul1946		Used the USGS daily Langley Flow
27Jul1946 to 15Feb1948	KANS = 51.308+0.995*Ellsworth	Based on linear regression with Ellsworth data
16Feb1948 to present		Kanopolis Inflow minus 12 hours

The regulation impacts of upstream Cedar Bluff Reservoir were not modeled as part of this analysis. Cedar Bluff controls 5,365 square miles and began storage on 13 Nov 1950. The majority of the Kanopolis inflow comes from regions downstream of Cedar Bluff as the eastern portion of the basin is much wetter than the west. Since this study is developing a period of record regulated data set, ideally the Kanopolis inflow would be a fully regulated data set. Since the extended inflow data set is a mixture of unregulated before 13 Nov 1950 and fully regulated after it, the extended inflows before Nov 1950 may tend to be higher than a fully regulated system as discussed in the following paragraphs.

Upstream reservoir holdouts have been calculated from 1950 through 2019 and routed to Kanopolis Reservoir. Holdouts are calculated by subtracting inflow from the outflow for a given day. Holdouts are positive when the reservoir is rising and negative when it is dropping. The upstream holdouts routed to Kanopolis were then used to calculate the unregulated Kanopolis inflow starting in 1950. To do this the routed holdouts are added to the daily inflow.

To understand the impact of regulation above Kanopolis the annual flow volume of holdouts, observed inflow and unregulated inflow were calculated and can be compared in Table 3-4. The percent difference between the inflow and the unregulated inflow is also shown. Some years there is very little difference or even increased flow because of the regulation. However, some years result in significantly reduced flows. The long-term average percent difference indicates a 10% reduction in annual flow volume by having Cedar Bluff Reservoir in place. If additional time and funding are available, it is recommended to further work on developing a fully regulated Kanopolis inflow. Some additional, event specific, plots are included in Section 2.1 of "Attachment 1 Supporting Plots" that show examples of observed and unregulated flows for Kanopolis during specific flood events.

Table 3-4. Annual flow volume for holdouts, inflows, and unregulated inflows at Kanopolis Reservoir.

	Annual Flow Volume			
Year	**Upstream Holdouts Routed to Kanopolis**	**Kanopolis Observed Inflow**	**Kanopolis Calculated Unregulated Inflow**	**Percent Difference**
1948		127,375		
1949		317,878		
1950		453,658		
1951	145,531	1,063,580	1,209,170	14%
1952	-41,303	172,680	131,416	-24%
1953	10,004	62,318	72,339	16%
1954	-1,459	66,061	64,626	-2%
1955	63,116	104,906	168,038	60%

Year	Annual Flow Volume			Percent Difference
	Upstream Holdouts Routed to Kanopolis	Kanopolis Observed Inflow	Kanopolis Calculated Unregulated Inflow	
1956	25,510	41,686	67,207	61%
1957	52,830	574,080	626,939	9%
1958	-17,514	394,855	377,339	-4%
1959	32,161	222,831	255,021	14%
1960	34,829	408,325	443,186	9%
1961	32,193	441,606	473,822	7%
1962	-1,060	302,468	301,414	0%
1963	32,363	77,763	110,174	42%
1964	19,087	75,304	94,418	25%
1965	58,264	242,449	300,755	24%
1966	892	120,795	121,728	1%
1967	25,140	305,679	330,843	8%
1968	2,999	111,465	114,465	3%
1969	36,209	319,472	355,726	11%
1970	1,882	166,383	168,283	1%
1971	882	247,423	248,322	0%
1972	26,863	115,173	142,067	23%
1973	50,157	800,417	850,614	6%
1974	-280	301,982	301,779	0%
1975	19,775	200,830	220,630	10%
1976	-5,294	85,696	80,422	-6%
1977	-3,604	113,541	109,960	-3%
1978	-11,675	65,341	53,694	-18%
1979	6,346	159,488	165,854	4%
1980	2,365	88,407	90,817	3%
1981	4,553	124,911	129,491	4%
1982	13,290	97,988	111,303	14%
1983	3,581	31,728	35,352	11%
1984	6,949	71,407	78,422	10%
1985	3,610	118,147	121,791	3%
1986	2,285	82,603	84,914	3%
1987	23,632	455,448	479,125	5%
1988	2,503	33,209	35,729	8%
1989	1,841	61,463	63,317	3%

Year	Annual Flow Volume: Upstream Holdouts Routed to Kanopolis	Annual Flow Volume: Kanopolis Observed Inflow	Annual Flow Volume: Kanopolis Calculated Unregulated Inflow	Percent Difference
1990	3,574	115,773	119,344	3%
1991	2,289	52,969	55,289	4%
1992	1,232	173,677	174,928	1%
1993	66,674	946,238	1,012,932	7%
1994	15,063	107,312	122,395	14%
1995	38,154	285,210	323,381	13%
1996	81,193	244,090	325,306	33%
1997	33,559	125,032	158,607	27%
1998	47,420	298,475	345,991	16%
1999	26,988	220,664	247,718	12%
2000	29,411	134,367	163,827	22%
2001	32,680	270,601	303,367	12%
2002	7,456	56,490	63,987	13%
2003	12,072	65,936	78,066	18%
2004	11,822	58,811	70,665	20%
2005	6,063	28,332	34,469	22%
2006	2,987	19,537	22,524	15%
2007	21,125	362,529	383,736	6%
2008	15,012	295,219	310,289	5%
2009	13,996	87,299	101,363	16%
2010	29,032	104,138	133,243	28%
2011	11,856	55,642	67,580	21%
2012	6,785	21,464	28,282	32%
2013	3,535	62,287	65,871	6%
2014	21,618	84,760	106,465	26%
2015	8,237	42,522	50,798	19%
2016	12,044	134,140	146,229	9%
2017	10,248	161,041	171,332	6%
2018	29,060	291,326	320,443	10%
2019	66,775	699,607	765,934	9%

To extend the Kanopolis inflow record, the first preference was to use the Langley flow since it is at the dam site and did not need to be transformed. This data set was available from October 1940 to July 1946.

The second preference was to use the multi-linear regression between Ellsworth and Lindsborg minus one day. The regression equation was matched to the Langley pre-dam data. Shifting Lindsborg back one day resulted in a more fitting regression since the peak flows at Ellsworth and Lindsborg were closer to each other. This equation did a good job of balancing the peak flows with the low flow conditions. This multi-linear regression yielded an R^2 value of 0.8429 which is the best of any of the methods; however, it also had the least amount of overlapping observed data since it was only correlated with the pre-dam Langley data. All other observed Lindsborg flow was a regulated data set and was not used for correlation. Figure 3-2 shows the relationship.

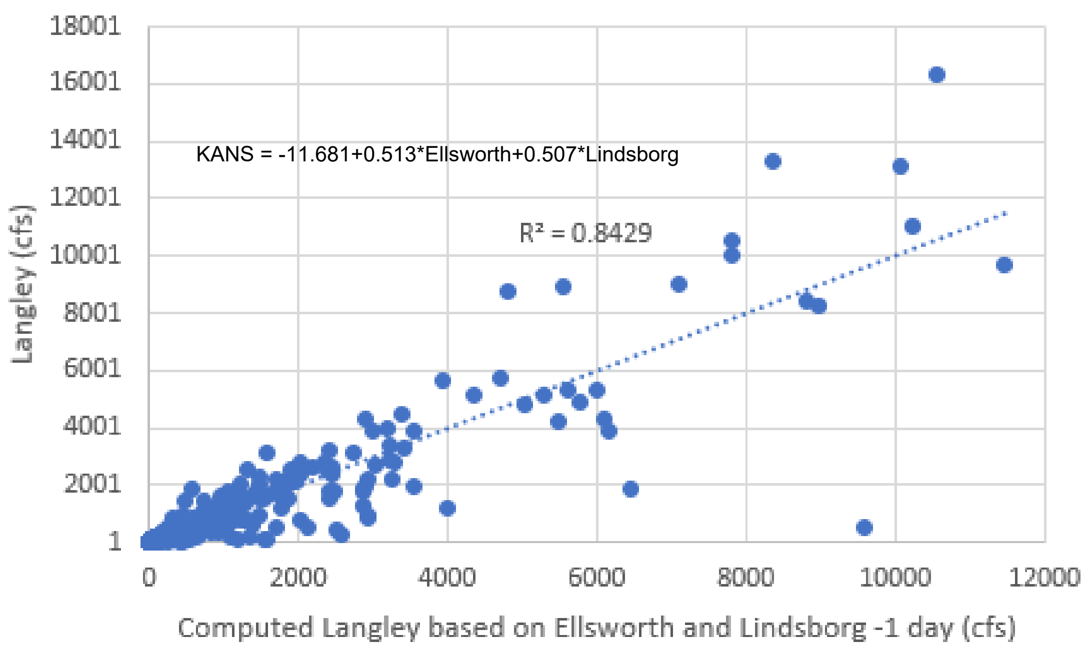


Figure 3-2. Relationship between the daily Langley flow and the computed daily flow from the multi-linear regression of Ellsworth and Lindsborg -1 day

The third preference was to use a linear regression with Ellsworth. This regression was developed using the period of record Ellsworth data as it correlated to the period of record Kanopolis inflow combined with the pre-dam Langley flow since all these records are either unregulated or impacted equally by regulation. The R^2 of 0.8018 is slightly worse than the multi-linear regression, but still shows a reasonable correlation. Figure 3-3 shows the data correlation and resulting regression equation between observed data.

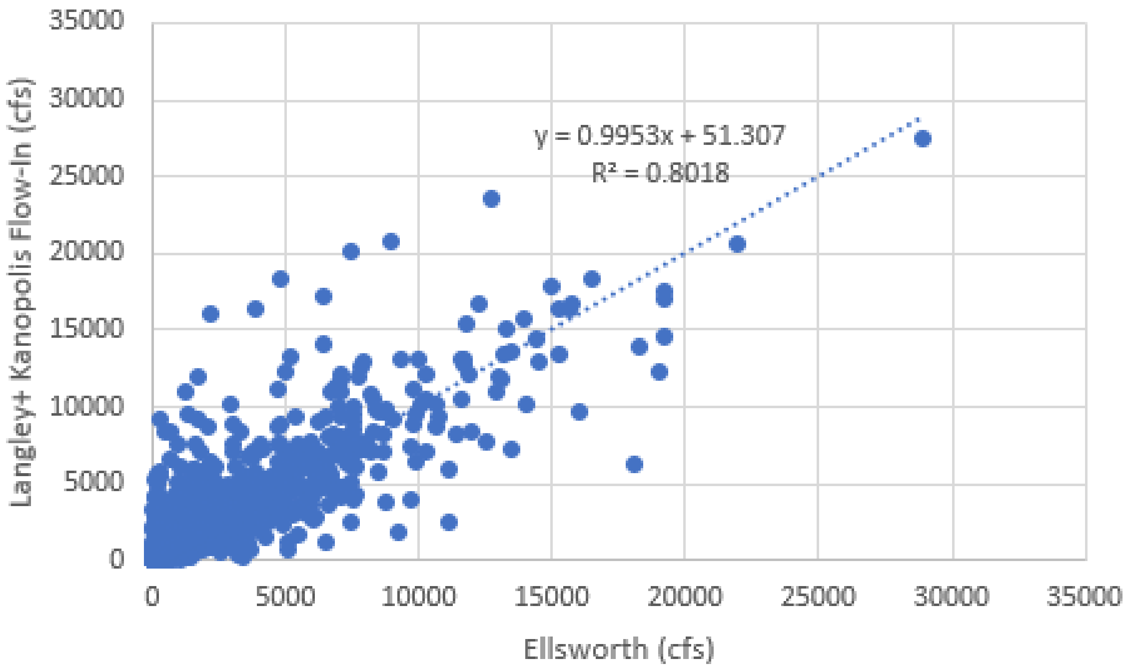


Figure 3-3. Relationship between pre-dam, daily Langley and Kanopolis Inflow observed data and observed Ellsworth data

After these methods are used a small portion of data is missing from 1925 to 1928. Unregulated data exists at Mentor during this time. However, there is very little overlap of Mentor data with any other dataset during the unregulated period to be used in developing regression equations. Consequently, the Mentor data set was transformed based on the watershed area ratio. There is approximately 6% increase in watershed area between Kanopolis and Mentor.

To test the accuracy of this transformation, the relationship between regulated Langley and Mentor observed was plotted. The travel time from Kanopolis to Mentor is two to three days. To account for this, the R^2 of the Langley vs. Mentor data was tested for observed data, Mentor minus one day, Mentor minus two days, and Mentor minus three days. The best R^2 value was the Mentor minus two days with an R^2 of 0.6747. The Mentor data was shifted backward two days and then divided by 1.06 to develop the transform of Mentor to Kanopolis which is shown in Figure 3-4. The plot shows a skew for occasional higher flow at Mentor. This occurs when rainfall in the watershed area downstream of Langley and upstream of Mentor contribute to significantly higher flows at Mentor than at Langley.

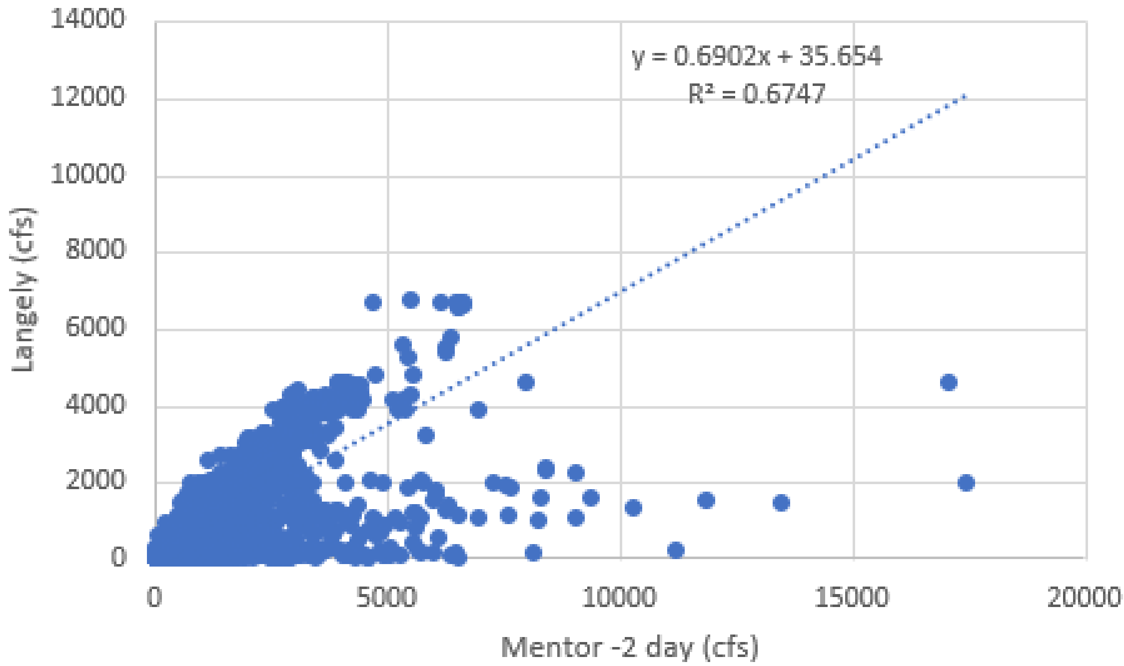


Figure 3-4. Relationship between regulated Langely and Mentor flow daily observed data.

A plot of the final extended Kanopolis inflow is provided in Figure 3-5.

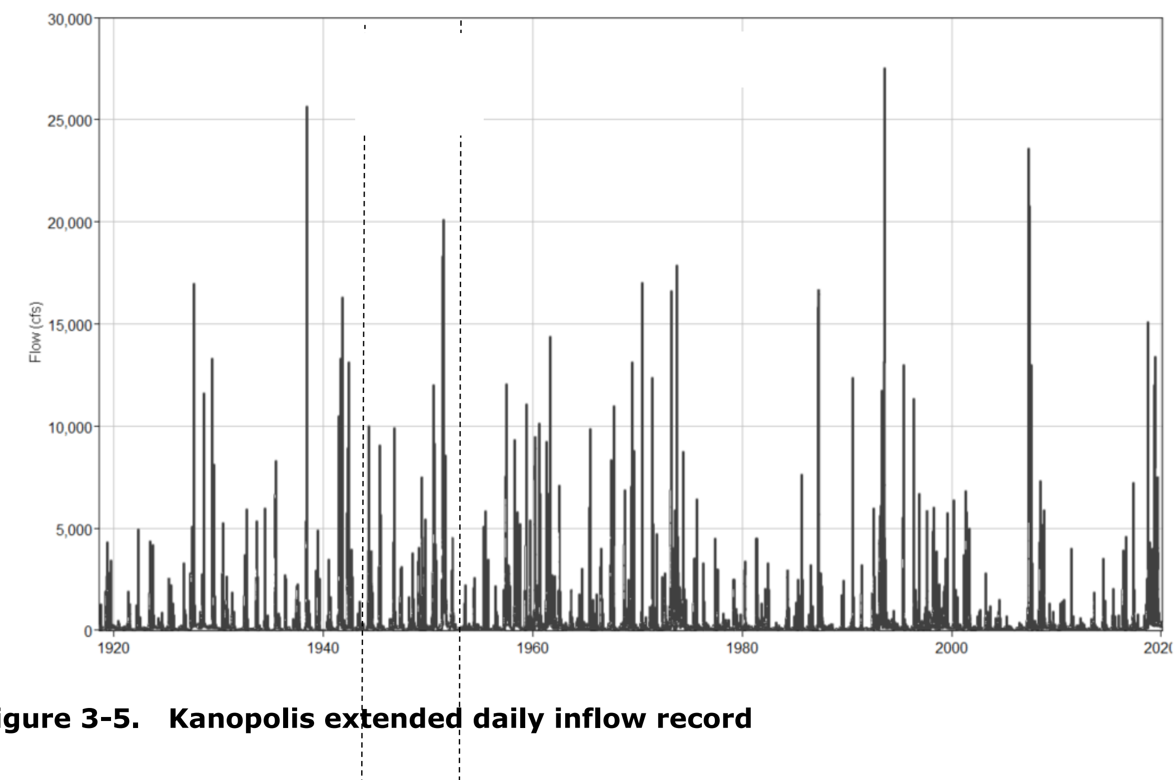


Figure 3-5. Kanopolis extended daily inflow record

3.2.1 Wilson Dam

Wilson Dam is located at river mile 153.9 of the Saline River and controls about 1,917 square miles of drainage area. The date of closure is September 3, 1963 and the lake began impounding water in January 1964. The multipurpose pool was initially filled in March 1973. Table 3-5 shows the available gage information. The Wilson gage, which was within the pool near the dam site, provides a historic record through 1963 until the gage was inundated by the lake. The Russell gage is upstream of the lake and provides current lake inflow data. The Tescott gage is far below the dam and there is a gain of over 900 square miles between the dam and Tescott.

Table 3-5. Pertinent Saline River gages

Gage	Drainage Area (mi^2)	Record
Saline River at Russell, KS	1,502	Oct 1, 1945 to Present
Saline River at Wilson, KS	1,900	May 11, 1929 to Sep 30, 1963
Saline River at Tescott, KS	2,820	Sept 1, 1919 to Present

The CWMS database records inflow data beginning on September 4, 1963 for Wilson Lake. As the stored data is 1200 UTC of the day before to 1200 UTC of the current day, the values have been shifted back 12 hours to make them representative of midnight-to-midnight flows. With the time shift, the observed inflow is used from 03 Sept 1963 through 31 Jan 2019.

For the period prior to May 1929, a regression equation based on the Tescott data was necessary. Observed unregulated (pre-dam) Tescott data was compared to the unregulated Wilson gage data. The best correlation was found by shifting Tescott back two days. This lined up the peak flow between the two gages. The regression equation intercept was set to zero to provide more reasonable flow results instead of the fully optimized R-Squared. The relationship is shown in Figure 3-6. The correlation is poor but considering the amount of watershed between the two gages, it is understandable. The equation used to estimate Wilson inflow from 01 Sept 1919 to 10 May 1929 based on time shifted Tescott flow is Wilson=0.4774*Tescott + 0.

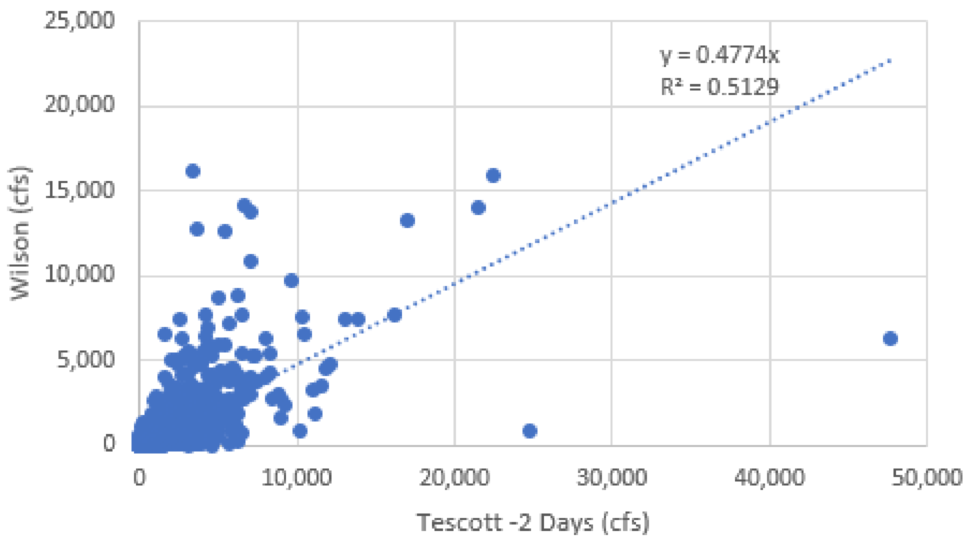


Figure 3-6. Relationship between daily Tescott flow shifted back two days and the Wilson observed flow

The poor relationship between Wilson and Tescott is concerning but alleviated somewhat by the fact that 1919 through 1926 were dry years with the peak flow at Tescott not exceeding 3000 cfs. More flow was observed in 1927 and 1928 with peak flows of 5,480 and 6,150 cfs, respectively. A plot of the inflow from 1919 to 2019 is provided as Figure 3-7.

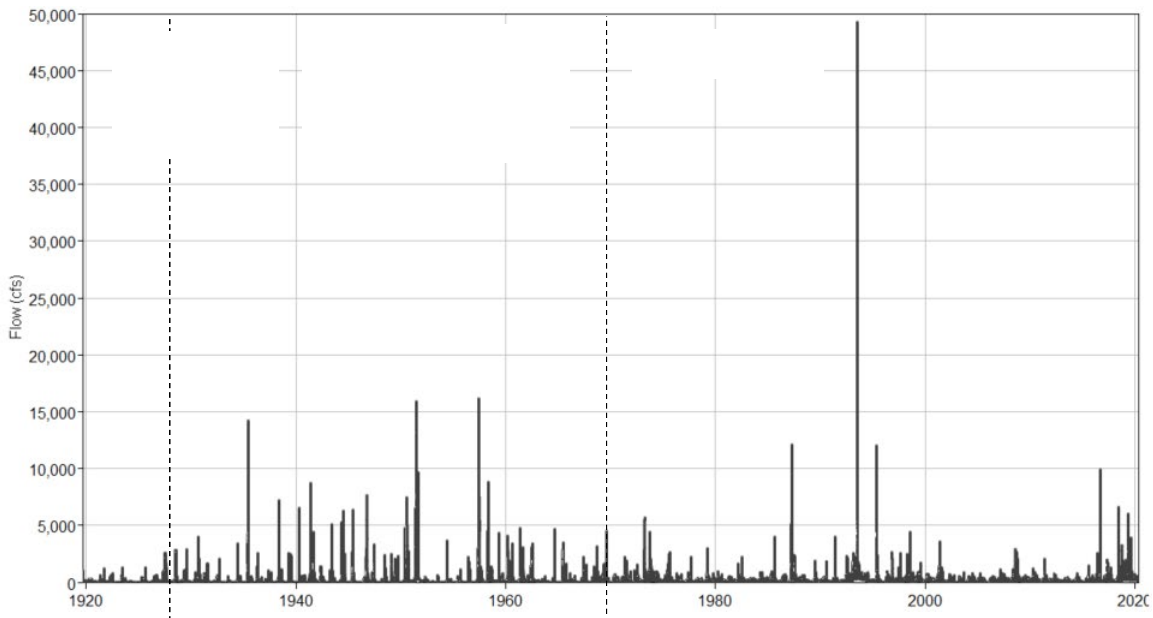


Figure 3-7. Wilson daily extended inflow record

3.2.2 Waconda Lake

Glen Elder Dam impounds Waconda Lake and is located at river mile 172.4 of the Solomon River. Glen Elder controls about 2,559 square miles drainage area below the upstream dams of Kirwin and Webster Reservoirs. The total drainage area including Kirwin (1,367 square miles) and Webster (1,150 square miles) is 5,076 square miles. Kirwin Reservoir is on the North Fork Solomon River and was initially closed on 07 Mar 1955, achieving full conservation pool (multi-purpose pool) on 02 Jul 1957. Webster Reservoir is on the South Fork Solomon River and was initially closed on 03 May 1956, achieving full conservation pool (multipurpose pool) on 18 June 1957. The date of Glen Elder dam closure was 18 Oct 1967. The reservoir did not initially fill to the top of the conservation pool until 16 May 1973.

Table 3-6 provides the available gage information. The North Fork Solomon River at Portis, which is upstream of the reservoir, was installed on 17 Sep 1945. The South Fork Solomon River at Osborne, which is also upstream of the reservoir, was installed on 28 Mar 1946. The Glen Elder gage, which is just downstream of the dam, was installed on 01 Oct 1964. The Beloit gage supplies historic stream flow data downstream of the dam site at river mile 145.7 on the Solomon River, from 14 Apr 1929 to 30 Sep 1965. Referencing recent gate changes and gage data, the Glen Elder gage is 3 to 6 hours travel time from Glen Elder Dam and Beloit is 12 to 24 hours travel time downstream of the dam.

Table 3-6. Pertinent Waconda Lake Gages

Gage	Drainage Area (mi^2)	Record
North Fork Solomon River at Kirwin, KS	1,367	Aug 30, 1919 to Sept 29, 2002
North Fork Solomon River at Portis, KS	2,315	Sept 17, 1945 to present
South Fork Solomon River at Alton, KS	1,720	Aug 31, 1919 to Sept 29,1957
South Fork Solomon River at Osborne, KS	2,012	Mar 28, 1946 to present
Solomon River near Glen Elder, KS	5,340	Oct 1, 1964 to present
Solomon River at Beloit, KS	5,440	Apr 14, 1929 to Sep 30, 1965 and July 17, 2012 to present
Solomon River at Niles, KS	6,770	May 6, 1897 to present

Waconda lake inflow from 18 Oct 1967 to the end of the study period originate from the CWMS database. As the stored data is 1200 UTC of the day before to 1200 UTC of the current day, the values have been shifted back 12 hours to make them representative of midnight-to-midnight flows. With the time shift, the observed inflow is used from 17 Oct 1967.

The Beloit gage can be used to determine lake inflow values from 14 Apr 1929 until the gage was discontinued on 30 Sep 1965. The Glen Elder gage represents the period from 01 Oct 1964 until the beginning of the Waconda inflow record (18 Oct 1967) and has a one-year overlap with the Beloit gage. Prior to 14 Apr 1929, a combination of Kirwin, Alton, and Niles data are used to extend the inflow record back to 1920.

Because there is very little data at the dam site prior to the dam, regression equations were used to extend the Beloit data record back to 1920. Afterward, all the pre-dam Beloit data was adjusted to the dam location. Shifting data twice appeared to be the best method because that allowed regression equations to have a long period of observed unregulated Beloit data for comparison.

The Beloit gage was extended by developing a multi-linear regression equation in DSS. This relationship was based on the fully unregulated Beloit data prior to 02 May 1956, Kirwin shifted forward one day, Alton shifted forward one day, and Niles shifted backward two days. These parameters resulted in a reasonable simulation of the Beloit data with an R^2 factor of 0.8677 as shown in Figure 3-8. Kirwin and Alton were not in operation from June 1925 to August 1928, so Niles was used to estimate Beloit during that time frame. It was found that the best linear relationship between Beloit and Niles came from shifting Niles back one day. This relationship is shown in Figure 3-9. The data and equations used to extend Beloit are shown in Table 3-7.

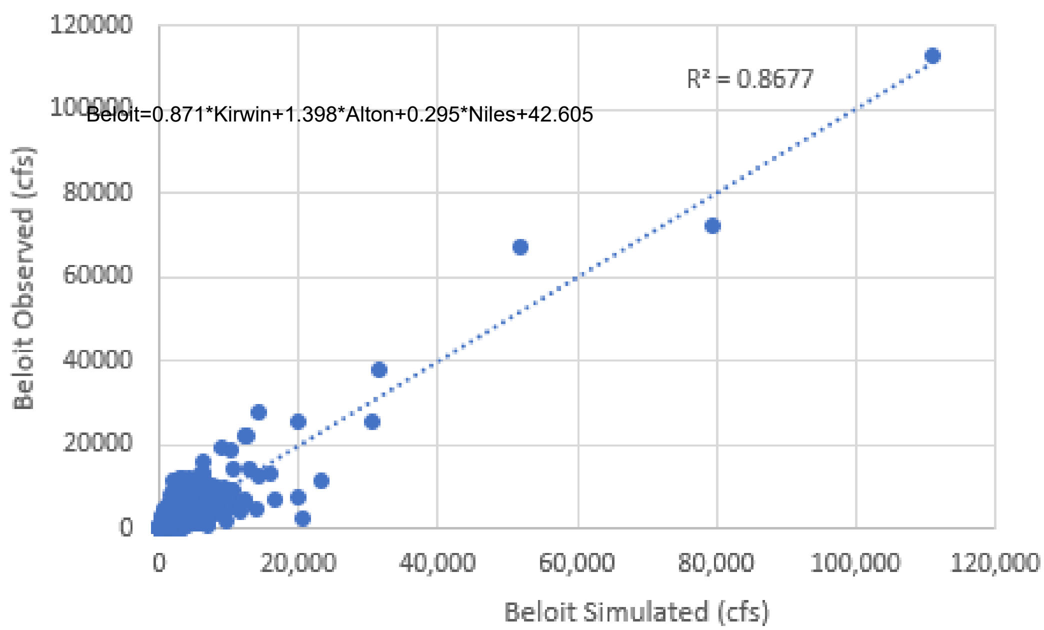


Figure 3-8. Beloit multi-linear regression relationship base on daily data.

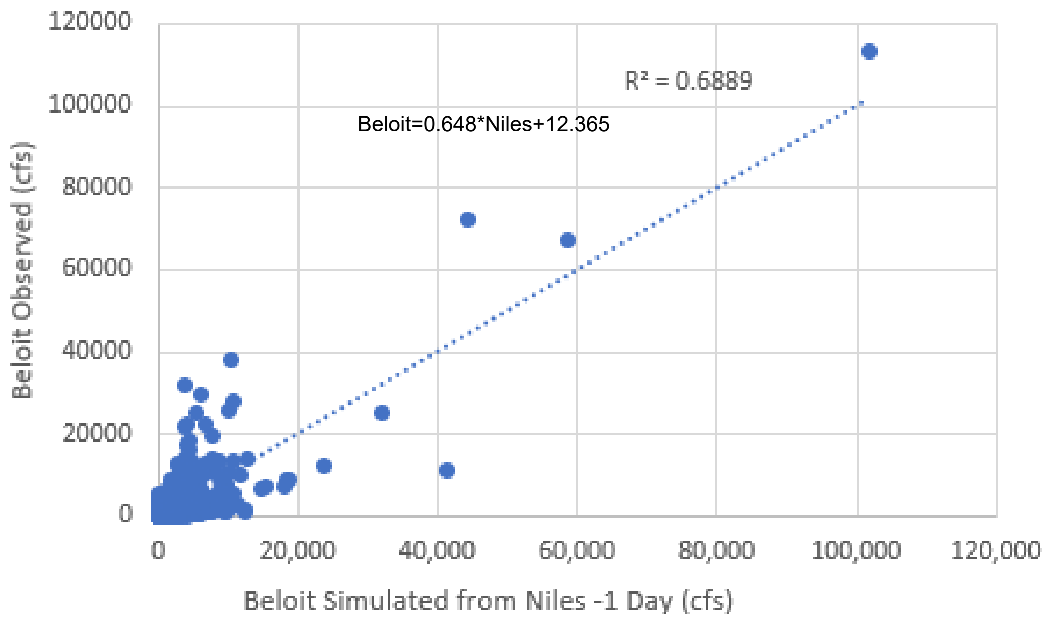


Figure 3-9. Beloit linear relationship with the daily Niles data set

Table 3-7. Data used to extend daily Beloit flow

Date Range	Equation Used	Comment
01Sept1919 to 01July1925	Beloit=0.871*Kirwin+1.398*Alton +0.295*Niles+42.605	Based on multi-linear regression with Kirwin plus 1 day, Alton plus 1 day, and Niles minus 2 days
02July1925 to 12Aug1928	Beloit=0.648*Niles+12.365	Based on linear regression with Niles minus 1 day
13Aug1928 to 13Apr1929	Beloit=0.871*Kirwin+1.398*Alton +0.295*Niles+42.605	Based on multi-linear regression with Kirwin plus 1 day, Alton plus 1 day, and Niles minus 2 days
14Apr1929 to 29Sep1965		Observed Beloit data

The Beloit gage is approximately 26 miles downstream of the dam and represented 364 more square miles of drainage basin. The ratio of the Beloit and Waconda Lake drainage basins is:

$$5076 \text{ mi}^2 / 5440 \text{ mi}^2 = 93.3\%$$

From 17 July 2012 to 31 Dec 2019 the Waconda outflow record overlaps with the Beloit gage data. While this is all a regulated data set, it provides insight into the relationship between the gages and how much discharge is provided by the uncontrolled drainage area below the dam. It was found that the best relationship comes from shifting Beloit back one day to help with travel time. The gages' relationship is provided in Figure 3-10. The regression equation indicates that about 80% of the Beloit flow comes from Waconda. The other 20% comes from below the dam which is more than the watershed area indicates; however, the basin is much wetter in the eastern portion of the basin. This relationship was compared to the annual flow volume at each gage from 2013 through 2019 and the Waconda outflow ranged from 66% to 86% of the Beloit flow with an average of 76%. This compares well to the regression equation.

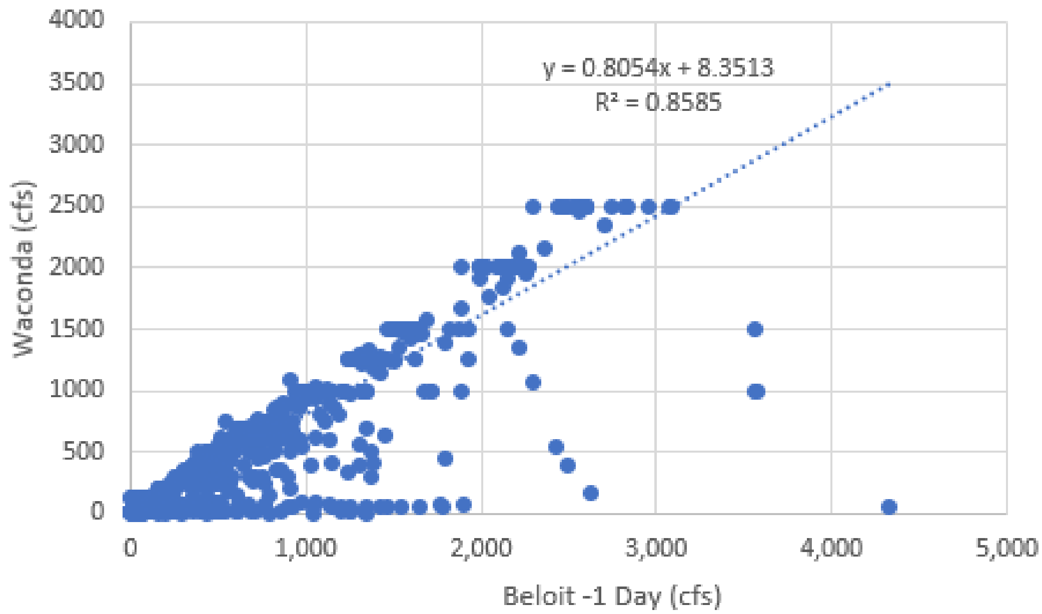


Figure 3-10. Relationship between Waconda outflow and regulated Beloit daily observed flow data

The extended Beloit data was used to estimate the Waconda inflow from 1919 through 1964. Once the Glen Elder gage flow becomes available it is adjusted to estimate inflow. Even though Glen Elder is the below gage for Waconda, an additional 264 mi^2 of drainage area is picked up between the dam and the gage primarily coming from the left bank tributary, Limestone Creek. The Glen Elder data was adjusted using the relationship shown in Figure 3-11. The linear equation indicates that about 87% of the Glen Elder flow comes from Waconda outflow. This relationship was compared to the annual flow volumes from both sites from 1968 to 2019. The percent of Glen Elder's flow originating from Waconda ranges from 40% to 119% with an average of 90%. The average compares favorably with the regression equation. Actual Waconda inflows are used for the period beginning 17 Oct 1967. Table 3-8 details the data that is used to estimate the Waconda inflow record.

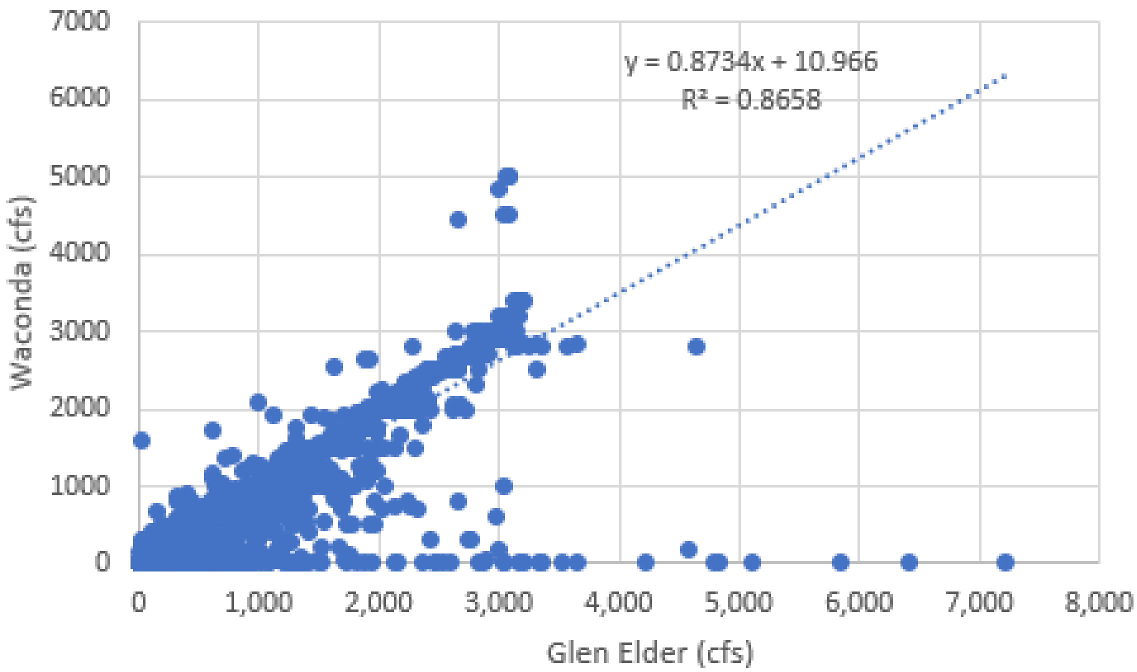


Figure 3-11. Relationship between Waconda outflow and the Glen Elder daily observed data

Table 3-8. Data used to extend the daily Waconda inflow

Date Range	Equation Used	Comment
31Aug1919 to 30Sep1964	GLEL=0.8054*Beloit+8.4201	Based on linear regression with the extended Beloit data minus 1 day
01Oct1964 to 16Oct1967	GLEL=0.873*Glen Elder+10.965	Based on linear regression with Glen Elder data
17Oct1967 to 31Dec2019		Observed Waconda Inflow

After 03 May 1956, Beloit flow is influenced by the regulation of Webster and Kirwin Reservoirs. Glen Elder inflow is influenced by this regulation. Since this KRRFSS modeling effort is not investigating these reservoirs, it is assumed that their influence on the gage record is minimal. The Solomon River basin is wetter in the east than the western side of the basin; however, depending on the event, the impact of the upstream reservoirs can influence inflows. Since this study is developing a period of record regulated data set, ideally the Glen Elder inflow would be a fully regulated data set. Since the extended inflow data set is a mixture of unregulated before 07 Mar 1955 (closure of Kirwin), partially regulated until 03 May 1956 (closure of Webster), and fully regulated after it, the extended

inflows before March 1955 may tend to be a little higher than a fully regulated system as discussed in the following paragraphs.

Upstream reservoir holdouts have been calculated from 1955 through 2019 and routed to Waconda Reservoir. Holdouts are calculated by subtracting inflow from the outflow for a given day. Holdouts are positive when the reservoir is rising and negative when it is dropping. The upstream holdouts routed to Waconda were then used to calculate the unregulated Waconda inflow starting in 1967. To do this the routed holdouts are added to the daily inflow.

To understand the impact of regulation above Glen Elder the annual flow volume of holdouts, observed inflow and unregulated inflow were calculated and can be compared in Table 3-9. The percent difference between the inflow and the unregulated inflow is also shown. Some years there is very little difference or even increased flow because of the regulation. However, some years result in significantly reduced flows. The long-term average percent difference indicates an 8% reduction in annual flow volume by having the upstream reservoirs in place. If additional time and funding are available, it is recommended to further work on developing a fully regulated Waconda inflow. Some additional, event specific, plots are included in Section 2.1 of "Attachment 1 Supporting Plots" that show examples of observed and unregulated flows for Waconda during specific flood events.

Table 3-9. Annual flow volume for holdouts, inflows, and unregulated inflows at Waconda Reservoir.

	Annual Flow Volume			
Year	**Upstream Holdouts Routed to Waconda**	**Waconda Observed Inflow**	**Waconda Calculated Unregulated Inflow**	**Percent Difference**
1955	8,696.70			
1956	6,873.60			
1957	154,844.90			
1958	42,009.50			
1959	8,488.40			
1960	28,304.50			
1961	25,231.10			
1962	30,207.70			
1963	17,946.70			
1964	-14,790.00			
1965	92,922.00			
1966	-32,450.10			
1967	8,132.40	26,310	30,487	16%

	Annual Flow Volume			
Year	**Upstream Holdouts Routed to Waconda**	**Waconda Observed Inflow**	**Waconda Calculated Unregulated Inflow**	**Percent Difference**
1968	33,596.50	98,281	131,969	34%
1969	40,725.20	160,080	200,946	26%
1970	-14,803.90	46,753	31,989	-32%
1971	-3,752.80	64,387	60,743	-6%
1972	6,663.60	55,210	61,981	12%
1973	32,405.40	443,089	475,668	7%
1974	4,552.10	199,774	204,428	2%
1975	69,722.00	170,507	240,370	41%
1976	-29,518.40	75,044	45,570	-39%
1977	-1,366.60	86,585	85,299	-1%
1978	22,121.00	83,311	105,557	27%
1979	33,914.90	202,853	236,901	17%
1980	-7,545.20	98,540	91,065	-8%
1981	17,484.60	76,761	94,360	23%
1982	21,467.40	270,585	292,160	8%
1983	-4,378.60	85,519	81,229	-5%
1984	16,999.60	145,061	162,151	12%
1985	23,810.90	92,253	116,200	26%
1986	9,744.90	104,967	114,813	9%
1987	51,386.50	516,814	568,346	10%
1988	-11,444.80	86,902	75,520	-13%
1989	3,654.60	160,792	164,574	2%
1990	329.3	101,218	101,628	0%
1991	1,501.50	43,642	45,252	4%
1992	23,870.40	170,422	194,373	14%
1993	222,041.90	1,463,164	1,684,900	15%
1994	-12,265.00	414,155	402,600	-3%
1995	38,038.60	532,588	570,734	7%
1996	33,777.00	316,115	349,935	11%
1997	9,512.90	182,059	191,697	5%
1998	22,536.50	277,551	300,152	8%
1999	43,830.40	229,342	273,267	19%
2000	-5,599.40	89,743	84,125	-6%
2001	19,129.90	167,907	187,125	11%

	Annual Flow Volume			
Year	**Upstream Holdouts Routed to Waconda**	**Waconda Observed Inflow**	**Waconda Calculated Unregulated Inflow**	**Percent Difference**
2002	-16,870.70	65,054	48,244	-26%
2003	-14,756.20	61,627	46,947	-24%
2004	-6,435.50	55,483	49,154	-11%
2005	17,359.60	66,801	84,322	26%
2006	9,524.80	28,743	38,462	34%
2007	20,467.70	74,912	95,422	27%
2008	137,266.10	410,707	548,240	33%
2009	48,200.40	219,702	267,751	22%
2010	19,683.50	492,165	512,090	4%
2011	44,033.90	437,322	481,465	10%
2012	-23,080.40	110,407	87,418	-21%
2013	-12,540.70	65,406	52,912	-19%
2014	11,768.10	68,907	80,825	17%
2015	10,221.20	106,349	116,669	10%
2016	111,730.00	194,910	306,806	57%
2017	57,680.80	200,553	258,297	29%
2018	44,555.60	306,253	350,914	15%
2019	30,584.60	785,815	819,898	4%

The extended Waconda Lake inflow hydrograph is provided as Figure 3-12.

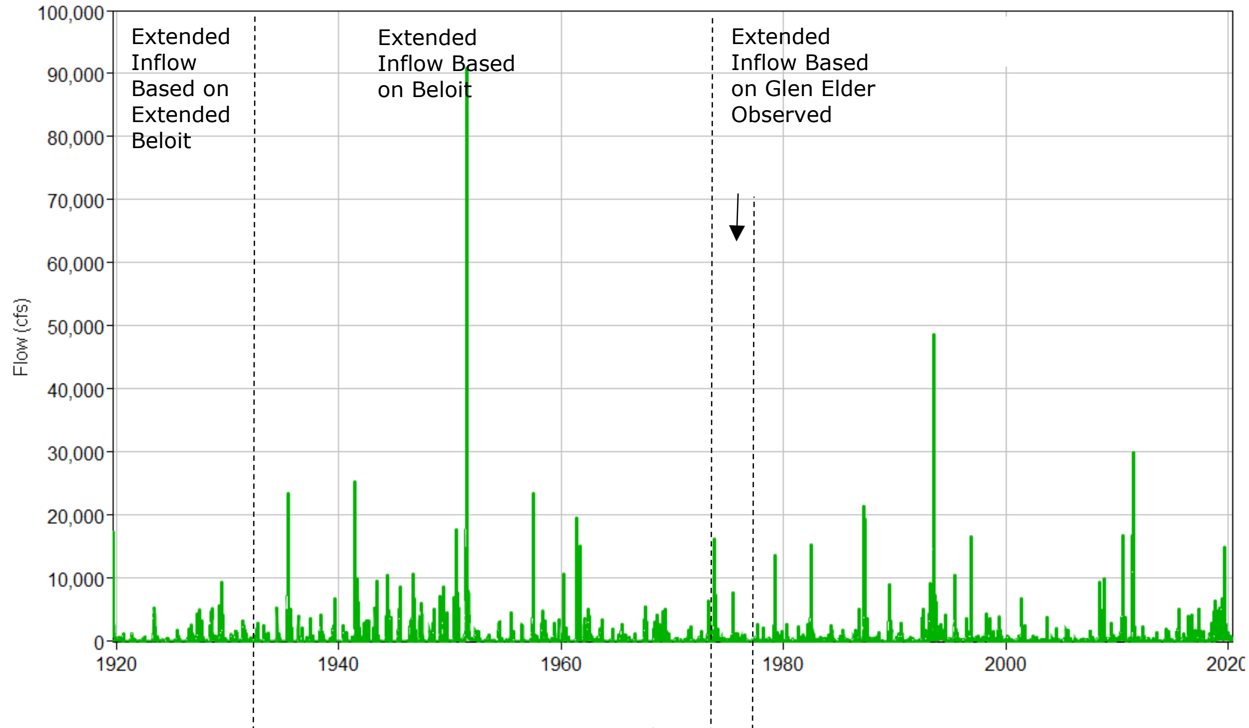


Figure 3-12. Waconda extended daily inflow record

3.2.3 Milford Lake

Milford Dam, which is located at river mile 7.7 of the Republican River, controls about 24,880 square miles of drainage area. A large portion of this basin is considered non-contributing. The closure of the dam was on 24 Aug 1964 and the database inflow begins on the same date. The dam began storing water on 16 Jan 1967 and the multipurpose pool was initially filled on 14 Jul 1967. Table 3-10 shows the key gages related to Milford Dam.

Table 3-10. Gages associated with Milford Dam.

Gage	Drainage Area (mi^2)	Record
Republican River at Clay Center, KS	24,542	01Jun1917 to present
Republican River at Milford, KS	24,900	01Jan1900 to 31Oct1905 01Oct1950 to 31Mar1964
Republican River at Milford Dam	24,900	24Aug1964 to present
Republican River at Junction City, KS	24,900	01Oct1963 to present

The observed Corps of Engineers reservoir stage, inflow, and outflow records are from 24 Aug 1964 through the present. As the stored data is 1200 UTC of the day before to 1200 UTC of the current day, the values have been shifted back 12 hours to make them representative of midnight-to-midnight flows. With the time shift, the observed inflow is used from 23 Aug 1964 through the end of the study period.

The regulation impacts of upstream Milford Reservoir were not modeled as part of this analysis. The total contributing watershed area into Milford is 17,388 square miles. The contributing watershed area below Harlan County and Lovewell and above Milford is 3,507 square miles. Although the south-eastern portion of the watershed tends to be much wetter than the western portion of the watershed, the large regulated area could be impactful on the Milford inflow depending on the location of rainfall. Since this study is developing a period of record regulated data set, ideally the Milford inflow would be a fully regulated data set. Since the extended inflow data set is a mixture of unregulated before 08 Aug 1949 (closure of the first upstream dam—Harry Strunk), partially regulated until 08 Jan 1964 (closure of the final upstream dam—Norton), and fully regulated after that, the extended inflows before this may tend to be higher than a fully regulated system as discussed in the following paragraphs.

Upstream reservoir holdouts have been calculated from 1950 through 2019 and routed to Milford Reservoir. Holdouts are calculated by subtracting inflow from the outflow for a given day. Holdouts are positive when the reservoir is rising and negative when it is dropping. The upstream holdouts routed to Milford were then used to calculate the unregulated Milford inflow starting in 1950. To do this the routed holdouts are added to the daily inflow.

To understand the impact of regulation above Milford the annual flow volume of holdouts, observed inflow and unregulated inflow were calculated and can be compared in Table 3-11. The percent difference between the inflow and the unregulated inflow is also shown. The Milford Reservoir unregulated inflow was consistently higher than the observed inflow. It ranged anywhere from 11% to 125% higher with an average of 51% higher than observed. The long-term average percent difference indicates a 51% reduction in annual flow volume by having the upstream reservoirs in place. If additional time and funding are available, it is recommended to further work on developing a fully regulated Milford inflow or at least expand the model to include Harlan County and Lovewell. Although the upstream reservoirs provide a significant flow volume reduction, the impacts may not create a large flow difference on the Kansas River below Milford. Milford will smooth any peak flows from the unregulated inflow data set. Some additional, event specific, plots are included in Section 2.1 of “Attachment 1 Supporting Plots” that show examples of observed and unregulated flows for Kanopolis during specific flood events.

Table 3-11. Annual flow volume for holdouts, inflows, and unregulated inflows at Milford Reservoir.

	Annual Flow Volume			
Year	**Upstream Holdouts Routed to Milford**	**Milford Observed Inflow**	**Milford Calculated Unregulated Inflow**	**Percent Difference**
1950	35,694			
1951	49,825			
1952	86,525			
1953	285,057			
1954	231,536			
1955	266,403			
1956	255,504			
1957	487,234			
1958	133,884			
1959	290,223			
1960	323,143			
1961	326,112			
1962	345,931			
1963	367,009			
1964	401,597			
1965	536,437	918,554	1,455,089	58%
1966	300,810	400,821	701,468	75%
1967	292,673	848,491	1,141,209	34%
1968	287,501	557,191	844,702	52%
1969	424,319	920,352	1,344,617	46%
1970	289,575	528,051	817,664	55%
1971	413,966	573,047	986,972	72%
1972	385,881	436,275	822,052	88%
1973	430,804	2,030,241	2,461,062	21%
1974	241,600	642,424	884,106	38%
1975	418,039	449,843	867,856	93%
1976	325,912	288,868	614,859	113%
1977	401,695	603,787	1,005,504	67%
1978	300,002	517,388	817,413	58%
1979	319,482	854,808	1,174,176	37%
1980	322,221	513,047	835,287	63%
1981	328,596	384,189	712,789	86%

Year	Annual Flow Volume			Percent Difference
	Upstream Holdouts Routed to Milford	Milford Observed Inflow	Milford Calculated Unregulated Inflow	
1982	283,131	880,972	1,163,978	32%
1983	196,728	775,107	971,940	25%
1984	295,852	891,306	1,187,156	33%
1985	302,013	671,648	973,628	45%
1986	276,993	1,127,605	1,404,593	25%
1987	318,534	1,348,463	1,667,001	24%
1988	284,844	259,164	543,996	110%
1989	244,853	346,726	591,636	71%
1990	221,896	350,529	572,506	63%
1991	206,159	165,064	371,107	125%
1992	260,360	651,391	911,791	40%
1993	343,920	3,027,674	3,371,685	11%
1994	181,914	592,422	774,169	31%
1995	241,894	856,634	1,098,618	28%
1996	334,910	731,336	1,066,184	46%
1997	215,983	482,467	698,402	45%
1998	241,759	869,001	1,110,883	28%
1999	272,871	706,757	979,583	39%
2000	189,544	187,699	377,323	101%
2001	274,924	533,090	807,999	52%
2002	137,341	134,828	272,231	102%
2003	119,210	246,475	365,690	48%
2004	94,404	257,468	351,855	37%
2005	128,285	191,532	319,794	67%
2006	87,488	91,335	178,818	96%
2007	303,164	497,730	800,904	61%
2008	225,133	763,766	988,945	29%
2009	164,279	390,363	554,510	42%
2010	185,341	989,653	1,175,012	19%
2011	197,126	805,043	1,002,252	24%
2012	80,419	322,298	402,732	25%
2013	111,410	289,462	400,877	38%
2014	178,050	218,313	396,587	82%
2015	192,444	579,230	771,663	33%

	Annual Flow Volume			
Year	**Upstream Holdouts Routed to Milford**	**Milford Observed Inflow**	**Milford Calculated Unregulated Inflow**	**Percent Difference**
2016	232,126	585,891	818,044	40%
2017	204,268	662,954	867,235	31%
2018	220,383	665,970	885,746	33%
2019	251,029	1,999,114	2,273,138	14%

Before the dam was constructed, inflow records are approximated using the gages listed in Table 3-9. The Republican River at Milford, KS and Junction City, KS gages were used with no adjustment from October 1950 to the start of the Milford CWMS data record. The watershed areas of these gages are very similar to the watershed area of the dam. Before October 1950, a linear relationship between the Clay Center gage and the extended inflow was used. The linear relationship is shown in Figure 3-13; it resulted in a very good fit of data. Routing time between Clay Center and Milford Reservoir is minimal, so no time shift was applied. The various methods are outlined in Table 3-12.

The extended Milford inflow is partially regulated by upstream reservoirs. The extended Milford Lake inflow hydrograph is provided as Figure 3-14. The Milford WCM references previous studies which calculated a peak 1935 flow of 168,000 cfs at Junction City. The documentation of that flow was not referenced. The approved USGS flow at Clay Center was 103,000 cfs and the river was fully unregulated at that time. Based on this Clay Center flow, the Milford inflow is estimated to crest at 108,841 cfs for the 1935 event.

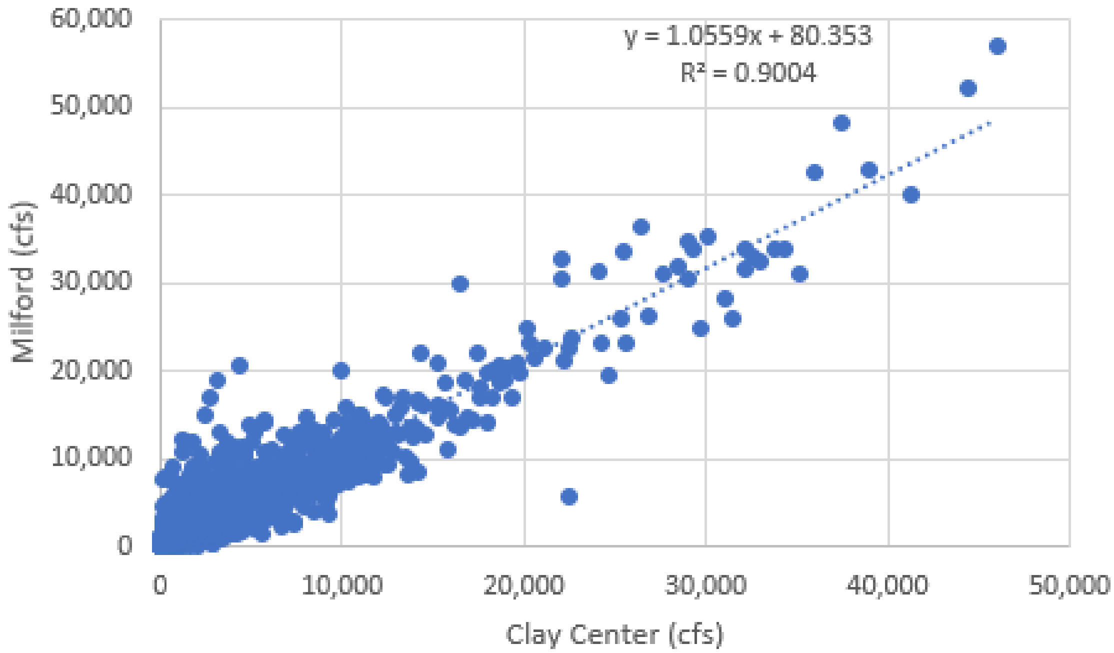


Figure 3-13. Relationship between daily observed Milford Inflow and Clay Center observed flow

Table 3-12. Data used to extend the daily Milford inflow

Date Range	Equation Used	Comment
01Jun1917 to 30Sep1950	MILD=1.056*Clay Center+80.356	Based on linear regression between Milford and Clay Center
01Oct1950 to 31Mar1964		Used the USGS daily Milford, KS Flow
01Apr1964 to 22Aug1964		Used the USGS daily Junction City Flow; this was before the dam was regulating Junction City.
23Aug1964 to 31Dec2019		Observed Milford Inflow

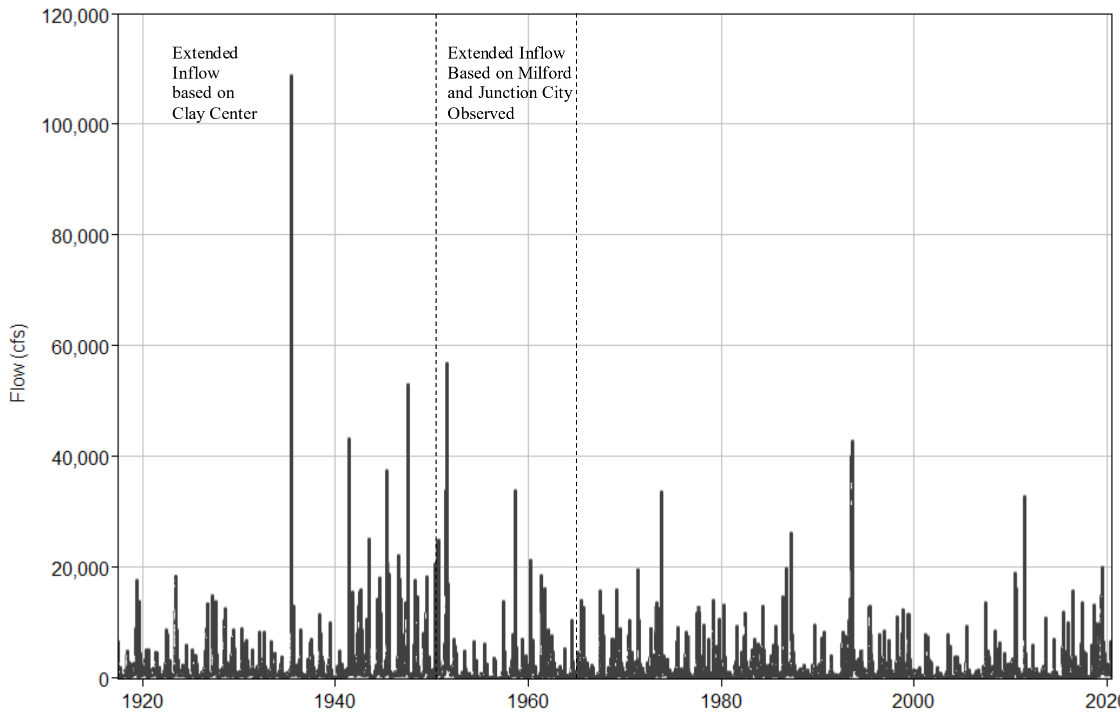


Figure 3-14. Milford Lake extended daily inflow record

3.2.4 Tuttle Creek Lake

Tuttle Creek Dam is located at river mile 10.0 of the Big Blue River and controls about 9,628 square miles of drainage area. The closure of the dam was on 20 Jul 1959 and the multipurpose pool was initially filled on 29 Apr 1963. Table 3-13 summarizes the available gage information for the Big Blue basin. Inflow gages are Marysville on the Big Blue River, Barnes on the Little Blue River, and Frankfort on the Black Vermillion River. The Waterville gage on the Little Blue River and Randolph gage on the Big Blue River (inundated by the pool) are sources of historic inflow data. The Manhattan gage, which is located 2.5 miles downstream of the dam, provides inflow data for the period prior to 19 Jul 1959 when calculated reservoir inflows were available and dam operation began to impact flows at this gage.

Table 3-13. Gages related to Tuttle Creek Dam.

Gage	Drainage Area (mi^2)	Record
Big Blue River at Randolph, KS	9,100	17Apr1918 to 29Sept1960
Big Blue River at Tuttle Creek Dam	9,628	21Jul1959 to present
Big Blue River at Manhattan, KS	9,640	01Oct1950 to present

The observed Corps of Engineers reservoir stage, inflow, and outflow records are from 21 Jul 1959 through the present. As the stored data is 1200 UTC of the day before to 1200 UTC of the current day, the values have been shifted back 12 hours to make them representative of midnight-to-midnight flows. With the time shift, the observed inflow is used from 20 Jul 1959 through the end of the study period.

Before the dam was constructed, inflow records are approximated using the gages listed in Table 3-13. The pre-dam inflow from October 1950 to the beginning of inflow at Tuttle Creek used the Manhattan gage with no shift as the watershed areas are very similar to the dam. Before October 1950, a linear relationship between the Randolph gage and the extended inflow was used. The linear relationship is shown in Figure 3-15; as can be seen a very good fit of data was observed. Routing time between Randolph and Tuttle Creek Reservoir is minimal, so no time shift was applied. The various methods are outlined in Table 3-14. The extended Tuttle Creek Lake inflow hydrograph is provided as Figure 3-16.

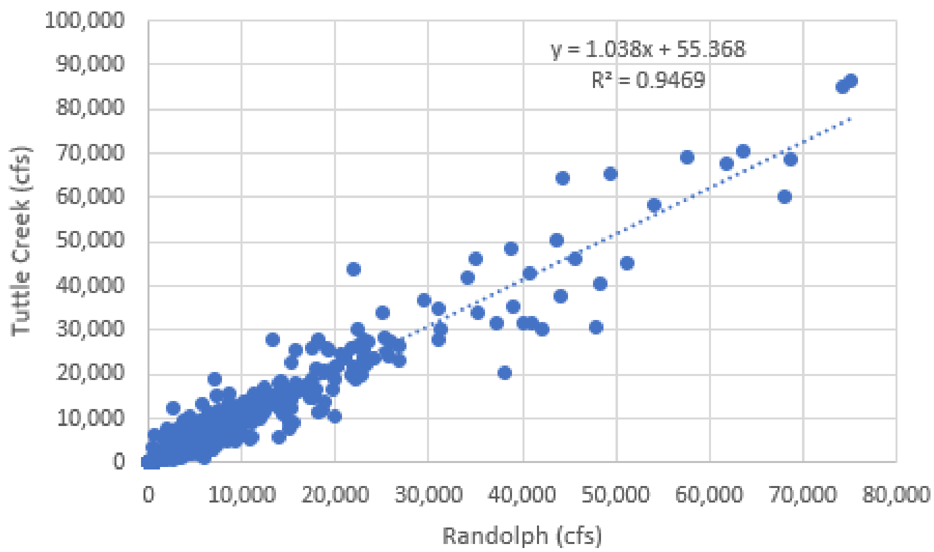


Figure 3-15. Relationship between observed daily Tuttle Creek Inflow and Randolph observed flow

Table 3-14. Data used to extend the daily Tuttle Creek inflow.

Date Range	Equation Used	Comment
01Jun1917 to 30Sep1950	TUCR=1.038*Randolph+55.368	Based on linear regression between Tuttle Creek and Randolph
01Oct1950 to 19Jul1959		Used the USGS daily Manhattan Flow; this was before the dam was regulating Manhattan.
20Jul1959 to 31Dec2019		Observed Tuttle Creek Inflow

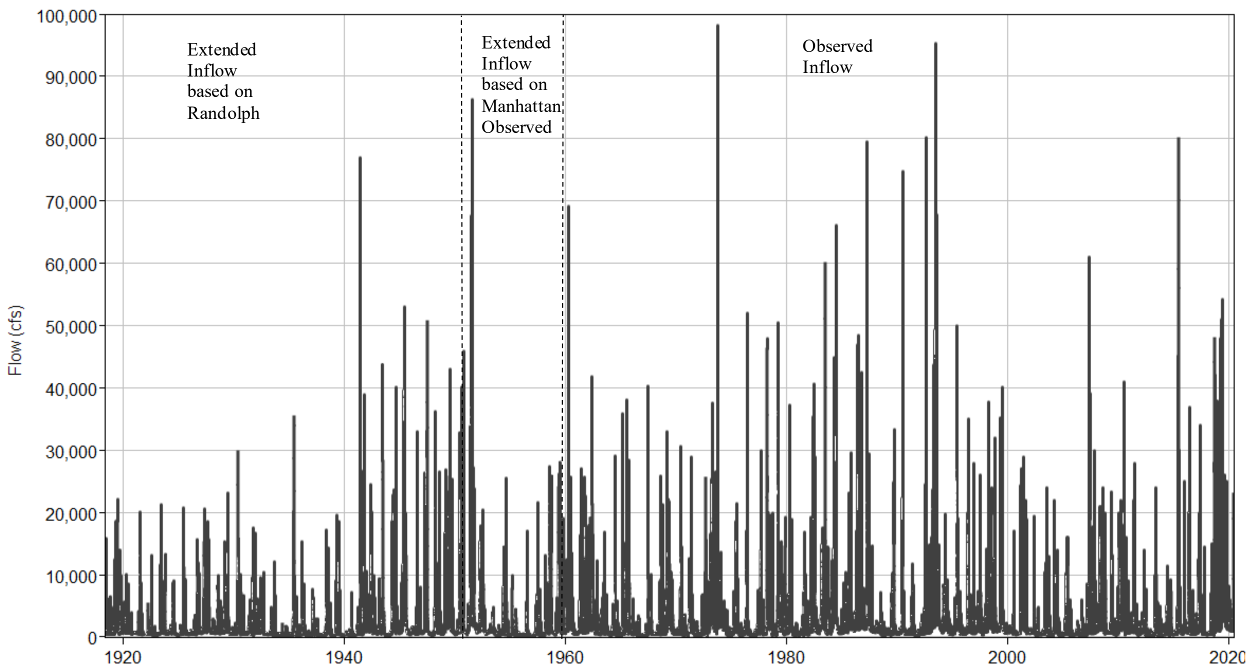


Figure 3-16. Tuttle Creek Lake extended daily inflow record

3.2.5 Perry Lake

The Perry Lake dam, which is located at river mile 5.3 of the Delaware River, controls about 1,117 square miles of the drainage area. The dam started impounding water on January 15, 1969 (even though data storage started before that date). Table 3-15 shows the available gage information. Muscotah is the current inflow gage on the Delaware River approximately 20 miles upstream from the full reservoir. The Valley Falls gage on the Delaware River (inundated by the pool) provides historic inflow data.

Table 3-15. Gages related to Perry Dam.

Gage	Drainage Area (mi²)	Record
Delaware River at Muscotah, KS	431	16Jul1969 to present
Delaware River at Valley Falls, KS	922	16Jun1922 to 29Sept1967
Delaware River at Perry Dam	1,117	01Aug1966 to present
Kansas River at Topeka, KS	56,720	12Jun1917 to present
Kansas River at Lecompton, KS	58,460	16Mar1936 to present
Kansas River at Desoto, KS	59,756	08Jul1917 to present

The observed Corps of Engineers reservoir stage, inflow, and outflow records extend from 01 Aug 1966 through the present. As the stored data is 1200 UTC of the day before to 1200 UTC of the current day, the values have been shifted back 12 hours to make them representative of midnight-to-midnight flows. With the time shift, the observed inflow is used from 31 Jul 1966 through the end of the study period. The ratio of the Perry Lake drainage area and the Valley Falls drainage area is 1.21 (1,117 mi^2/ 922 mi^2).

Before the dam was constructed, inflow records are approximated using the Valley Falls gage. There is just over one year of overlap data after Perry Dam inflow records began and Valley Falls gage data ended. A linear relationship between these two data sources is shown in Figure 3-17. The data appears to be a good fit, but the small overlap of data could lead to some errors. Routing time between Valley Falls and Perry Reservoir is minimal, so no time shift was applied.

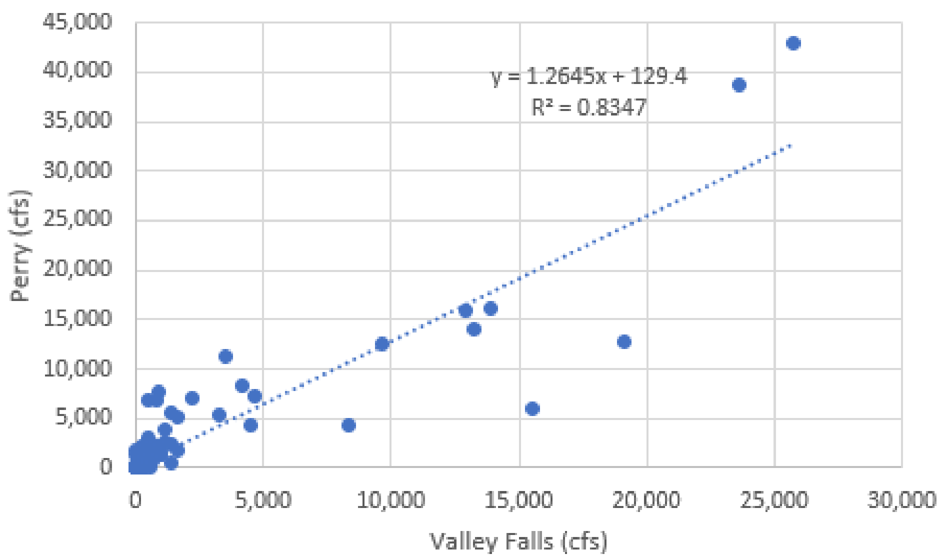


Figure 3-17. Relationship between observed daily Perry Inflow and Valley Falls flow.

For the period before the Valley Falls gage came into existence, the inflow record was estimated by looking at the Kansas River flow. This was to provide inflow data for 1919 (used as lookback in the model), 1920, 1921, and January through June of 1922. The Kansas River at Lecompton data record was extended as detailed in Section 3 by using the relationship between the Topeka and Desoto data. The Delaware River is the largest tributary between Topeka and Lecompton and a relationship was developed based on the annual flow volume of the extended Lecompton flow record. There is a lot of variability of where rains fall in the basin, so the estimated inflows are subject to judgement. However, the Kansas River flow gives insights into the wetness of these years.

Annual flow volume was calculated for the extended Kansas River at Lecompton and the extended Perry inflow data sets then the percent of Lecompton flow that comes from the Delaware River at Perry Dam was determined. The average was 10.7% but it ranged anywhere from 4.2% to 29.7% depending on the rain patterns for any given year. The annual flow volume of the local flow was also calculated. Some years the flow volume resulted in an annual negative flow. This came from comparing observed flow between gages, so the negative flow could be the result of water withdrawals from the river, seepage, or data errors. Because the gage record demonstrates that 1920-1922 were relatively low flow years at Topeka and DeSoto, the Perry inflow volume was estimated to be 5.5% of the extended Kansas River at Lecompton flow in 1920 and 8.5% in 1921 and 1922. The 1920 Lecompton flow volume and 5.5% are similar to 2003. The 1921 and 1922 Lecompton flow volumes and 8.5% are similar to 1990 and 2004.

Once the annual flow volume for Perry inflow was determined, the daily Lecompton flow was multiplied times a pair of high and low factors that were selected to result in the desired annual flow volume. Review of the gage data indicated that when Lecompton is high more flow tends to come from the Delaware River and when there are low flow conditions less flow is coming from the Delaware. The threshold between flow regime differs depending on the event, but higher flow contributions from the Delaware River tended to occur above 5000 cfs. Below this threshold, a greater contribution of the Kansas River at Lecompton flow tends to come from sources upstream of the Delaware River. Table 3-16 illustrates the flow thresholds and percentages applied. An "if statement" was used to determine if Lecompton flow was above the flow threshold, then the Lecompton flow was multiplied by the high flow percentage to get the Perry inflow. If Lecompton flow was below the flow threshold, then the Lecompton flow was multiplied by the low flow percentage to generate the Perry inflow values. These percentages were used to match the annual flow volume but are not indicative of accuracy during a specific event.

Table 3-16. Data used to extend the Perry inflow

Year	Lecompton Flow Threshold (cfs)	Percent of Lecompton High Flow that Comes from Perry	Percent of Lecompton Low Flow that Comes from Perry
1919	5000	13.8%	1.38%
1920	5000	11.0%	1.10%
1921	5000	14.8%	1.48%
1922	5000	12.4%	1.10%

Table 3-17 summarizes the equations used to extend the Perry inflow. The extended Perry Lake inflow hydrograph is provided as Figure 3-18.

Table 3-17. Data used to extend the daiy Perry inflow

Date Range	Equation Used	Comment
01Jan1919 to 31Dec1919	If LEKS>5000, PERY=0.138*LEKS If LEKS<5000, PERY=0.02*LEKS	Based on extended Lecompton (LEKS) flow.
01Jan1920 to 31Dec1920	If LEKS>5000, PERY=0.11*LEKS If LEKS<5000, PERY=0.011*LEKS	Based on extended Lecompton (LEKS) flow.
01Jan1921 to 31Dec1921	If LEKS>5000, PERY=0.148*LEKS If LEKS<5000, PERY=0.0148*LEKS	Based on extended Lecompton (LEKS) flow.
01Jan1922 to 15Jun1922	If LEKS>5000, PERY=0.124*LEKS If LEKS<5000, PERY=0.011*LEKS	Based on extended Lecompton (LEKS) flow.
16Jun1922 to 30Jul1966	PERY=1.26*Valley Falls+129.4	Based on linear regression between Perry and Valley Falls
31Jul1966 to 31Dec2019		Observed Perry Inflow

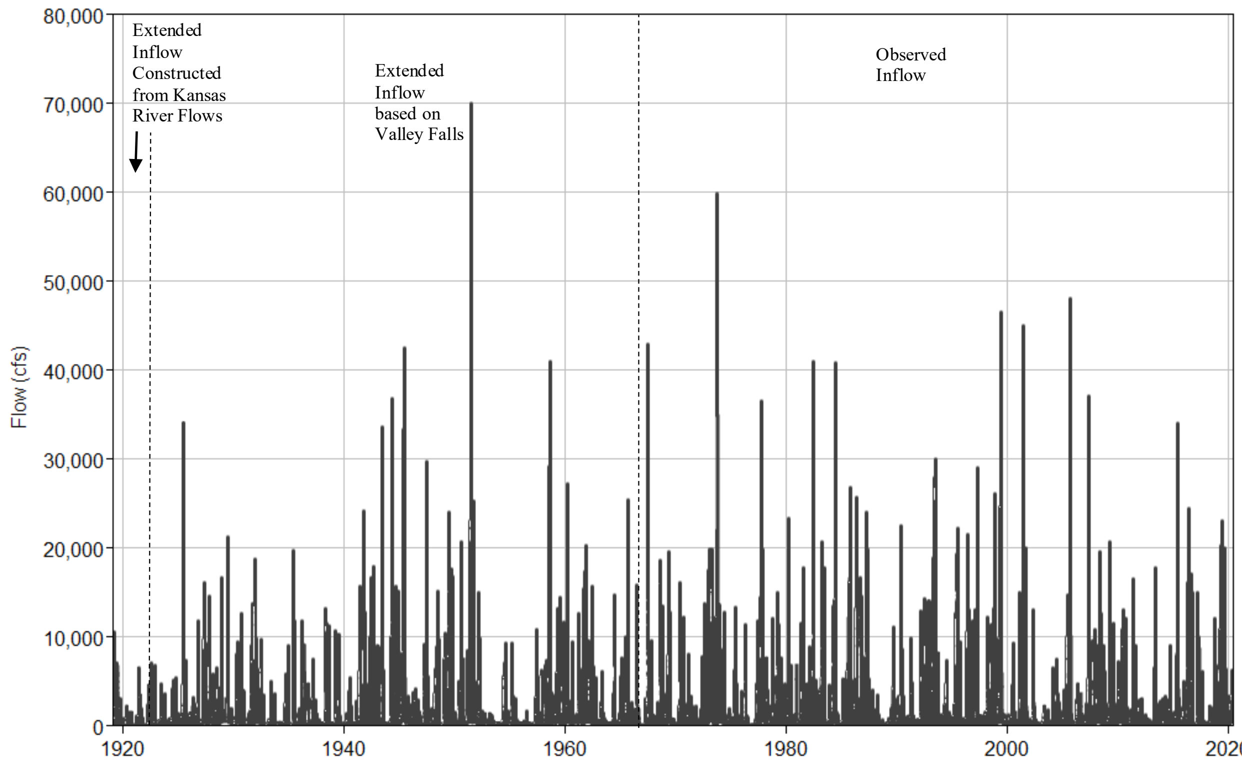


Figure 3-18. Perry Lake extended daily inflow record

3.2.6 Clinton Lake

Clinton Dam, which is located at river mile 22.2 of the Wakarusa River, controls about 367 square miles of drainage area. The dam closure occurred 23 Aug 1975 and the dam started impounding water on 30 Nov 1977. The lake first filled to multipurpose level on 03 Apr 1980. Table 3-18 shows the available gage information. The Richland gage is upstream of Clinton Dam and represents a little less than half the drainage area. The Lawrence gage is located approximately six miles downstream of the dam on the Wakarusa River, and provides down stream flow data and a historic record. The Richland gage was placed into service after the closure of the dam and is used as an inflow gage. The Lawrence gage has a very long record but is six miles downstream of the dam and includes 58 square miles of additional drainage area.

Table 3-18. Gages related to Clinton Dam.

Gage	Drainage Area (mi^2)	Record
Wakarusa River at Richland, KS	164	22Oct2002 to present
Wakarusa River at Clinton Dam	367	01Dec1977 to present
Wakarusa River near Lawrence, KS	425	27Apr1929 to present
Kansas River at Topeka, KS	56,720	12Jun1917 to present
Kansas River at Lecompton, KS	58,460	16Mar1936 to present
Kansas River at Desoto, KS	59,756	08Jul1917 to present

The observed Corps of Engineers reservoir stage, inflow, and outflow records extend from 01 Dec 1977 through the present. As the stored data is 1200 UTC of the day before to 1200 UTC of the current day, the values have been shifted back 12 hours to make them representative of midnight-to-midnight flows. With the time shift, the observed inflow is used from 30 Nov 1977 through the end of the study period.

The daily flows values for the Lawrence gage were taken from the USGS database and represent mean daily flows. The percentage of the Lawrence gage watershed controlled by Clinton Lake is:

$$367\ mi^2 / 425\ mi^2 = 86.4\%$$

From the start of the Clinton outflow record, a comparison can be made between the regulated releases and the Wakarusa River at Lawrence gage data. While this is all a regulated data set, it provides insight into the relationship between the gages and how much flow comes in below the dam and the gage. The gages' relationship is provided in Figure 3-19. This relationship was used to extend the Clinton inflow from 27 Apr 1929 to the start of the inflow record. No time shift was conducted on the gage data as travel time from

Clinton Dam to the Lawrence gage is approximately 6 hours. The regression equation indicates that about 83% of the Lawrence flow comes from Clinton. The other 17% comes from below the dam which is very similar to the watershed area. This relationship was compared to the annual flow volume at each gage from 1978 through 2019 and similar results were found. The Clinton outflow ranged from 78% to 128% of the Lawrence flow with an average of 93%.

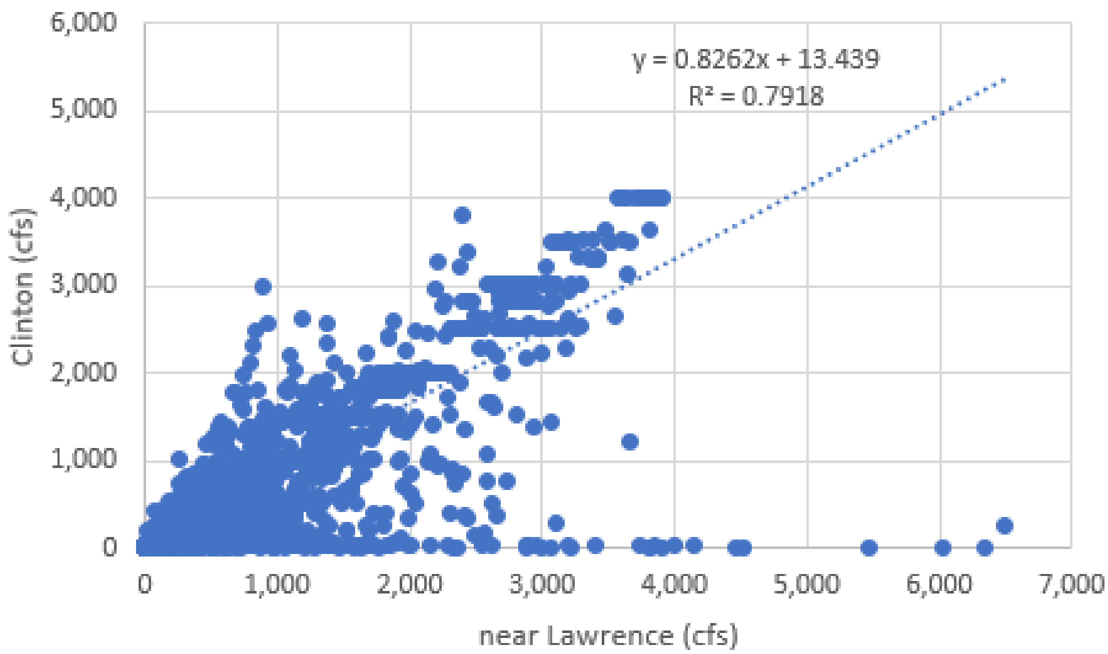


Figure 3-19. Relationship between Clinton daily outflow and regulated Lawrence daily observed flow data

For the period before the Wakarusa River at Lawrence gage came into existence, the Clinton inflow record was estimated by looking at the Kansas River flow, in a process analogous to how Perry's inflows were extended. This was to provide inflow data for 1919 (used as lookback in the model) and 1920 through April 1929. The Kansas River at Lecompton data record was extended as detailed in Section 3 by using the relationship between the Topeka and Desoto data. The Wakarusa River is the largest tributary between Lecompton and Desoto although it is similar in size with Stranger Creek. A relationship with the Clinton inflow was developed based on the annual flow volume of the Desoto flow record. There is a lot of variability of where rains fall in the basin, so the estimated inflows are subject to judgement. However, the Kansas River flow gives insights into the wetness of these years.

Annual flow volume was calculated for the Kansas River at Desoto and the previously extended Clinton inflow (from April 1929 through 2019) data sets. The percent of Desoto flow that comes from the Wakarusa River at Clinton Dam was then determined. The average was 2.79% but it ranged anywhere from 0.5% to 7.2% depending on the rain patterns for any given year. The annual flow volume of the local flow was also calculated. The annual flow volume at Desoto was average to below average for 1919-1929 except for 1927 which was above average by a little. However, the calculated local flow was above average for 1921, 1922, 1925, and 1927. Because of this, it was assumed that 4% of the Desoto flows came from the Wakarusa during those years. Local flow was low in 1920, 1923, and 1928, so it was assumed that 1% of the Desoto flows came from the Wakarusa those years. The other four years used the long-term average of 2.79% of the Desoto flows coming from the Wakarusa.

Once the annual flow volume for Clinton inflow was determined, the daily Desoto flow was multiplied times a pair of high and low factors that were selected to result in the desired annual flow volume. Review of the gage data indicated that when Desoto is high more flow tends to come from the Wakarusa River and when there are low flow conditions less flow is coming from the Wakarusa. The threshold between flow regime differs depending on the event, but higher flow conditions tended to occur above 7500 cfs. Table 3-19 identifies the flow thresholds and percentages used. As can be seen, the percentage changes quite a bit per year depending on the type of flow year. An "if statement" was used to determine if Desoto flow was above the flow threshold, then the Desoto flow was multiplied by the high flow percentage to get the Clinton inflow. If Desoto flow was below the flow threshold, then the Desoto flow was multiplied by the low flow percentage to generate the Clinton inflow values. These percentages were used to match the annual flow volume but are not indicative of accuracy during a specific event.

Table 3-19. Data used to extend the Clinton inflow

Year	High Flow Threshold (cfs)	Percent of Desoto High Flow that Comes from Clinton	Percent of Desoto Low Flow that Comes from Clinton
1919	7500	3.90%	0.37%
1920	7500	3.30%	0.29%
1921	7500	7.50%	1.19%
1922	7500	7.26%	1.00%
1923	7500	1.49%	0.09%
1924	7500	7.91%	1.65%
1925	7500	8.20%	1.59%
1926	7500	6.14%	0.70%
1927	7500	4.92%	0.50%
1928	7500	1.68%	0.05%
1929	7500	4.40%	0.39%

Table 3-20 summarizes the equations used to extend the Clinton inflow. The extended Clinton Lake inflow hydrograph is provided as Figure 3-20.

Table 3-20. Data used to extend the daily Clinton inflow record.

Date Range	Equation Used	Comment
01Jan1919 to 31Dec1919	If DESO>7500, CLIN=0.039*DESO If DESO<7500, CLIN=0.0037*DESO	Based on observed Desoto (DESO) flow.
01Jan1920 to 31Dec1920	If DESO>7500, CLIN=0.033*DESO If DESO<7500, CLIN=0.0029*DESO	Based on observed Desoto (DESO) flow.
01Jan1921 to 31Dec1921	If DESO>7500, CLIN=0.075*DESO If DESO<7500, CLIN=0.0119*DESO	Based on observed Desoto (DESO) flow.
01Jan1922 to 31Dec1922	If DESO>7500, CLIN=0.0726*DESO If DESO<7500, CLIN=0.010*DESO	Based on observed Desoto (DESO) flow.
01Jan1923 to 31Dec1923	If DESO>7500, CLIN=0.0149*DESO If DESO<7500, CLIN=0.0009*DESO	Based on observed Desoto (DESO) flow.
01Jan1924 to 31Dec1924	If DESO>7500, CLIN=0.0791*DESO If DESO<7500, CLIN=0.0165*DESO	Based on observed Desoto (DESO) flow.
01Jan1925 to 31Dec1925	If DESO>7500, CLIN=0.082*DESO If DESO<7500, CLIN=0.0159*DESO	Based on observed Desoto (DESO) flow.
01Jan1926 to 31Dec1926	If DESO>7500, CLIN=0.0614*DESO If DESO<7500, CLIN=0.007*DESO	Based on observed Desoto (DESO) flow.
01Jan1927 to 31Dec1927	If DESO>7500, CLIN=0.0492*DESO If DESO<7500, CLIN=0.005*DESO	Based on observed Desoto (DESO) flow.
01Jan1928 to 31Dec1928	If DESO>7500, CLIN=0.0168*DESO If DESO<7500, CLIN=0.0005*DESO	Based on observed Desoto (DESO) flow.
01Jan1929 to 26Apr1929	If DESO>7500, CLIN=0.044*DESO If DESO<7500, CLIN=0.0039*DESO	Based on observed Desoto (DESO) flow.
27Apr1929 to 29Nov1977	CLIN=0.826*Lawrence+13.441	Based on linear regression with Lawrence
30Nov1977 to 31Dec2019		Observed Clinton Inflow

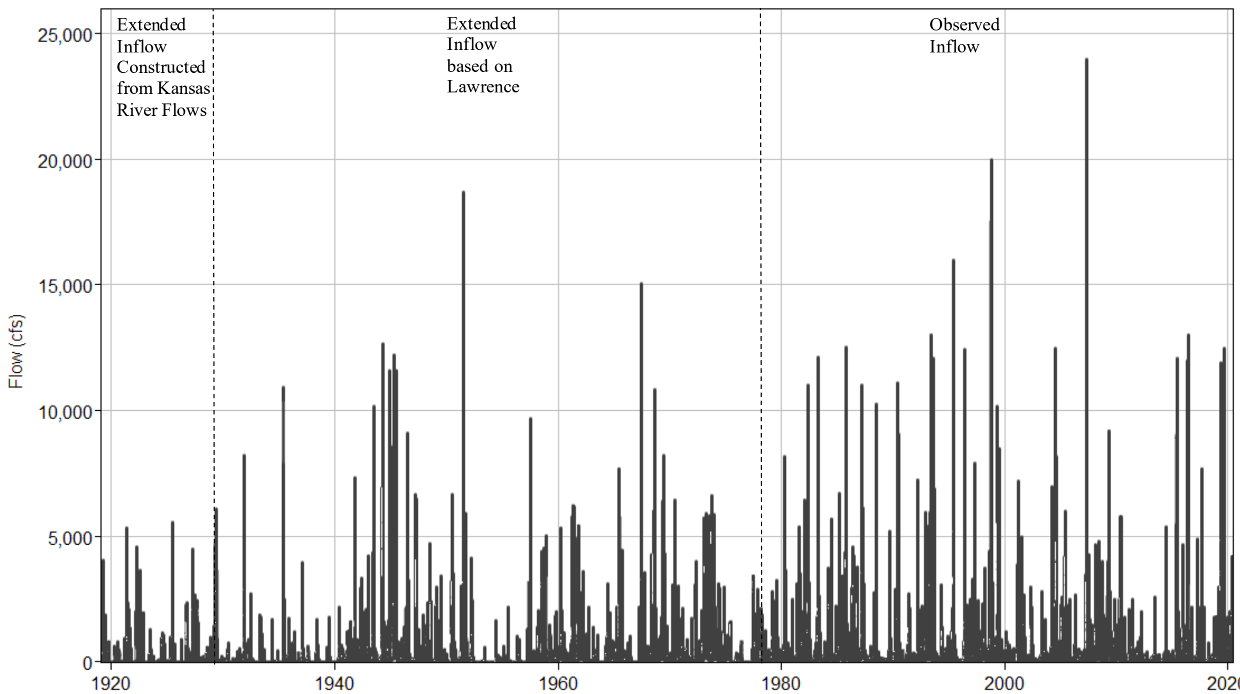


Figure 3-20. Clinton Lake extended daily inflow record

3.3 Gage Data Extension

The HEC-ResSim model requires inputs at the reservoir inflow locations and some tributaries. In addition, several gages are set up to receive local flows which enter the river at a given stream gage location and model junction. The local flows are all input at the downstream gage. Each of these flow locations required the full data set of 1920 to 2019 therefore it was best to pick gages that had long periods of record. The model input locations for flow are detailed in Table 3-21.

Table 3-21. HEC-ResSim flow locations requiring daily data input

River	Location	Parameter
Smoky Hill River	Kanopolis Dam	Inflow
Smoky Hill River	Lindsborg, KS	Local Flow
Smoky Hill River	Mentor, KS	Local Flow
Saline River	Wilson Dam	Inflow
Saline River	Tescott, KS	Local Flow
Smoky Hill River	New Cambria, KS	Local Flow
Solomon River	Waconda Dam	Inflow
Solomon River	Beloit, KS	Local Flow

River	Location	Parameter
Salt Creek	Ada, KS*	Flow
Solomon River	Niles, KS	Local Flow
Smoky Hill River	Enterprise, KS	Local Flow
Chapman Creek	Chapman, KS*	Flow
Republican River	Clay Center, KS	Flow
Republican River	Milford Dam	Local Flow
Kansas River	Fort Riley, KS	Local Flow
Big Blue River	Tuttle Creek Dam	Inflow
Kansas River	Wamego, KS	Local Flow
Vermillion Creek	Wamego, KS*	Flow
Mill Creek	Paxico, KS*	Flow
Kansas River	Topeka, KS	Local Flow
Soldier Creek	Topeka, KS*	Flow
Delaware River	Perry Dam	Inflow
Kansas River	Lecompton, KS	Local Flow
Wakarusa River	Clinton Dam	Inflow
Wakarusa River	Lawrence, KS	Local Flow
Stranger Creek	Tonganoxie, KS*	Flow
Kansas River	Desoto, KS	Local Flow
Missouri River	Saint Joseph, MO	Flow
Platte River	Sharps Station*	Flow
Missouri River	Kansas City, MO	Local Flow
Blue River	Kansas City, MO*	Flow
Little Blue River	Lake City, MO*	Flow
Missouri River	Waverly, MO	Local Flow

*Tributary boundary condition locations used observed flow with no data extension. When observed gage data was unavailable, the tributary flow was set to zero and all flow from that tributary was incorporated into the local flow for its respective river reach.

3.3.1 Smoky Hill River at Lindsborg, KS

The Smoky Hill River at Lindsborg, KS data record was filled in using a combination of Ellsworth, Langley and Mentor observed flows. Table 3-22 shows the various relationships used. Linear and multi-linear relationships were developed depending on the availability of data. The final method used for a given time period was based on the best R^2 value and the availability of data. Figure 3-21 shows the relationship between Lindsborg and Ellsworth. Figure 3-22 shows the relationship between Lindsborg and Mentor. Figure 3-23 shows the multi-linear relationship between Lindsborg, Langley, and Mentor. Some small differences exist between the equations in the table and those in excel. The equations in the table were developed in DSS and used for the data extension. The equations shown in the plots that were developed in Excel to graphically show the relationship. DSS and Excel may have slightly different methods of optimizing the best fit curve.

Table 3-22. Data relationships used to extend the Smoky Hill River at Lindsborg daily data.

Date Range	Equation Used	Comment
01Jan1919 to 31July1919		Lindsborg observed flow
01Aug1919 to 29Feb1920	Lindsborg = 0.71*Ellsworth(shifted) + 100.22	Linear relationship with Ellsworth shifted forward two days
01Mar1920 to 30Sep1920		Lindsborg observed flow
01Oct1920 to 28Feb1921	Lindsborg = 0.71*Ellsworth(shifted) + 100.22	Linear relationship with Ellsworth shifted forward two days
01Mar1921 to 30Sep1921		Lindsborg observed flow
01Oct1921 to 28Feb1922	Lindsborg = 0.71*Ellsworth(shifted) + 100.22	Linear relationship with Ellsworth shifted forward two days
01Mar1922 to 30Sep1922		Lindsborg observed flow
01Oct1922 to 28Feb1923	Lindsborg = 0.71*Ellsworth(shifted) + 100.22	Linear relationship with Ellsworth shifted forward two days
01Mar1923 to 29Sep1923		Lindsborg observed flow
30Sep1923 to 30Nov1923	Lindsborg = 0.71*Ellsworth(shifted) + 100.22	Linear relationship with Ellsworth shifted forward two days
01Dec1923 to 31July1930	Lindsborg = 0.911*Mentor + 16.053	Linear relationship with Mentor
01Feb1930 to 29Sep1965		Lindsborg observed flow
29Sep1965 to 30Jul2014	Lindsborg = 0.41988*Langley + 0.59612*Mentor + 0.95137	Multi-linear relationship between Langley and Mentor
30Jul2014 to present		Lindsborg observed flow

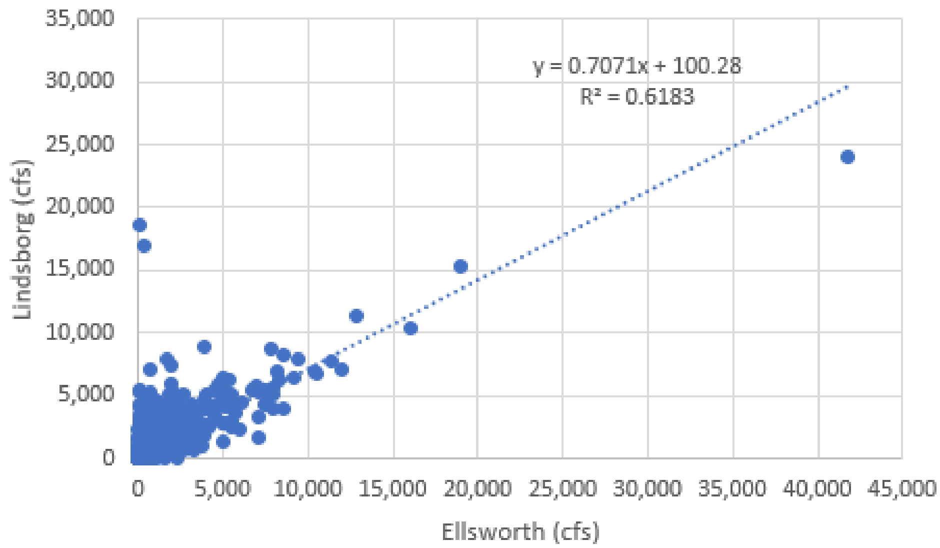


Figure 3-21. Linear relationship between Lindsborg and Ellsworth daily flow data.

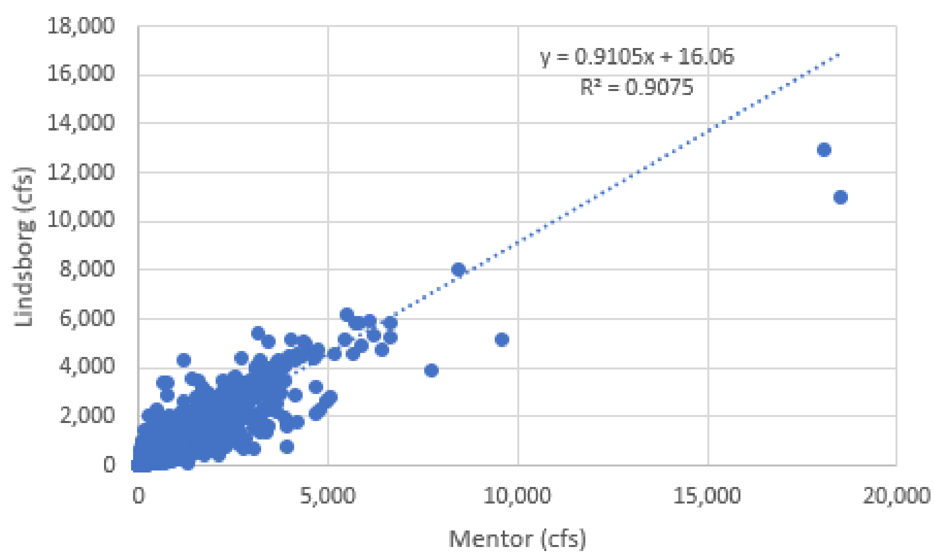


Figure 3-22. Linear relationship between Lindsborg and Mentor daily flow data

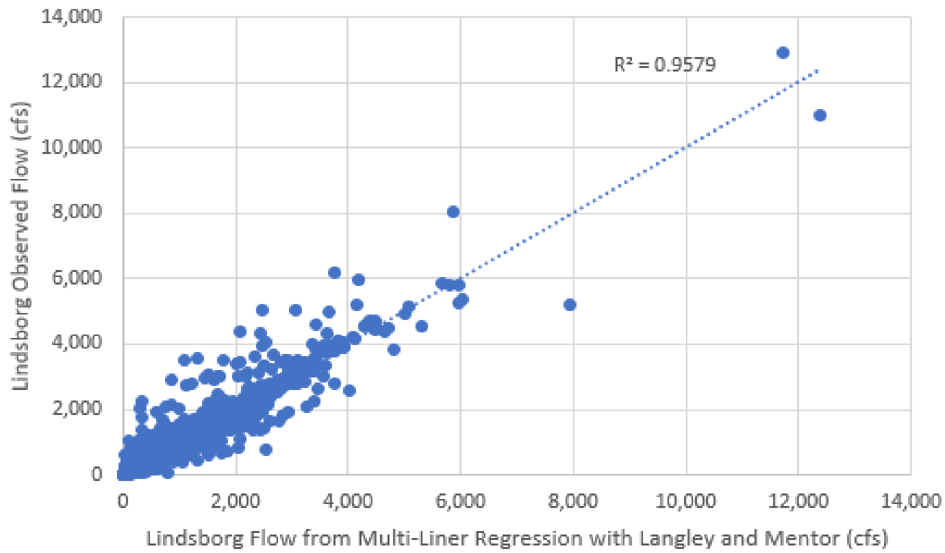


Figure 3-23. Multi-linear relationship between Lindsborg, Langley, and Mentor daily flow data

3.3.2 Smoky Hill River at Mentor

The Smoky Hill River at Mentor has data from Dec 1923 to Oct 1930, May 1931 to June 1932, and Oct 1947 to present. To fill in the missing data, a linear relationship was developed with the Lindsborg observed data. The linear relationship is Mentor = 0.997*Lindsborg + 23.097. Lindsborg was missing a few months of data prior to Dec 1923, and during that time the extended Lindsborg record was used rather than building a relationship between Ellsworth and Mentor. This simplifying assumption appears to be reasonable considering it is filling in a few months of data. Figure 3-24 shows the linear relationship between Mentor and Lindsborg.

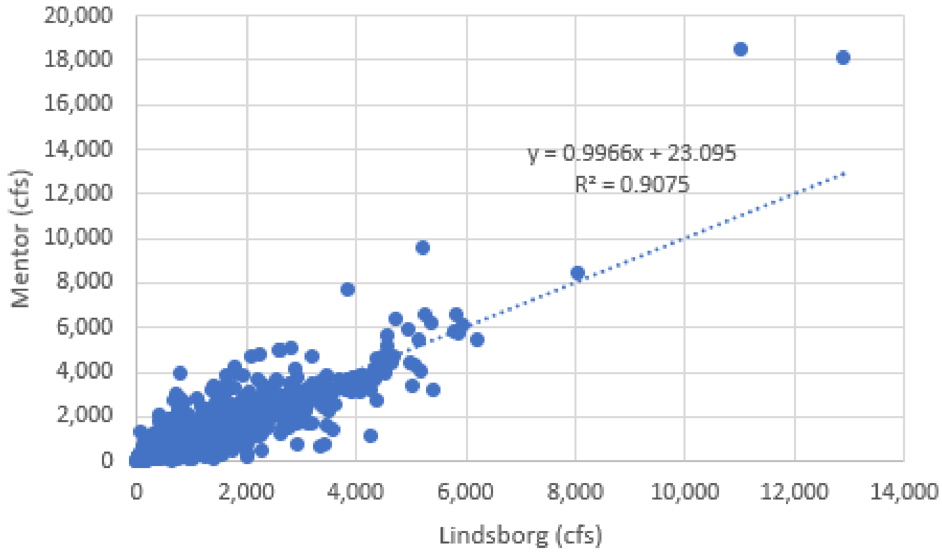


Figure 3-24. Linear relationship between Mentor and Lindsborg daily flow data

3.3.3 Saline River at Tescott, KS

The Saline River at Tescott was used directly from the USGS since it covers the full modeling period. A little missing data from December 11-30, 1926 and January 5-29, 1927 was linearly interpolated.

3.3.4 Smoky Hill River at New Cambria, KS

The Smoky Hill River at New Cambria was extended using combinations of the Mentor, Tescott, and Enterprise gages. The historic Smoky Hill River at Solomon gage was also used to extend the Enterprise data as detailed below. Table 3-23 documents the final regression equation that was used for a given time period. The final method used was based on the best R^2 value and the availability of data. The relationship between New Cambria and Tescott is detailed in Figure 3-25. The relationship between New Cambria, Tescott, and Mentor is shown in Figure 3-26. The relationship between New Cambria, Tescott, and Enterprise is shown in Figure 3-27. The relationship between New Cambria and the Smoky Hill River at Enterprise/Solomon is shown in Figure 3-28. Finally, the relationship between New Cambria, Tescott, Enterprise and Mentor is shown in Figure 3-29.

Table 3-23. Data relationships used to extend the Smoky Hill River at New Cambria daily data

Date Range	Equation Used	Comment
01Sep1919 to 29Sep1921	New Cambria = 0.458*Tescott + 0.378*Enterprise + 25.786	Multi-linear relationship between Tescott and Enterprise (extended using Solomon, KS)
30Sep1921 to 30Sep1922	New Cambria = 2.01*Tescott + 266.17	Linear relationship with Tescott
01Oct1922 to 30Nov1923	New Cambria = 0.458*Tescott + 0.378*Enterprise + 25.786	Multi-linear relationship between Tescott and Enterprise (extended using Solomon, KS)
01Dec1923 to 01Nov1930	New Cambria = 0.483*Tescott + 0.226*Enterprise + 0.750*Mentor - 25.869	Multi-linear relationship between Tescott, Enterprise (extended), and Mentor, due to missing data 11-30Dec1926 and 05-29Jan1927 were filled with linear interpolation
01Nov1930 to 21May1931	New Cambria = 0.458*Tescott + 0.378*Enterprise + 25.786	Multi-linear relationship between Tescott and Enterprise (extended using Solomon, KS), the three-part multi-linear equation was used for 17Feb and 09May1931 as data was available for those days
22May1931 to 30Jun1932	New Cambria = 0.483*Tescott + 0.226*Enterprise + 0.750*Mentor - 25.869	Multi-linear relationship between Tescott, Enterprise (extended), and Mentor
01Jul1932 to 31Dec1933	New Cambria = 0.4489*Enterprise	Linear relationship with Enterprise (extended using Solomon, KS)
01Jan1934 to 30Sep1947	New Cambria = 0.458*Tescott + 0.378*Enterprise + 25.786	Multi-linear relationship between Tescott and Enterprise (extended using Solomon, KS)
01Oct1947 to 30Nov1948	New Cambria = 0.483*Tescott + 0.226*Enterprise + 0.750*Mentor - 25.869	Multi-linear relationship between Tescott, Enterprise (extended), and Mentor
01Dec1948 to 29Sep1953		New Cambria observed data, the three-part multi-linear regression was use 7-15June1951, 22Jun-08Jul1951, 10-21July1951, 05-14Sep1951
29Sep1953 to 30Sep1962	New Cambria = 0.483*Tescott + 0.226*Enterprise + 0.750*Mentor - 25.869	Multi-linear relationship between Tescott, Enterprise (extended), and Mentor
01Oct1962 to 28Feb2007		New Cambria observed data
01Mar2007 to 29Nov2007	New Cambria = 0.483*Tescott + 0.226*Enterprise + 0.750*Mentor - 25.869	Multi-linear relationship between Tescott, Enterprise (extended), and Mentor
30Nov2007 to 29Sep2010		New Cambria observed data, the three-part multi-linear regression was use 29,30Jul2008, 26,27,29,30Apr and 01May2009, 12-14Aug2009, 17-19Aug2009,23Aug-18Sep2009,07Oct2009,05-08Jun2010
30Sep2010 to present	New Cambria = 0.483*Tescott + 0.226*Enterprise + 0.750*Mentor - 25.869	Multi-linear relationship between Tescott, Enterprise (extended), and Mentor

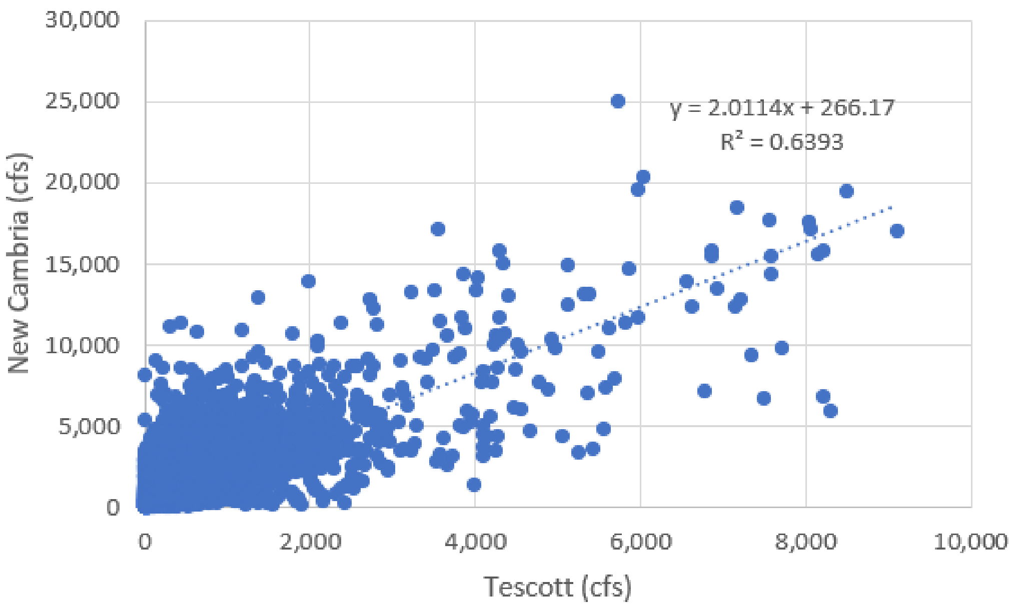


Figure 3-25. Linear relationship between New Cambria and Tescott daily flow data

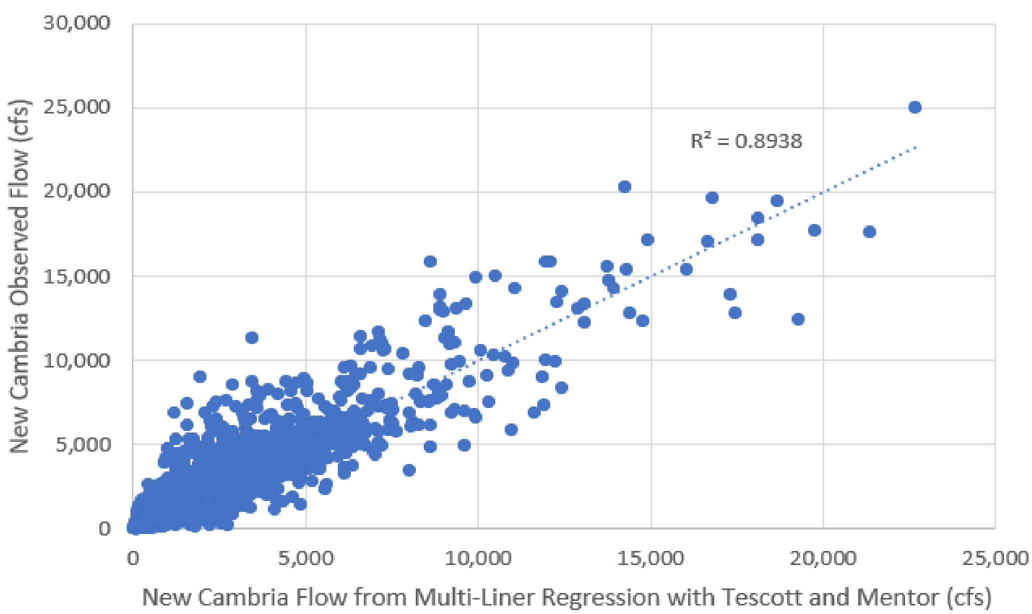


Figure 3-26. Multi-linear relationship between New Cambria, Tescott, and Mentor daily flow data

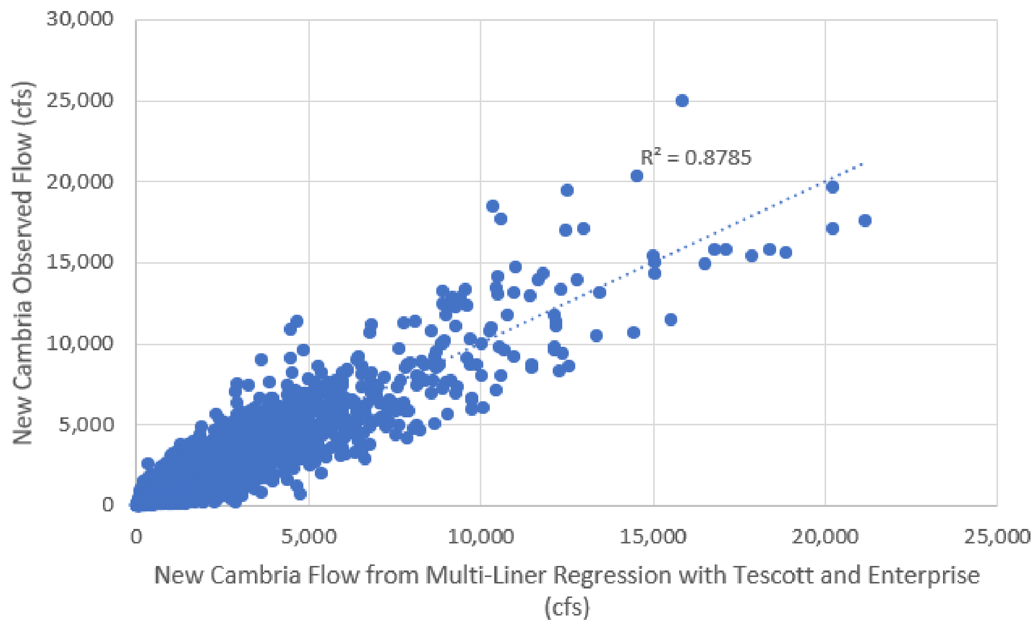


Figure 3-27. Multi-linear relationship between New Cambria, Tescott, and Enterprise daily flow data

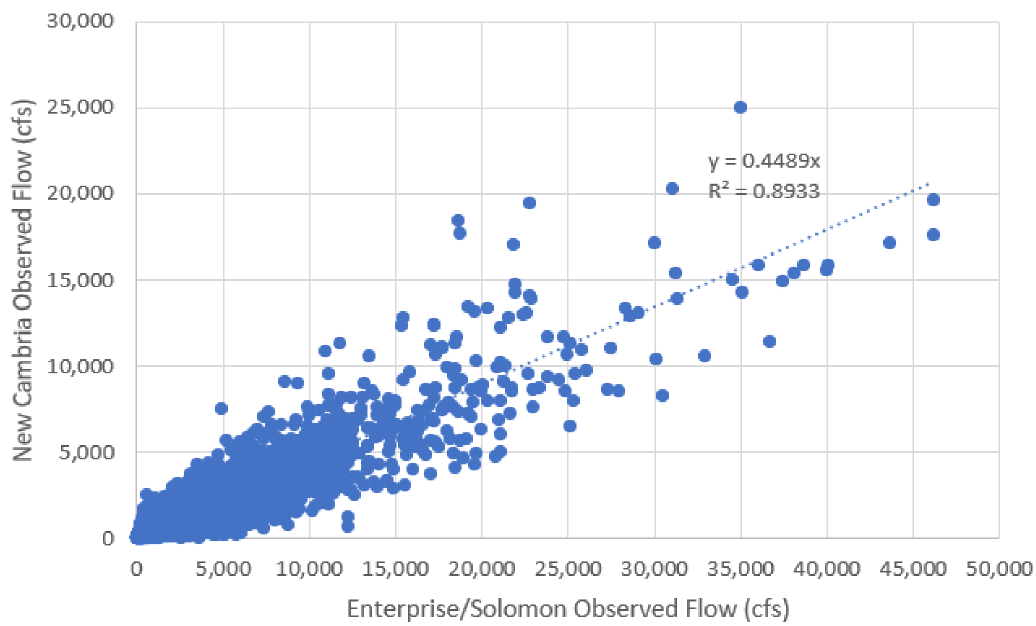


Figure 3-28. Linear relationship between New Cambria and Enterprise/Solomon daily flow data

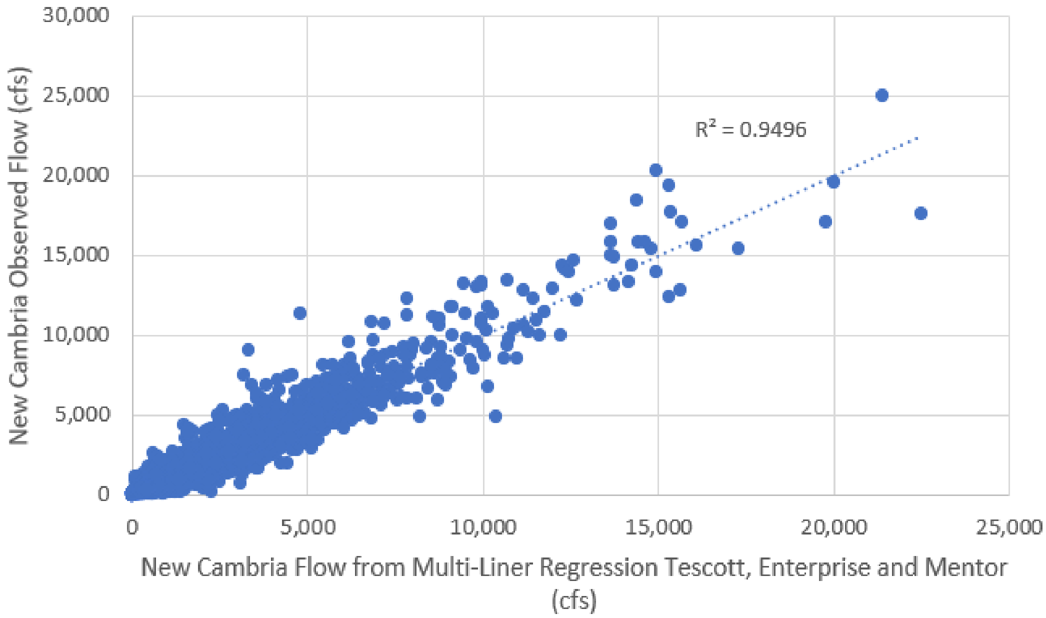


Figure 3-29. Multi-linear relationship between New Cambria, Tescott, Enterprise, and Mentor daily flow data

3.3.5 Solomon River at Beloit, KS

The Solomon River at Beloit was extended before 1929 as part of the Waconda inflow extension process. That method is detailed in the Waconda inflow discussion in Section 3.1.3. For the regulated period from Oct 1966 to July 2012, Beloit data needed to be estimated as the gage was not operational during that time. The Solomon River at Simpson was in operation from September 1990 to September 2005; it is downstream of Beloit and has less than 100 mi^2 additional watershed. Beloit accounts for 98.2% of the Simpson contributing area. The Simpson data never overlapped Beloit so a regression could not be developed, but the Simpson data was multiplied by 0.982 and used as Beloit for the period extending from 01 Sep 1990 to 29 Sep 2005. The rest of the missing Beloit data was filled using a multi-linear relationship between Glen Elder and Niles. The relationship used was Beloit = 0.9857*Glen Elder + 0.0670*Niles -4.0981. Table 3-24 shows the gages that were used to extend the Beloit data both before and after the construction of Waconda. The regression relationship of the Glen Elder and Niles correlation is shown in Figure 3-30.

Table 3-24. Data relationships used to extend the Solomon River at Beloit daily data

Date Range	Equation Used	Comment
01Sept1919 to 01July1925	Beloit=0.871*Kirwin+1.398*Alton +0.295*Niles+42.605	Based on multi-linear regression with Kirwin plus 1 day, Alton plus 1 day, and Niles minus 2 days
02July1925 to 12Aug1928	Beloit=0.648*Niles+12.365	Based on linear regression with Niles minus 1 day
13Aug1928 to 13Apr1929	Beloit=0.871*Kirwin+1.398*Alton +0.295*Niles+42.605	Based on multi-linear regression with Kirwin plus 1 day, Alton plus 1 day, and Niles minus 2 days
14Apr1929 to 29Sep1965		Observed Beloit data
30Sep1965 to 31Aug1990	Beloit = 0.9857*Glen Elder + 0.0670*Niles -4.0981	Based on multi-linear regression with Glen Elder and Niles
01Sep1990 to 29Sep2005	Beloit = 0.982*Simpson	Watershed area adjustment on the Simpson data
30Sep2005 to 16Jul2012	Beloit = 0.9857*Glen Elder + 0.0670*Niles -4.0981	Based on multi-linear regression with Glen Elder and Niles
17Jul2012 to Present		Observed Beloit data

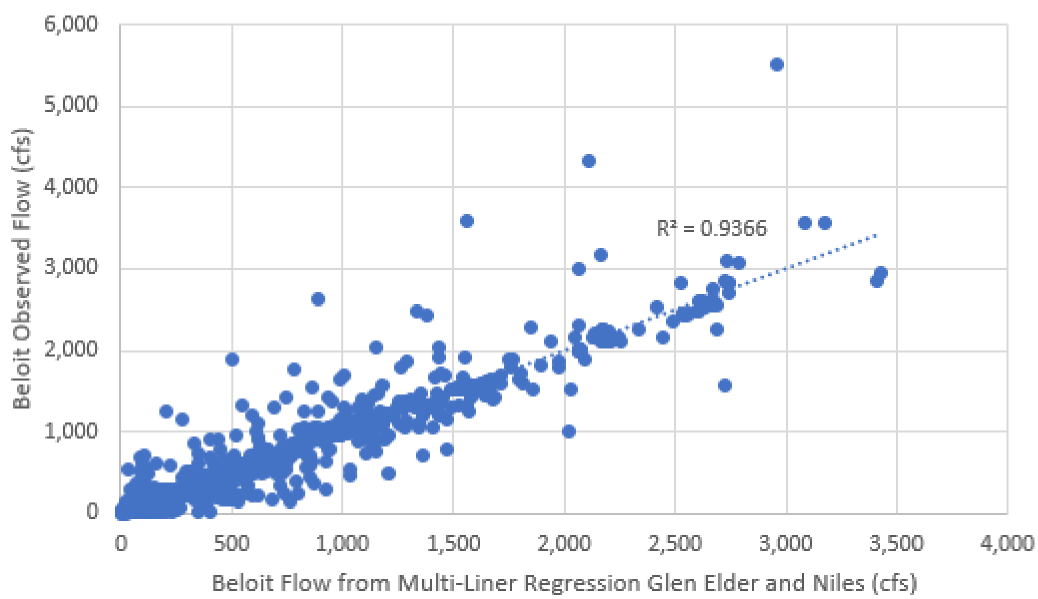


Figure 3-30. Multi-linear relationship between Beloit and Glen Elder and Niles daily flow data

3.3.6 Salt Creek at Ada, KS

The Salt Creek at Ada data set starts in June 1959. Before that time flows were set to zero and the Salt Creek flow was included in the local flow calculation between Beloit and Niles.

3.3.7 Solomon River at Niles, KS

The Solomon River at Niles was used directly from the USGS since it covers the full modeling period. A little missing data from March 12 to April 15, 2014 was linear interpolated.

3.3.8 Smoky Hill River at Enterprise, KS

Smoky Hill River at Enterprise began collecting data on 01Oct1934. Prior to this time, data was extended using the historic record from USGS 06877000 Smoky Hill River at Solomon, KS. This gage has data from 01 October 1918 to 29 September 1934. This gage was near the mouth of the Solomon River. Using basin delineation in the Kansas CWMS HEC-HMS model it is estimated that 448 mi2 of watershed exists between the Solomon and Smoky Hill River confluence and the Enterprise gage. Approximately 97.7 percent of the Enterprise drainage area is accounted for by the Solomon gage. The Solomon data was multiplied by 1.023 to account for this small increase in watershed. Solomon is missing data from October 1921 to September 1922. To fill in this gap, a multi-linear regression was developed between upstream Niles and Tescott and downstream Kansas River at Ogden (near the current Fort Riley gage). This relationship provided a reasonable correlation as shown below. The regression equation is Enterprise = 0.301*Ogden + 0316*Tescott + 0.809*Niles -66.028. The multi-linear regression is shown below in Figure 3-31.

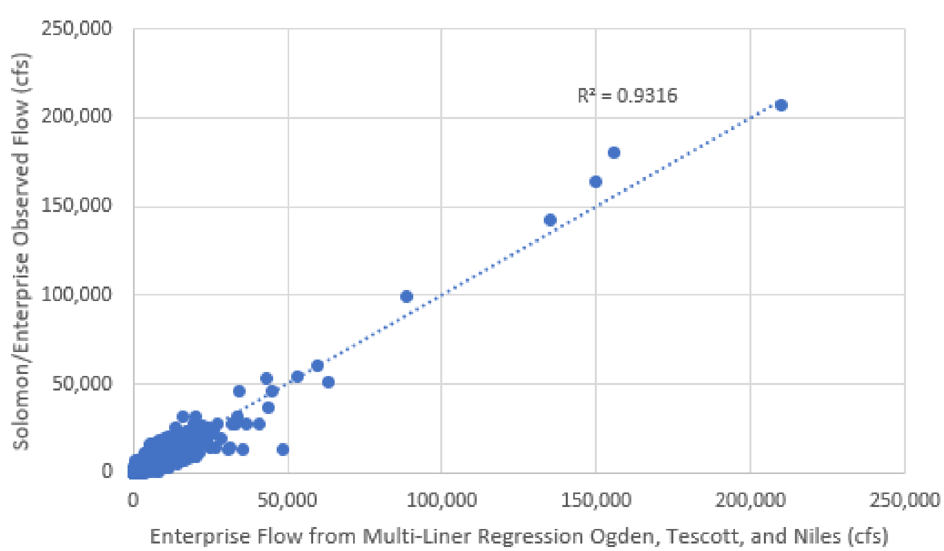


Figure 3-31. Multi-linear relationship between Enterprise and Ogden, Tescott, and Niles daily flow data

3.3.9 Chapman Creek at Chapman, KS

The Chapman Creek at Chapman data set starts in December 1953. Before that time flows were set to zero and the Chapman Creek flow was included in the local flow calculation between Enterprise and Fort Riley.

3.3.10 Republican River at Clay Center

Republican River at Clay Center was used directly from the USGS since it covers the full modeling period.

3.3.11 Kansas River at Fort Riley

Kansas River at Fort Riley begins December 1963. From June 1917 to September 1951 data was collected at USGS 06879500 Kansas River at Ogden which is just downstream of the current Fort Riley gage. Fort Riley accounts for 99.2% of the Ogden watershed and Ogden was used as observed. There is a little missing data in the Ogden data set from Nov 1926 to Mar 1927 that needed to be estimated in addition to the gap between the two gage data sets. To fill these gaps a multi-linear relationship was developed utilizing the Republican River at Clay Center (upstream) and the Kansas River at Wamego (downstream). This relationship is Fort Riley = 0.47*Wamego + 0.42*Clay Center – 350.35. The R^2 is shown in Figure 3-32 below. For data gaps between Sept 1951 and Dec 1963, a multi-linear relationship was developed based on Enterprise and Clay Center. This relationship is Fort Riley = 0.55*Clay Center + 1.21*Enterprise + 158.37. The R^2 is shown in Figure 3-33 below.

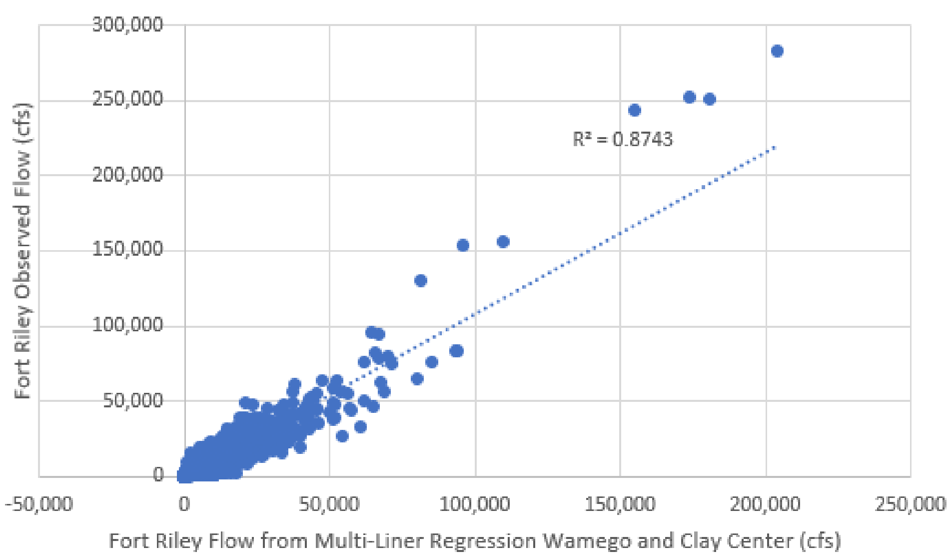


Figure 3-32. Multi-linear regression between Fort Riley and Wamego and Clay Center daily flow data

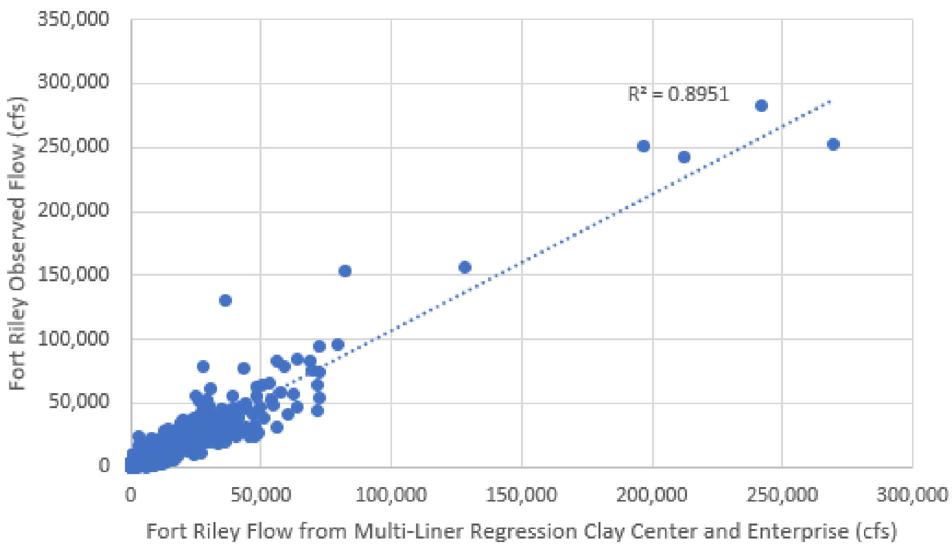


Figure 3-33. Multi-linear regression between Fort Riley and Clay Center and Enterprise daily flow data

3.3.12 Kansas River at Wamego, KS

Kansas River at Wamego was used directly from the USGS since it covers the full modeling period.

3.3.13 Vermillion Creek at Wamego, KS

Vermillion Creek at Wamego has data from April 1936 through June 1946, January 1954 to June 1972, and February 2002 to current. Where there is missing data, flows were set to zero and the Vermillion Creek flow was included in the local flow calculation between Wamego and Topeka.

3.3.14 Mill Creek at Paxico, KS

Mill Creek at Paxico data set starts in December 1953. Before that time flows were set to zero and the Mill Creek flow was included in the local flow calculation between Wamego and Topeka.

3.3.15 Kansas River at Topeka, KS

Kansas River at Topeka was used directly from the USGS since it covers the full modeling period.

3.3.16 Soldier Creek at Topeka, KS

Soldier Creek at Topeka has data from May 1929 through September 1932 and July 1935 to current. Where there is missing data, flows were set to zero and the Soldier Creek flow was included in the local flow calculation between Topeka and Lecompton.

3.3.17 Kansas River at Lecompton, KS

Kansas River at Lecompton data record begins in March 1936. Before this time the data record was extend using a multi-linear relationship utilizing Topeka (upstream) and Desoto (downstream). This relationship is Lecompton = 0.3801*Desoto + 0.6723*Topeka – 9.3797. The R^2 is shown in Figure 3-34 below.

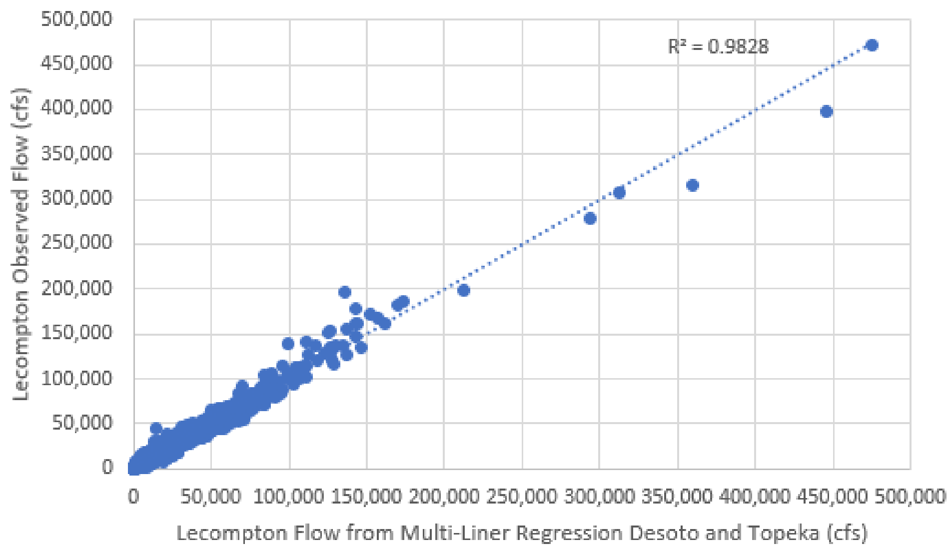


Figure 3-34. Multi-linear Regression between Lecompton and Desoto and Topeka daily flow data

3.3.18 Stranger Creek at Tonganoxie, KS

Stranger Creek at Tonganoxie data set starts in April 1929. Before that time flows were set to zero and the Stranger Creek flow was included in the local flow calculation between Lecompton and Desoto.

3.3.19 Kansas River at Desoto, KS

Kansas River at Desoto was used directly from the USGS since it covers the full modeling period.

3.3.20 Missouri River at Saint Joseph, MO

HEC-ResSim was used to produce regulated Missouri River at Saint Joseph flows for the time period 31 Jan 1930 through Feb 2020. The HEC-ResSim model is developed and maintained by the Northwest Division Missouri River Basin Water Management office. The period of record data set was developed as part of the ongoing Missouri River Flow Frequency Study. Before 31 Jan 1930, data was extended using regulated flow data from the peer-reviewed Upper Mississippi River System Flow Frequency Study (UMRSFFS).

3.3.21 Platte River at Sharps Station, MO

Platte River at Sharps Station data starts in Dec 1978. Before this time, data was estimated using the Platte River at Agency and the Little Platte River at Smithville gages where available. If these gages were not available, flows were set to zero and the Platte River flow was included in the local flow calculation between St. Joseph and Kansas City. Table 3-25 details the data used. Figure 3-25 show the multi-linear relationship between Sharps Station and the Platte River at Agency and the Little Platte River at Smithville. Figure 3-26 shows the linear relationship between Sharps Station and Agency.

Table 3-25. Data relationships used to extend the Platte River at Sharps Station daily data

Date Range	Equation Used	Comment
01Jan1920 to 21May1924		Estimated based off local flow between St. Joseph and Kansas City
22May1924 to 10Aug1930	Sharps Station = 0.92*Agency + 665.9	Linear relationship with Agency
10Aug1930 to 12May1932		Estimated based off local flow between St. Joseph and Kansas City
13May1932 to 31May1965	Sharps Station = 0.92*Agency + 665.9	Linear relationship with Agency
01Jun1965 to 29Nov1978	Sharps Station = 1.11*Smithville + 0.90*Agency + 494.79	Multi-linear relationship between Agency and Smithville
01Dec1978 to present		Observed USGS Data

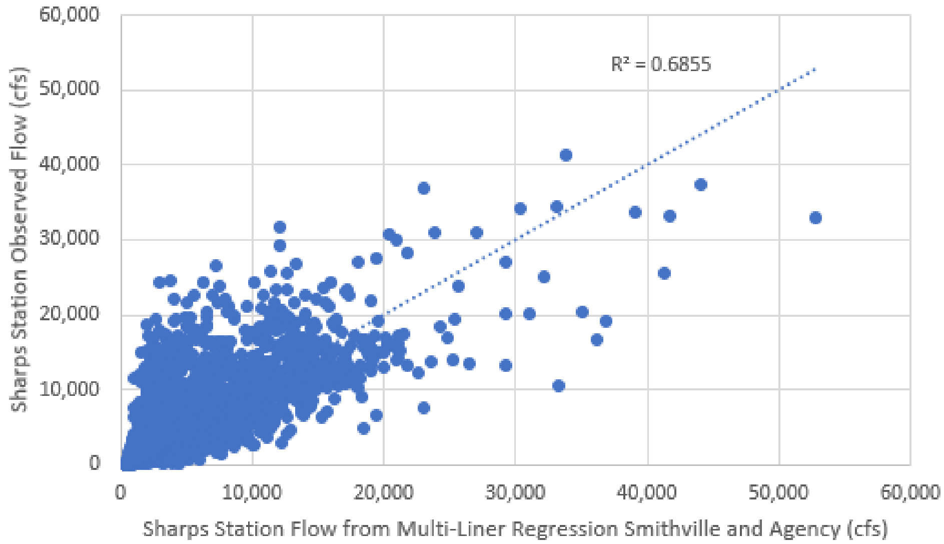


Figure 3-35. Multi-linear relationship between Sharps Station and Smithville and Agency daily flow data

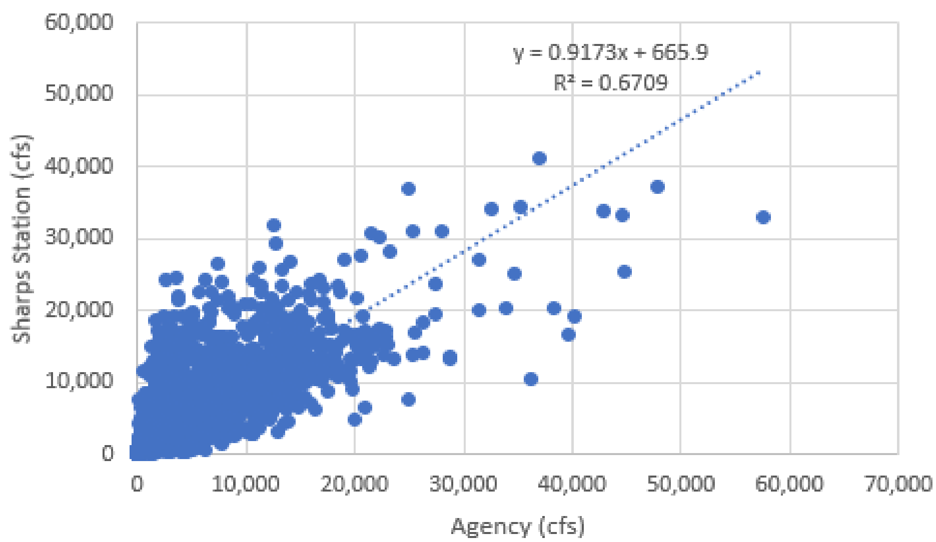


Figure 3-36. Linear Relationship between Sharps Station and Agency daily flow data

3.3.22 Missouri River at Kansas City, MO

Missouri River at Kansas City data set starts in October 1928. Before this time, data was extended using the peer-reviewed data extension from the UMRSFFS.

3.3.23 Blue River at Kansas City, MO

Blue River at Kansas City data set starts in May1939. Before that time flows were set to zero and the Blue River flow was included in the local flow calculation between Kansas City and Waverly.

3.3.24 Little Blue River at Lake City, MO

Little Blue River at Lake City data set starts in April 1948. Before that time flows were set to zero and the Blue River flow was included in the local flow calculation between Kansas City and Waverly.

3.3.25 Missouri River at Waverly, MO

Missouri River at Waverly data set starts in October 1928. Before this time, data was extended using the peer-reviewed data extension from the UMRSFFS. There was also missing data from April 1977 to March 1978 that was filled in with UMRSFFS data.

3.4 Observed Flow and Pool Elevation

HEC-ResSim allows an alternative to be setup that utilizes observed flow in addition to all the necessary model data inputs. The observed flow is ancillary to the necessary model boundary condition data inputs. It is used for a comparison to the model output. It can be viewed in the model output plots or data files, but are not used for model computations. The KRRFSS model was set up with observed reservoir inflow, elevation, and outflow which was pulled directly from the CMWS database. Extended gage records were not utilized for the observed data since it is used for viewing purposes only. All stream-gage junctions were also setup with USGS observed flows when available.

3.5 Reservoir Evaporation

Reservoir evaporation was set up in the model as monthly total evaporation. The amounts varied by lake. The CWMS database has daily pan evaporation values that are provided by each lake project office. During the winter months, an estimated daily evaporation is used since the evaporation pans are not operational during freezing conditions. The monthly evaporation data in the model is calculated by accumulating the CWMS daily pan evaporation values over each month and then calculating each month’s period of record average. The pan evaporation was not corrected for the open water body of a reservoir so it may be over-estimating evaporation especially during the warmer months. Any error from the adjustment factor should only have minor impacts on the HEC-ResSim results. Monthly evaporation used in in the model is shown in Table 3-26.

Table 3-26. Monthly evaporation values for each reservoir

Month	Kanopolis Evap (inches)	Wilson Evap (inches)	Waconda Evap (inches)	Milford Evap (inches)	Tuttle Creek Evap (inches)	Perry Evap (inches)	Clinton Evap (inches)
January	1.42	1.40	1.16	1.14	1.01	1.40	1.16
February	1.54	1.53	1.38	1.35	1.30	1.53	1.35
March	1.58	2.57	2.37	2.24	2.16	2.57	2.04
April	6.24	6.13	6.00	5.99	5.74	6.13	6.15
May	7.21	7.54	7.38	7.39	6.65	7.54	6.92
June	9.07	9.40	9.61	8.89	8.04	9.40	8.24
July	11.21	11.32	11.52	10.71	9.36	11.32	9.42
August	9.45	9.64	9.59	9.27	8.09	9.64	8.17
September	7.43	7.46	7.53	7.28	6.19	7.46	6.70
October	5.03	4.92	4.97	5.21	4.14	4.92	4.51
November	2.80	2.80	2.70	2.65	2.55	2.80	2.50
December	1.47	1.49	1.35	1.27	1.21	1.49	1.15

3.6 Depletions

River depletions can have a large impact on the hydrology of the Kansas River basin especially for low flow conditions. The USBR conducted modeling for historic depletions over the period 31Jan1929 to 31Dec2017 for the Missouri River basin using weather, census, and land use data to model depletions from reservoir operation (evaporation), agriculture, industrial supply, public supply, and trans basin diversion. Depletions are calculated as monthly acre-feet in a Hydrologic Accounting Unit (HUC) 8-digit watershed. The USBR model does not consider water availability in their model which produces results of some unreasonably large depletions during drought years when they would have been restricted due to insufficient flows. The total depletions were provided for historic, present, and present incremental levels. This study utilized the present incremental data set since the historic depletion is already manifest in the observed data. Utilizing the present incremental data set results in the model accounting for all the depletions at the current level for the entire forecast period.

The modeled depletions were further processed by Missouri River Basin Water Management (MRBWM) to accumulate the full depletion contributing to a reservoir or gage location. The HUC8s were added, and the monthly acre-feet were converted to daily cubic feet per second. A 15-day running average was used to smooth flows between months. If a partial HUC8 contributed to a gage or reservoir, a percent of the HUC depletion was calculated based on the watershed area that contributed. The data was also extended from 31Dec2017 to Jan 2020. For the present incremental data, the most recent depletion was generally zero, so zero depletion was continued for the most recent years after 2017.

NWK further processed the depletion data as some of the large depletions were causing extended periods of negative inflows or river flows. The negative flows probably took place because of lack of water to supply the modeled depletion. A script was set-up to process the data. First, the script extended the depletions to start in 1919. The average daily depletion from 31Jan1929 to 01Jan1940 was used to extend the dataset back to 1919. This average was used without regard to weather or land use data. After the data was extended, the 5th percentile flow was calculated to use as minimum threshold. If the inflow or gage flow added to the depletion was less than the 5th percentile then the depletion was adjusted so the final sum would match the threshold. If the inflow or gage flow was lower than the 5th percentile before adding depletions, the depletion was set to zero.

The processed depletion data set was added as a local flow time series in the ResSim junction. Using the processed depletion data resulted in reasonable model results that account for present level depletions throughout the full period of record.

3.7 Navigation Flows

The HEC-ResSim model is set up with a rule to provide navigation flows from Milford, Tuttle Creek, and Perry, if necessary, to support Missouri River navigation. Because navigation support is provided on an ad-hoc basis, simulations were set up with and without navigation to help quantify the impact that navigation releases may or may not have on the water levels in the basin. Navigation releases can target a flow of 4,000 cfs or less at the Kansas River at Desoto, KS. The Missouri River Master Manual specifies flow for several navigation targets including the Missouri River at Kansas City, MO which is the only target that is impacted by the Kansas River flows. The Kansas City navigation season is officially from March 28 to Nov 27 during a typical year and flows can range from the full service 41,000 cfs to the minimum service 35,000 cfs. The navigation season can be shortened by one or two months based on the July 1 system storage check for the Missouri River reservoir system storage. Missouri River Basin Water Management can call for Kansas River navigation flow support whenever necessary. However, the main use of the Kansas River navigation storage is in dry years simply to balance overall regional system storage. Other times, it becomes necessary during the nesting season of endangered species of birds that take up residence either on the shores of the mainstem reservoirs above Gavins Point, South Dakota or on the banks of the Missouri River below Gavins Point. Either circumstance prevents necessary release increases from Gavins Point.

Tuttle Creek is the only Kansas Basin reservoir allocated with specific navigation storage. It has 72,000 acre-feet allocated for navigation, water quality and other purposes. Future use water supply storage at Milford and Perry can also be utilized for navigation until all this storage is called into service by the State of Kansas. This storage is 198,350 acre-feet at Milford and 125,000 acre-feet at Perry. These storage amounts are limited and 4,000 cfs can deplete available storage in a few weeks. Navigation support is provided in a stepped approach where storage above one threshold can be utilized before October 1 and more storage can be utilized from October 1 until the end of the navigation season. These thresholds are elevation 1072 ft NGVD29 before Oct 1 and 1069 feet NGVD29 after Oct 1 at Tuttle Creek, 1141.4 ft NGVD29 before Oct 1 and 1138.4 after Oct 1 at Milford, and 888.5 feet NGVD29 before Oct 1 and 885.5 feet NGVD29 after Oct 1 at Perry.

To handle the nuances of Kansas River navigation flows, an "if block" was setup to specify the navigation flows to be available during the navigation season and for the correct pool elevations. Also, the if-block checks if the Missouri River at Kansas City drops below the navigation flow target which was derived from a timeseries that was developed by MRBWM for 1930 through 2020. This time series was provided as a time series of Missouri River service level; if the navigation season has ended or if navigation is not being provided for a given year, the service level is set to missing. There were three years that did not have navigation support flows. This time series was modified to be the Missouri River at Kansas City navigation flow target by adding 6,000 cfs to the service level and non-navigation dates were set to zero. The timeseries was extended for the 1920s by assuming full service of 41,000 cfs for the full navigation season. The Tuttle Creek if-block is shown as an example in Figure 3-37. An "else if statement" provides the alternate reservoir elevation that can be utilized after Oct 1. Figure 3-38 shows the Tuttle Creek "else if statement". The Milford and Perry if and else if statements are identical except the elevations represent each lake's elevation thresholds. If all conditions in the if or else if statements are met, the navigation release rule is utilized. The navigation release rule is a downstream control rule that specifies a minimum flow of 4000 cfs at the Kansas River at Desoto. Figure 3-39 shows the navigation release rule. This rule is identical for all three reservoirs. All three lakes work together to provide this flow support. HEC-ResSim balances the releases using the established system storage balance.

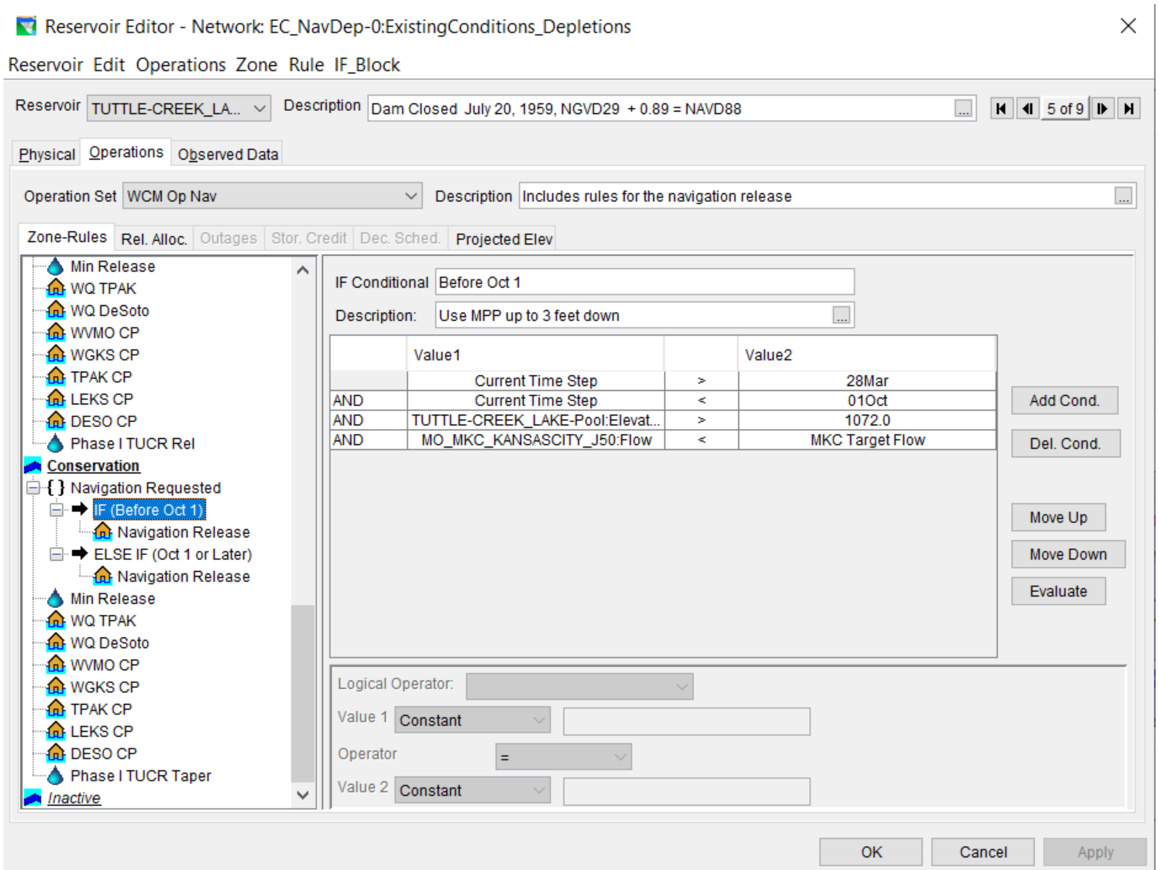


Figure 3-37. Tuttle Creek Navigation "if-statement" for navigation releases

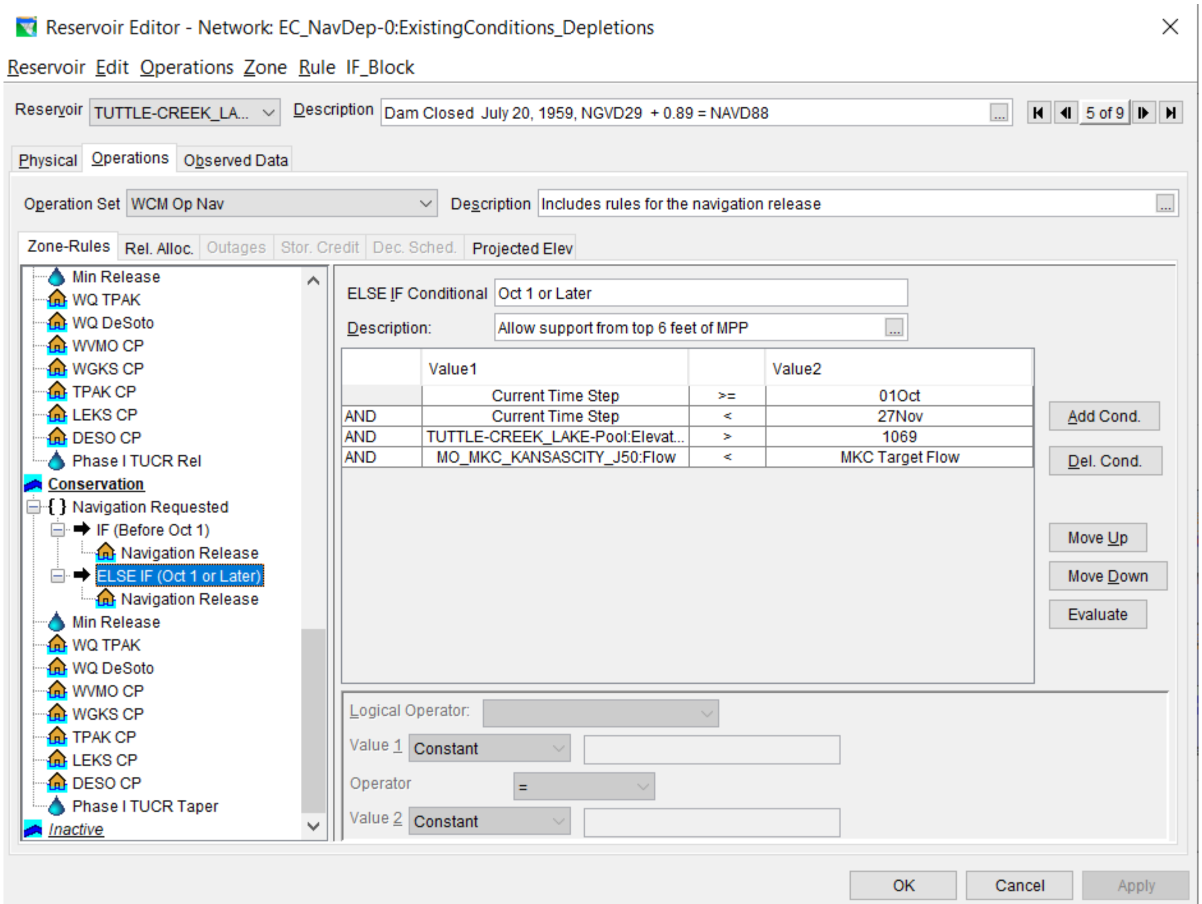


Figure 3-39. Tuttle Creek "else if statement" for navigation releases

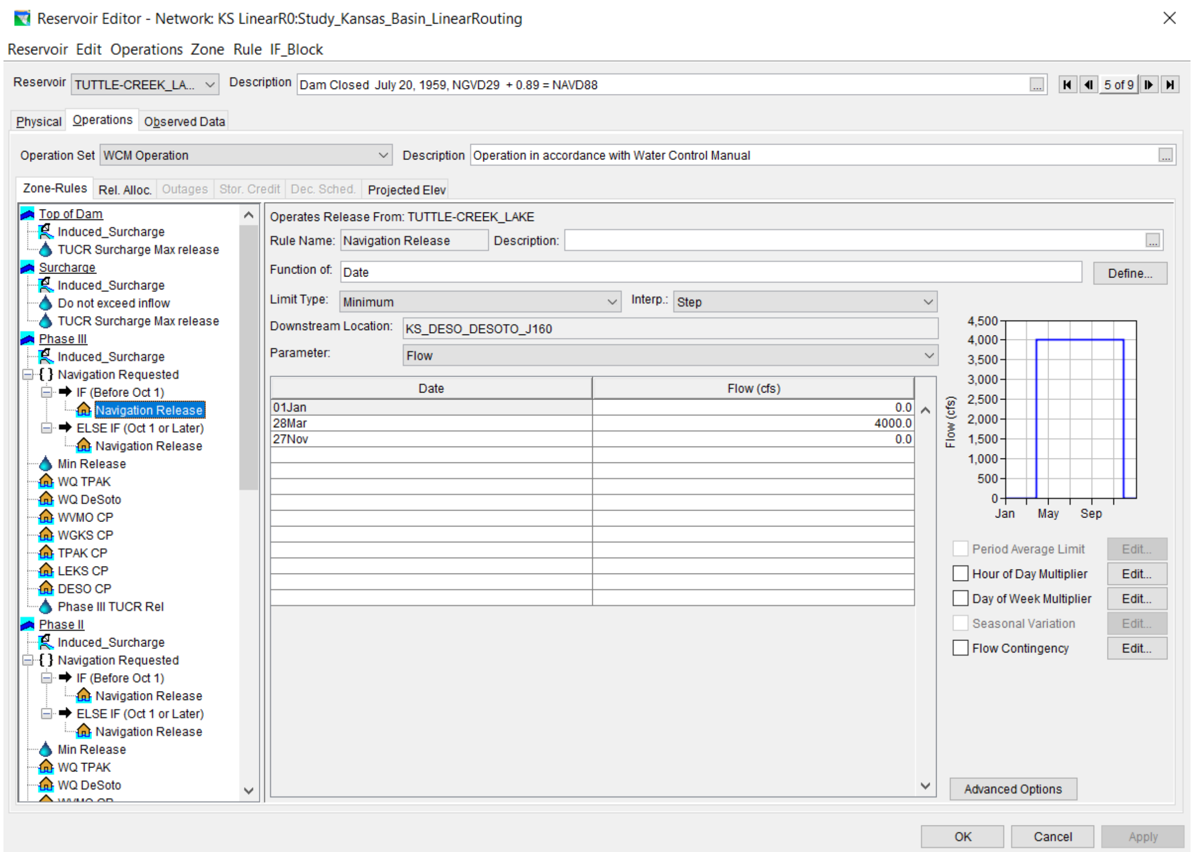


Figure 3-39. ResSim navigation release rule for Tuttle Creek

3.8 Routing Reaches

The KRRFSS HEC-ResSim was setup using the same routing reaches as the Kansas CWMS ResSim model. However, the routing methods were changed. The Kansas CWMS model uses Muskingum and Modified Puls. The KRRFSS routing was changed to coefficient and null routings for all reaches below the reservoirs to simplify the model and allow better downstream control rule performance during the daily time step in the long-term simulations. The routing reaches that were not below reservoirs use similar routing to the CWMS model other than some adjustments to the number of subreaches because of the change from the model running hourly to daily.

The CWMS model included more junctions and routing reaches than were necessary in the KRRFSS model. Instead of removing or consolidating reaches, the superfluous reaches were maintained with null routing. Coefficient routing was initially estimated using parameters from the water management annual benefits spreadsheet. These routing coefficients are established between gages. If there are multiple reaches between gages generally one reach was established with the coefficient routing and the other reaches were set to null. As the local flow simulations were run, modeled and observed flows were compared and evaluated at each gage. This permitted the coefficient routings to be adjusted as necessary to match the observed flows. The reach routing parameters for the reaches downstream of the reservoirs are shown in Table 3-27. Routing reaches for tributaries with Muskingum routing are shown in Table 3-28. Routing reaches on the Missouri River upstream of Kansas City use Modified Puls routing and were not modified during these analyses. Therefore, the Modified Puls values are not shown.

Table 3-27. Routing Reach Parameters for the reaches downstream of the Kansas River Reservoirs

Reach	Location	Routing Method	Day 1	Day 2	Day 3	Day 4
SH_SmokyHillR_R20	Kanopolis to Lindsborg	Coef. Routing	0.4	0.6	-	-
SH_SmokyHillR_R30	Lindsborg to Mentor	Coef. Routing	0.3	0.6	0.1	-
SH_SmokyHillR_R40	Mentor to New Cambria	Null	-	-	-	-
SH_SmokyHillR_R50	Mentor to New Cambria	Coef. Routing	0.4	0.6	-	-
SA_SalineR_R30	Wilson to Tescott	Null	-	-	-	-
SA_SalineR_R40	Wilson to Tescott	Null	-	-	-	-
SA_SalineR_R50	Wilson to Tescott	Coef. Routing	0.0	0.0	0.4	0.6
SA_SalineR_R60	Tescott to New Cambria	Coef. Routing	0.2	0.3	0.5	-
SA_SalineR_R70	Tescott to New Cambria	Null	-	-	-	-
SO_SolomonR_R10	Waconda to Beloit	Null	-	-	-	-
SO_SolomonR_R20	Waconda to Beloit	Coef. Routing	0.2	0.8	-	-
SO_SolomonR_R30	Beloit to Niles	Null	-	-	-	-
SO_SolomonR_R40	Beloit to Niles	Coef. Routing	0.0	0.2	0.8	-
SO_SolomonR_R50	Beloit to Niles	Null	-	-	-	-
SO_SolomonR_R60	Beloit to Niles	Null	-	-	-	-
SO_SolomonR_R70	Beloit to Niles	Coef. Routing	0.1	0.9	-	-
SO_SolomonR_R80	Beloit to Niles	Null	-	-	-	-
SO_SolomonR_R90	Niles to the Smoky Hill River	Coef. Routing	0.5	0.4	0.1	-
SH_SmokyHillR_R60	New Cambria to Enterprise	Coef. Routing	0.0	0.7	0.3	-
SH_SmokyHillR_R70	New Cambria to Enterprise	Null	-	-	-	-
SH_SmokyHillR_R80	New Cambria to Enterprise	Null	-	-	-	-
SH_SmokyHillR_R90	New Cambria to Enterprise	Null	-	-	-	-
SH_SmokyHillR_R100	New Cambria to Enterprise	Null	-	-	-	-

Reach	Location	Routing Method	Day 1	Day 2	Day 3	Day 4
SH_SmokyHillR_R110	Enterprise to Fort Riley	Null	-	-	-	-
SH_SmokyHillR_R120	Enterprise to Fort Riley	Coef. Routing	0.1	0.9	-	-
SH_SmokyHillR_R130	Enterprise to Fort Riley	Null	-	-	-	-
RE_RepublicanR_R180	Milford to the Kansas River	Coef. Routing	0.4	0.6	-	-
KS_KansasR_R10	Fort Riley to Wamego	Null	-	-	-	-
KS_KansasR_R20	Fort Riley to Wamego	Coef. Routing	0.4	0.6	-	-
KS_KansasR_R30	Fort Riley to Wamego	Null	-	-	-	-
KS_KansasR_R40	Fort Riley to Wamego	Null	-	-	-	-
BB_BigBlueR_R150	Tuttle Creek to the KS River	Coef. Routing	0.5	0.5	-	-
KS_KansasR_R50	Wamego to Topeka	Null	-	-	-	-
KS_KansasR_R60	Wamego to Topeka	Null	-	-	-	-
KS_KansasR_R70	Wamego to Topeka	Null	-	-	-	-
KS_KansasR_R80	Wamego to Topeka	Null	-	-	-	-
KS_KansasR_R90	Wamego to Topeka	Coef. Routing	0.4	0.6	-	-
KS_KansasR_R100	Topeka to Lecompton	Null	-	-	-	-
KS_KansasR_R110	Topeka to Lecompton	Null	-	-	-	-
KS_KansasR_R120	Topeka to Lecompton	Coef. Routing	0.6	0.4	-	-
DE_DelawareR_R40	Perry to the Kansas River	Coef. Routing	0.7	0.3	-	-
KS_KansasR_R130	Lecompton to Desoto	Coef. Routing	0.5	0.5	-	-
KS_KansasR_R140	Lecompton to Desoto	Null	-	-	-	-
KS_KansasR_R150	Lecompton to Desoto	Null	-	-	-	-
WA_WakarusaR_R30	Clinton to Lawrence	Coef. Routing	0.9	0.1	-	-
WA_WakarusaR_R40	Lawrence to the Kansas River	Coef. Routing	0.5	0.5	-	-
KS_KansasR_R160	Desoto to Kansas City	Null	-	-	-	-
KS_KansasR_R170	Desoto to Kansas City	Coef. Routing	0.8	0.2	-	-
KS_KansasR_R180	Desoto to Kansas City	Null	-	-	-	-
MO_MissouriR_R50	Kansas City to Waverly	Null	-	-	-	-
MO_MissouriR_R60	Kansas City to Waverly	Coef. Routing	0.9	0.1	-	-
MO_MissouriR_R70	Kansas City to Waverly	Null	-	-	-	-
MO_MissouriR_R80	Kansas City to Waverly	Null	-	-	-	-
MO_MissouriR_R90	Kansas City to Waverly	Coef. Routing	0.1	0.8	0.1	-
MO_MissouriR_R100	Kansas City to Waverly	Null	-	-	-	-
MO_MissouriR_R110	Kansas City to Waverly	Null	-	-	-	-

Table 3-28. Routing Parameters for Tributary Reaches

Reach	Location	Muskingum Parameters		
		K (hrs)	X	Number of Subreaches
SO_SaltCr_R020	Salt Creek to junction with Solomon River	4.0	0.25	1
SH_ChapmanCr_R010	Chapman Creek to junction with Smoky Hill River	2.0	0.25	1
KS_VermillionCr_R010	Vermillion Creek to junction with Kansas River	3.0	0.25	1
KS_MillCr_R010	Mill Creek to junction with Kansas River	3.0	0.25	1
SC_SoldierCr_R020	Soldier Creek to junction with Kansas River	3.0	0.25	1
ST_StrangerCr_R30	Stranger Creek to junction with Kansas River	3.0	0.25	1
MO_BlueR_J10	Blue River to junction with Missouri River	3.0	0.25	1
LM_LittleBlueR_R40	Little Blue River to junction with Missouri River	4.0	0.25	4

3.9 Local Flow Calculation

An HEC-ResSim simulation was setup to pass observed inflows past the dams. The ResSim network was modified to remove reservoirs and all observed inflow was input at the reservoir outflow junction. The observed flows were the extended inflow records to represent the pre-dam period and observed releases after the start of regulation. This combination of data was to pass flows that happened at the dam location. Once the observed flows were routed to the downstream gages, the modeled data was compared to observed to ensure the timing and attenuation matched the observed.

Raw local flows were computed using model output and the extended official streamflow records at each gage location. The equation for the raw computed local flows at a gage is shown below.

$$Gage_{local} = Gage_{obs} - Gage_{model}$$

At each location, all model input parameters were held to 0 cfs except for the gage(s) immediately upstream. The official extended streamflow record at the upstream gage was routed downstream to do the local flow computation. For example, at Lindsborg, the extended data set at Kanopolis was used as the local flow at that location. All other model parameters were held to 0 cfs. The observed record was routed down to Lindsborg, and then the above equation could be used to compute a raw local flow time series.

3.9.1 Local Flow Manipulation

The calculated local flows had some large negative values especially during the time when the data record was extended. This is probably due to uncertainties in routing times and flow at a given location when the data was extended using other gages. To help with some of these data discrepancies, once raw local flows had been computed, flows were blended and distributed using a spreadsheet method as detailed in sections 3.7.1 to 3.7.3. The spreadsheet required the raw local flow and the modeled flow after the initial routing at each location (i.e., $Gage_{local}$ and $Gage_{model}$ from the raw local flow equation). Once data was input, the further calculations could be made as detailed in the following sections.

3.9.2 Blending

Raw local flow was split into positive and negative values, then the negative values were blended using a running average that ranged between 3 and 15 days. The length of the running average depended on the number and magnitudes of the negative values. Where there occurred fewer negatives in the data set, fewer days were used for blending. Those blended negative values were then summed with the positive values to obtain a blended local flow.

3.9.3 Apportioning

After calculating a blended local flow, that flow could be added to the modeled flow to obtain a blended total flow at each location. This time series was checked for negative stream flow. A small percentage of flow from positive values was skimmed from the time series and distributed into the negative local flow when the stream flow went negative. This percentage was very small, with the largest percentage being near 3%.

The apportioned and blended flows were added together to create a final local flow time series. Negatives still existed in the time series but were reduced to the point where the modeled river flow and the final local flow summation did not result in negative total flows in the model. The raw local flow and final local flow time series are plotted together at the Smoky Hill River at Lindsborg, KS and shown in Figure 3-40.

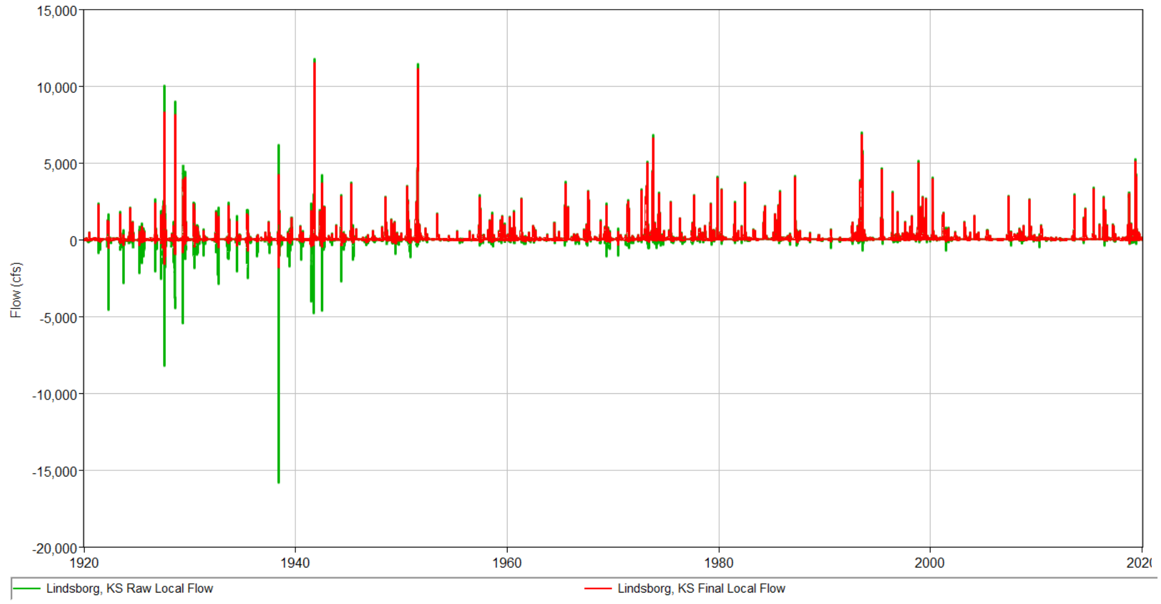


Figure 3-40. Smoky Hill River at Lindsborg, KS raw, calculated, daily local flow compared with the final blended, apportioned, daily local flow

Much of the large negative flow was removed by this process; however, some negative modeled river gage flows persisted when running the regulated simulation. Small negative flow in the local flow data sets is understandable considering uncertainties in gage rating curves and water usage. The modeled regulated negative flows are not ideal, but they did not appear to have much of an impact on the annual peak stream flow or the annual flow volume. Table 3-29 identifies the number of days that were used for blending the negative local flows and the percentage that was skimmed off for the final apportionment of flows at each local flow location.

Table 3-29*. Parameters used to process the final local flow data set

Stream Gage	Days Used to Blend Negative Local Flows	Percent of Positive Local Flows Used to Fix Negative Stream Flow
Smoky Hill River at Lindsborg	15	2.56%
Smoky Hill River at Mentor	11	2.98%
Saline River at Tescott	15	0.30%
Smoky Hill River at New Cambria	15	0.80%
Solomon River at Beloit	15	0.43%
Solomon River at Niles	11	0.39%
Smoky Hill River at Enterprise	7	0.05%
Republican River at Milford Dam	3	0.18%

Stream Gage	Days Used to Blend Negative Local Flows	Percent of Positive Local Flows Used to Fix Negative Stream Flow
Kansas River at Fort Riley	7	0.08%
Kansas River at Wamego	7	0.02%
Kansas River at Topeka	7	0.01%
Kansas River at Lecompton	7	0.29%
Wakarusa River at Lawrence	7	0.81%
Kansas River at Desoto	7	0.01%
Missouri River at Kansas City	3	0.00%
Missouri River at Waverly	3	0.00%

3.10 HEC-ResSim Reservoir Rules

HEC-ResSim rules were used to determine modeled releases throughout the period of record. The rules were set up in accordance with the approved water control manuals at each reservoir. The existing Kansas CWMS HEC-ResSim model rules were utilized for this study, but some rules were modified to get appropriate modeled results.

Release function rules were used to specify maximum and minimum releases in a zone. Separate reservoir zones were setup for Conservation, Phase I, Phase II, Phase III, Surcharge, and Top of Dam. Dividing the flood control pool into the separate phases allowed the model to respond to the seasonal changes in threshold elevations. Maximum releases for a zone were established based on the water control manual limits. In most cases these limits are higher than typical releases, but the authorized maximum was used to allow the full range of releases in the model. A more typical release rate is set to draw the lake down to target in 10 days. For smaller events, HEC-ResSim will often draw down the lake in a day or two if the downstream control allows maximum release.

Downstream control rules were used to set maximum or minimum flows at the downstream control points. The maximum flood control rules utilized a scripted state variable to calculate the current pool zone to determine the maximum release. The downstream control rules did not always maximize the downstream channel space. When this occurred, the rule advanced options were adjusted to help the model calculation. Figure 3-41 shows an example of the downstream control point advanced options. Adjusting the settings in advanced options provided reasonable use of the downstream control point available channel capacity.

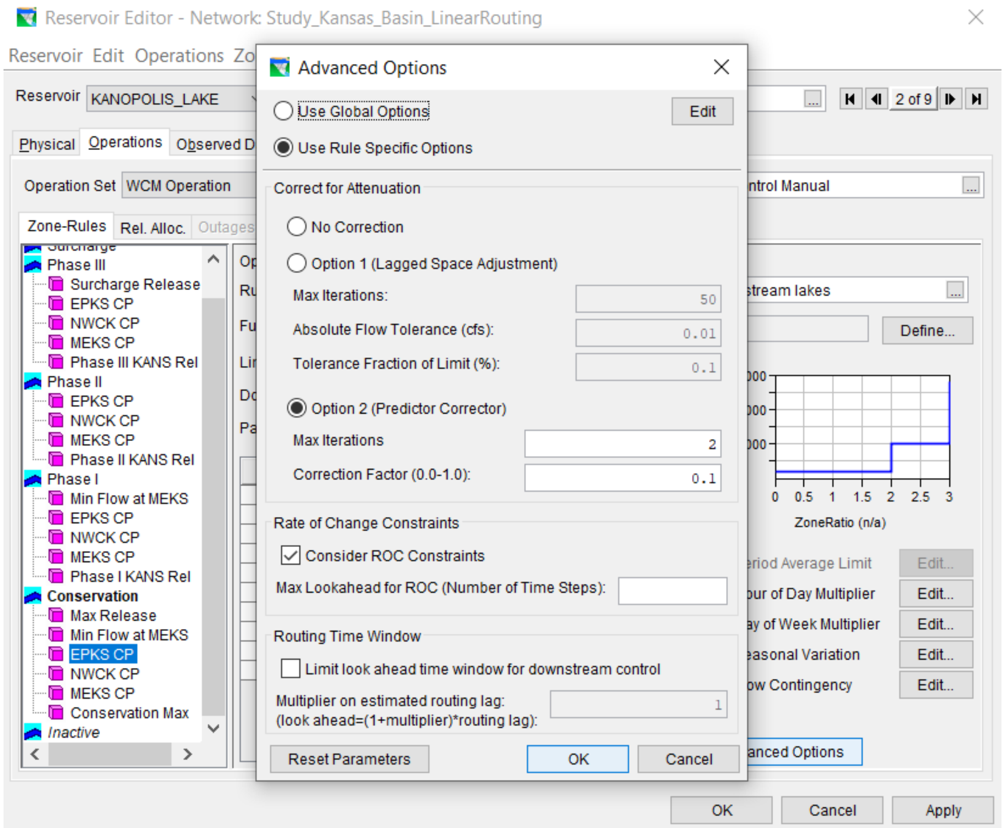


Figure 3-41. Downstream Control Rule Advanced Options

Reservoir surcharge rules utilized a range of options depending on the physical setup of the dam and the water control manual criteria. Wilson and Clinton did not enter surcharge during the period of analysis. Perry and Milford were both compared to their respective surcharge events and seemed to perform reasonably well. The water control manual surcharge criteria are for hourly reservoir operation during extreme events. The daily time step in the model tends to generalize releases and does not always follow the desired surcharge criteria because of the time step. This became a problem with Waconda surcharge operations during the 1951 flood event. Manual overrides were used to force the model to release a more reasonable rate less than inflows.

4. Model Results

The "Existing Conditions" simulations (with and without navigation) were run using a lookback period of 01Dec1919 to 31Dec1919; the forecast time was 01 Jan 1920 to 02 Jan 2020. The main intent of the HEC-ResSim model is to produce regulated data for the full period of record. Model results were graphically compared to observed time series data where available.

There were many reasons why modeled results may not match observed. Before the dams were in place, the observed flow at the gages downstream of the dams was unregulated. After the dams were constructed, reservoir operations have at times formally deviated from the water control plan (modeled rules) for specific flood control purposes approved by Missouri River Basin Water Management or significant dam maintenance. Also, reservoir release decisions are being made with a certain amount of forecast uncertainty relating to the flow at downstream control points when reservoir releases reach that location. As much as possible decisions are based on water on the ground forecasts, but there is uncertainty about future conditions especially where long travel time from reservoir to gage location exist (such as from Milford to the Missouri River at Waverly). The ResSim downstream control point rules, used in this study, incorporate elements of forecast uncertainty, but these decisions are different than in real-time operations. For instance, some of the Kansas reservoirs are 4-5 days of travel time away from the Missouri River control points. Real-time operations may decide to maintain ongoing reservoir releases even though the Missouri River rises above criteria from a local rainfall, because the river is forecast to drop before any proposed reservoir release reduction could effectively propagate downstream to alleviate conditions at the control point. ResSim does route all inflows and local flows, both present and future, to the downstream control point. However, ResSim does not match the target flows perfectly at the downstream control points because of its internal forecast uncertainty. Factors such as attenuation and routing times were adjusted in this model, but these factors can vairy depending on the event leading to downstream flows missing the desired target at a control point.

The navigation flow support scenario resulted in navigation releases being made in approximately half of the years; however, four main time periods had multi-year reservoir drawdowns as a result the navigation releases. These time periods were 1932 to 1941, 1953 to 1957, 1988 to 1992, and 2002 to 2007. These were some of the dry periods when the Missouri River at Kansas City, MO dropped below the minimum service level during the navigation season. Peak reservoir pool elevations and flows were virtually the same in both existing conditions scenarios. Navigation flow support resulted in slightly lower pool elevations during the drought years, but that additional storage was quickly filled when flood flows occurred.

To compare the observed and modeled data, pool elevation duration graphs were assessed. Figure 4-1 shows the Kanopolis pool elevation duration plot from 01Aug1948 (time of first fill) to 01Jan2020. Both model scenarios result in the same pool duration since navigation flow is not supported from Kanopolis. Comparison of the observed and modeled duration indicate that the model keeps the reservoir at multi-purpose pool more often than in real-time. Seasonal water level management plans will keep the lake above multi-purpose pool during periods of the year, but the water level management plan was not put into the model since it is discretional and may not be followed depending on the basin conditions. The multi-purpose pool elevation has also been raised since the initial fill. Figure 4-2 shows the observed and modeled annual flow volume from 1949 (when outflow data started) through the end of 2019. The modeled scenarios with and without navigation are identical. The volumes match closely with the observed tending to be slightly higher. The differences are due to estimated evaporation in the model, carryover storage from year to year, and the present incremental depletions. The full water balance was analyzed for Wilson and Tuttle Creek ensuring that the model maintains mass balance. This analysis is shown in section 2.2 of "Attachment 1 Supporting Plots".

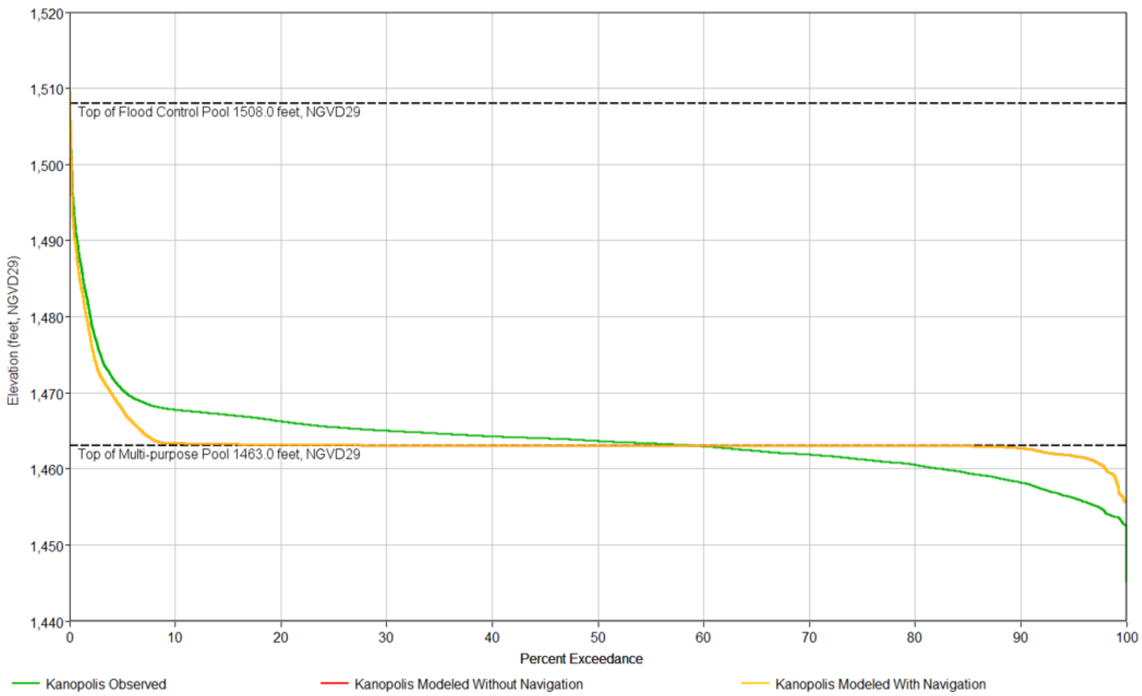


Figure 4-1. Kanopolis observed and modeled pool elevation duration from 01Jul1948 to 01Jan2020

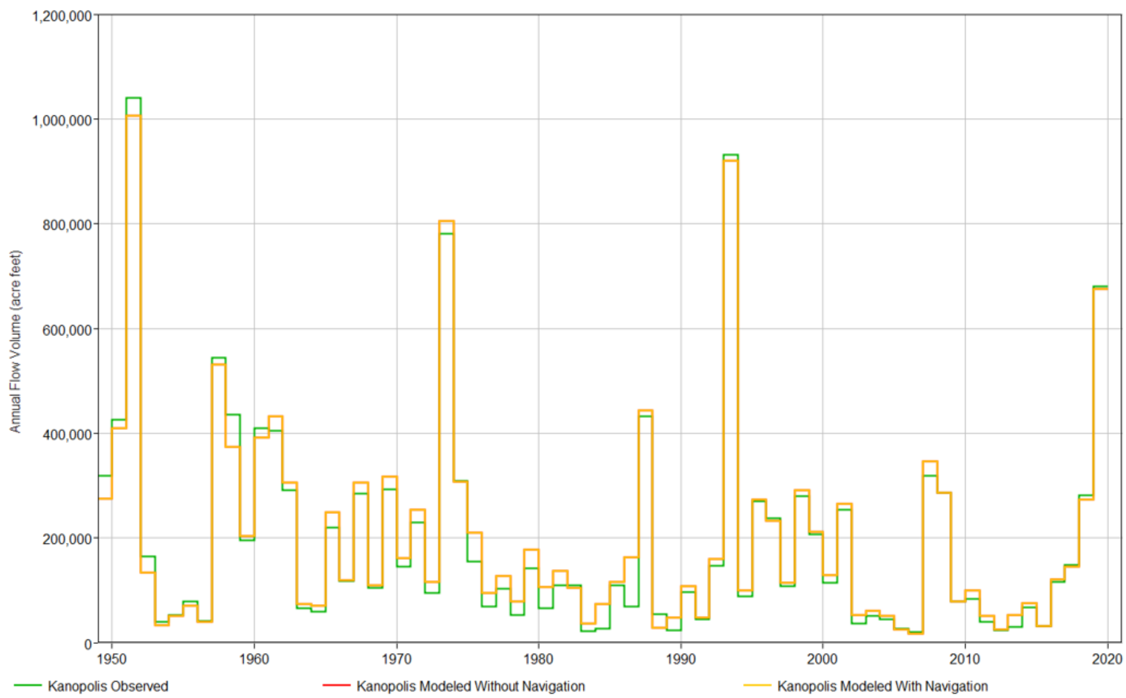


Figure 4-2. Kanopolis Observed and Modeled Annual Flow Volume for 1949 through 2019

Downstream of Kanopolis the Smoky Hill River at Lindsborg and Mentor annual flow volumes are compared in Figure 4-3 and Figure 4-4. These plots start in 1949 after the effects of the Kanopolis regulation begin at these gages allowing a comparison of regulated observed and modeled. Lindsborg does not have observed data from 1966 through 2013.

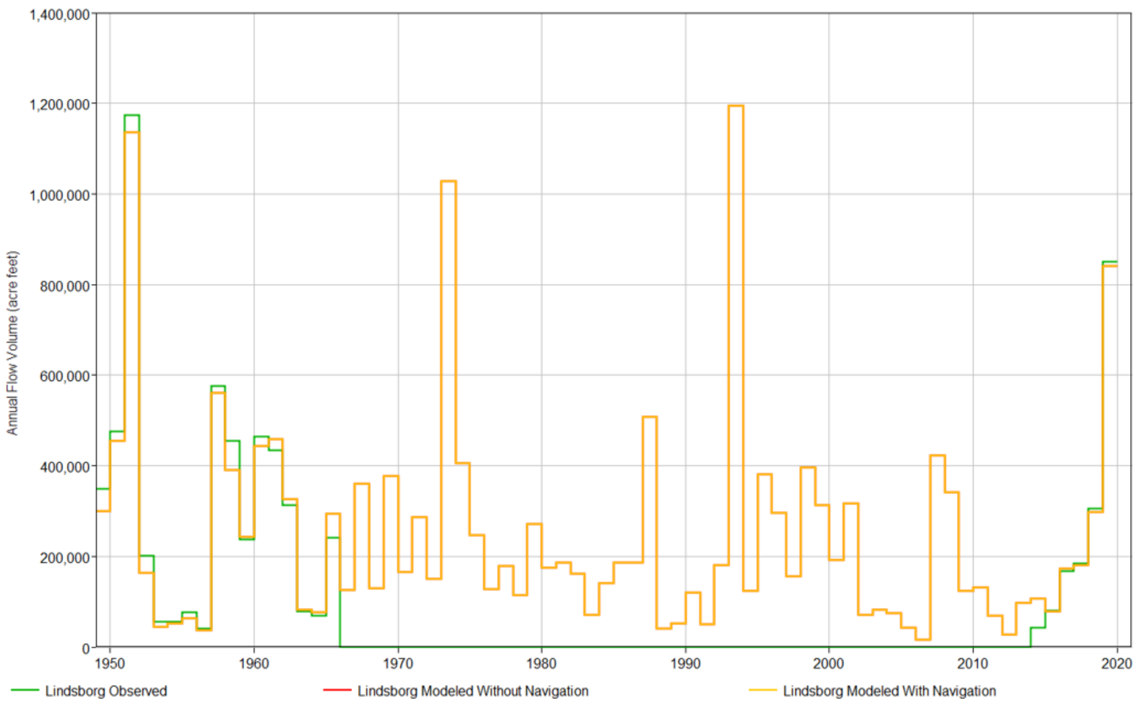


Figure 4-3. Lindsborg Observed and Modeled Annual Flow Volume for 1949 through 2019

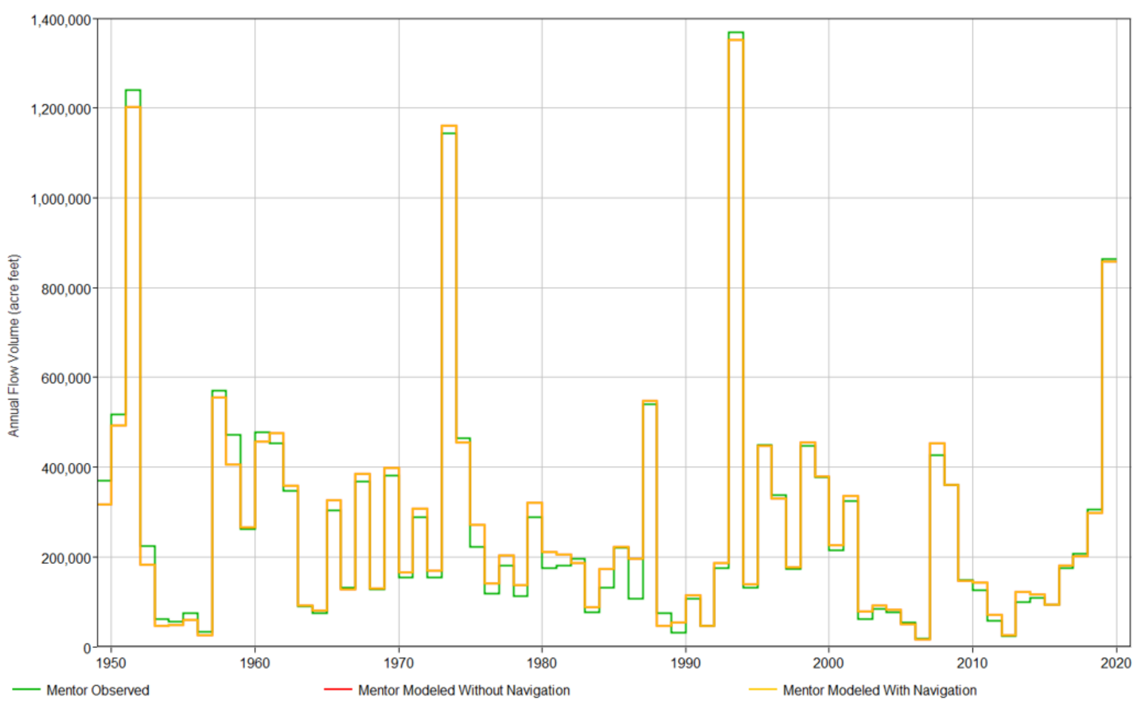


Figure 4-4. Mentor Observed and Modeled Annual Flow Volume for 1949 through 2019

The Wilson Reservoir pool elevation duration plot from 01 Jan 1973 (approximate time of first fill) to 01 Jan 2020 is shown in Figure 4-5. Both model scenarios result in the same pool duration since navigation flow is not supported from Wilson. Comparison of the observed and modeled duration indicate that, similar to Kanopolis, the model tends to under-predict the pool elevation. This basin is prone to extended droughts. Estimated modeled evaporation and basin depletions are the reason for the modeled pool elevation being lower on the dry end of the curve. Seasonal water level management plans will keep the lake above multi-purpose pool during wet periods which may be the reason for the observed being higher than modeled in the 1516 to 1517 elevation range. The water level management plan was not put into the model since it is discretional and may not be followed depending on the basin conditions. Figure 4-6 shows the observed and modeled annual flow volume from 1964 (when outflow data started) through 2019. The modeled scenarios with and without navigation are identical. The observed volumes tend to be higher than modeled and with greater separation than characterized in the Kanopolis data.

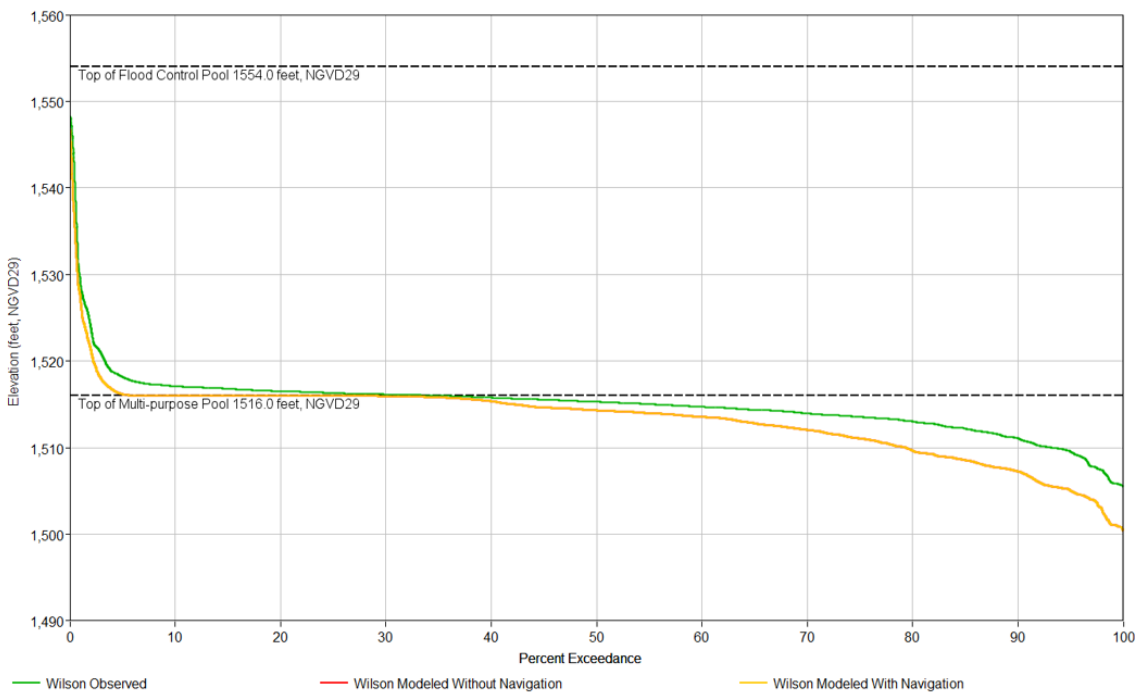


Figure 4-5. Wilson observed and modeled pool elevation duration from 01Mar1973 to 01Jan2020

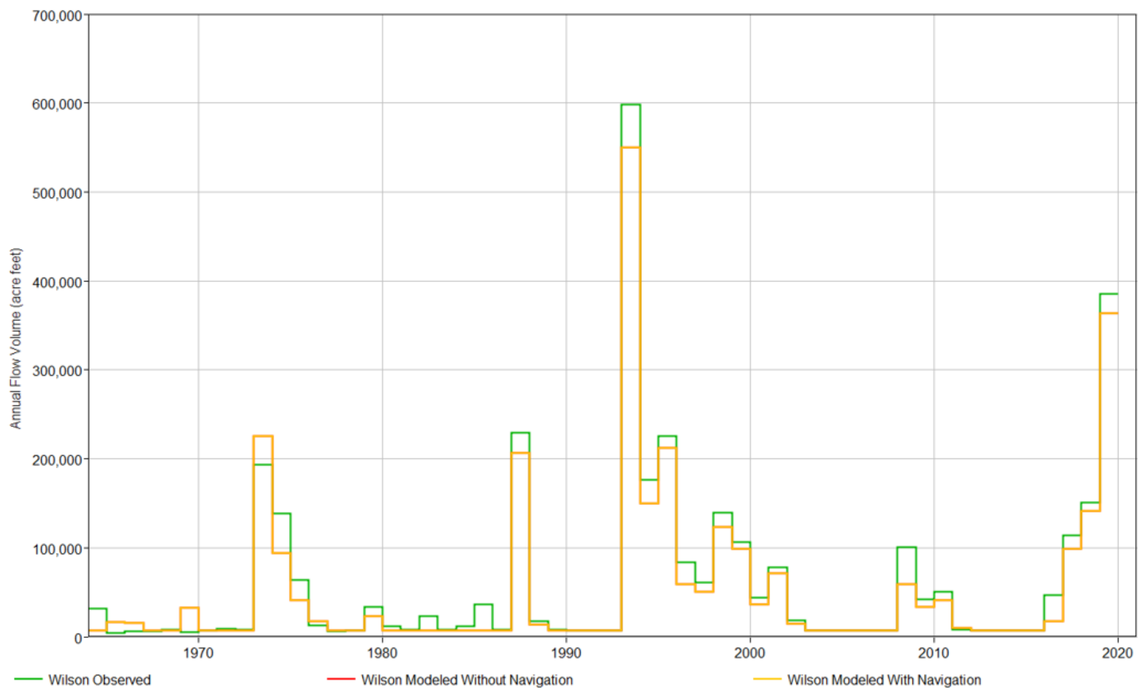


Figure 4-6. Wilson Observed and Modeled Annual Flow Volume for 1964 through 2019

Downstream of Wilson the Saline River at Tescott and the Smoky Hill River at New Cambria (impacted by Kanopolis and Wilson regulation) annual flow volumes are compared in Figure 4-7 and Figure 4-8. These plots start in 1973 after the effects of the Wilson regulation begin at these gages allowing a comparison of regulated observed and modeled. New Cambria does not have flow data in 2007 and from 2010 through the present.

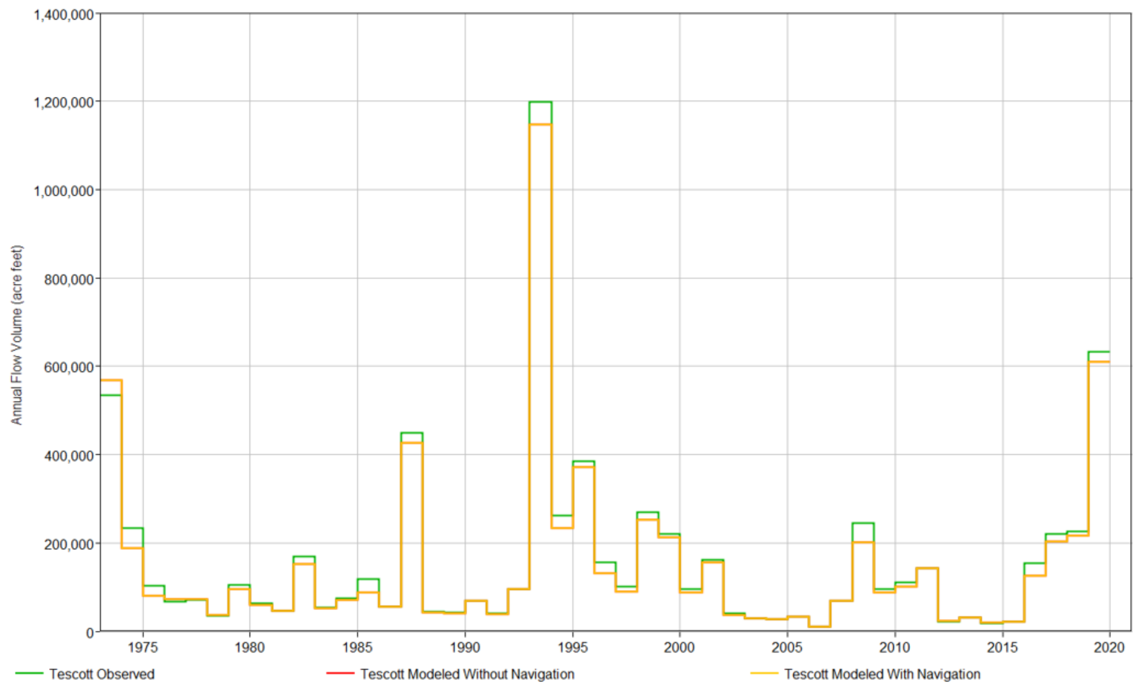


Figure 4-7. Tescott Observed and Modeled Annual Flow Volume for 1973 through 2019

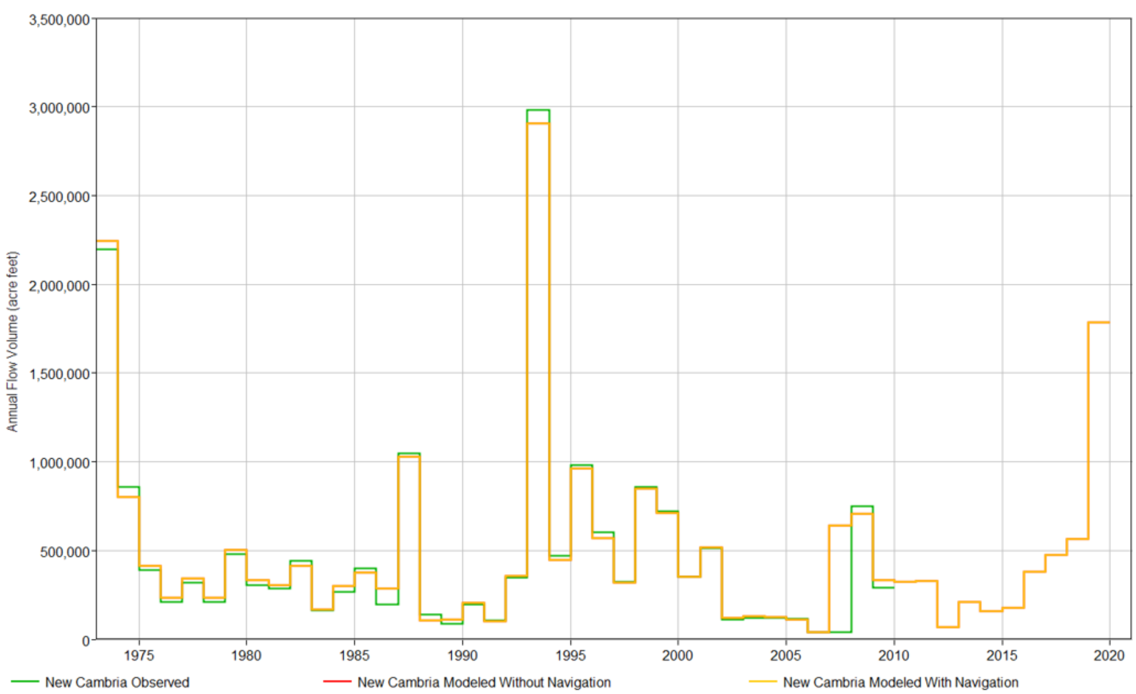


Figure 4-8. New Cambria Observed and Modeled Annual Flow Volume for 1973 through 2019

The Waconda Reservoir pool elevation duration plot from 15 May 1973 (approximate time of first fill) to 01 Jan 2020 is shown in Figure 4-9. Both model scenarios result in the same pool duration since navigation flow is not supported from Waconda. Comparison of the observed and modeled duration indicate that the model tends to over-predict the pool elevation below the conservation pool. Seasonal water level management plans will keep the lake below the multi-purpose pool during the winter and above the multi-purpose pool during the spring and fall which may be the reason for the observed differing from the modeled. The water level management plan was not put into the model since it is discretional and may not be followed depending on the basin conditions. Figure 4-10 shows the observed and modeled annual flow volume from 1968 (when outflow data started) to 2019. The modeled scenarios with and without navigation are identical. The observed volumes tend to be slightly higher than modeled.

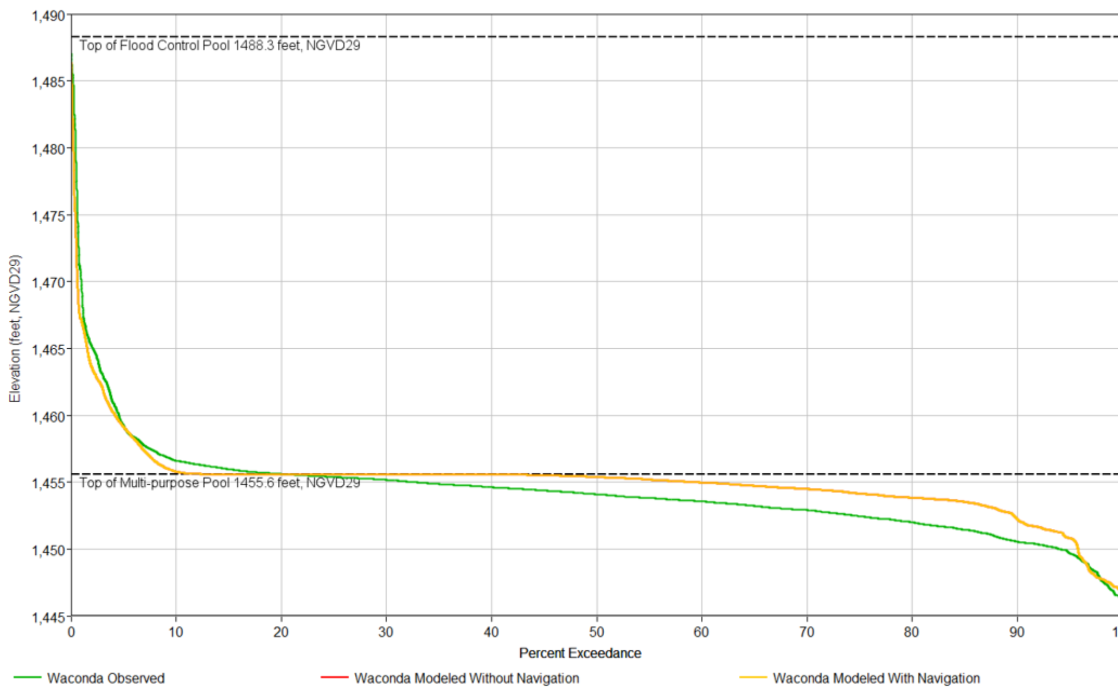


Figure 4-9. Waconda observed and modeled pool elevation duration from 01May1973 to 01Jan2020

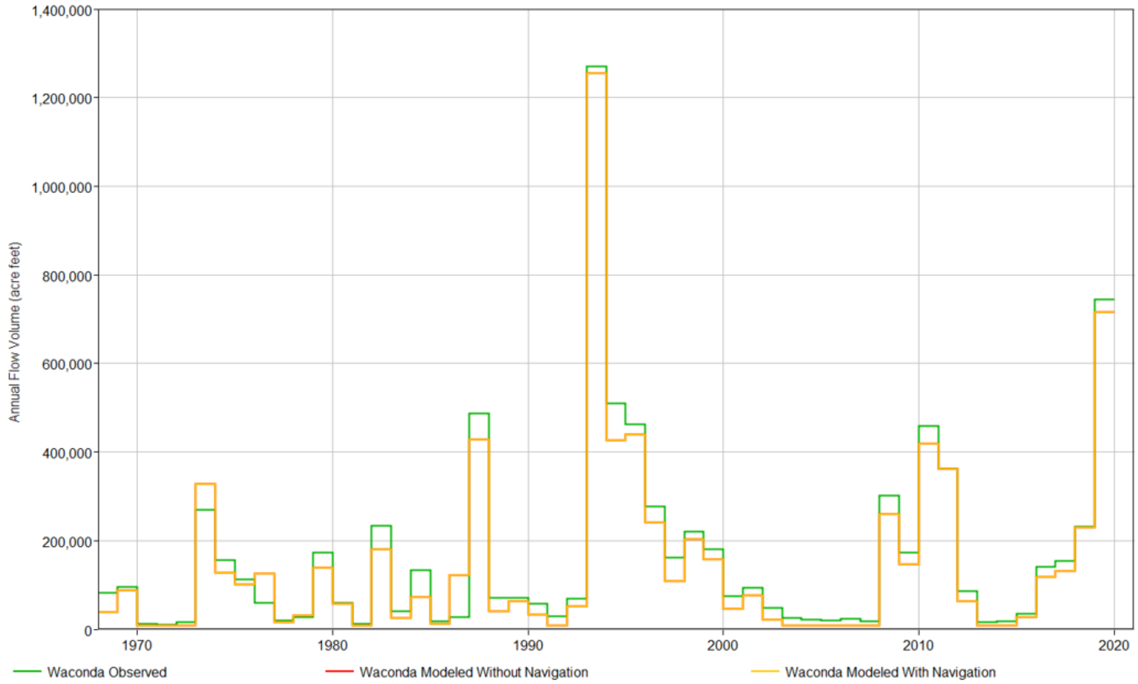


Figure 4-10. Waconda Observed and Modeled Annual Flow Volume for 1968 through 2019

Downstream of Waconda the Solomon River at Beloit and Niles and the Smoky Hill River at Enterprise (impacted by regulation from all three Smoky Hill reservoirs) annual flow volumes are compared in Figure 4-11 through Figure 4-13. These plots start in 1973 which is about when the impacts of the regulation of all three reservoirs began at these gages allowing a comparison of regulated observed and modeled. During the regulated period, Beloit only has data from 2013 through the present.

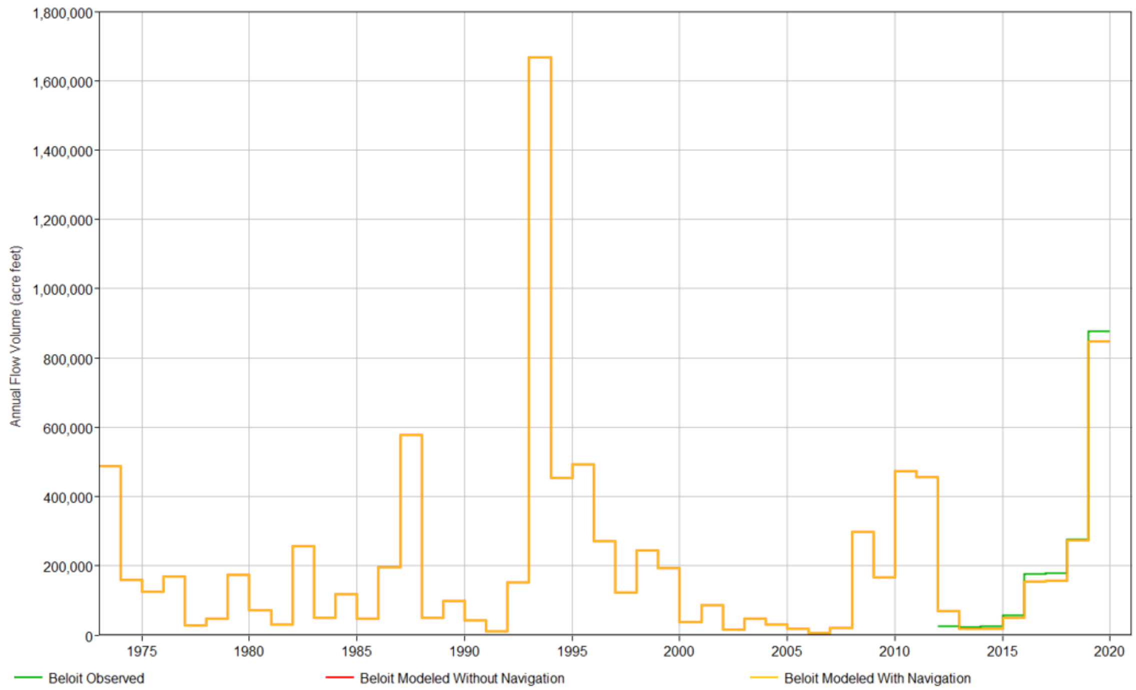


Figure 4-11. Beloit Observed (2013 to 2019) and Modeled Annual Flow Volume for 1973 through 2019

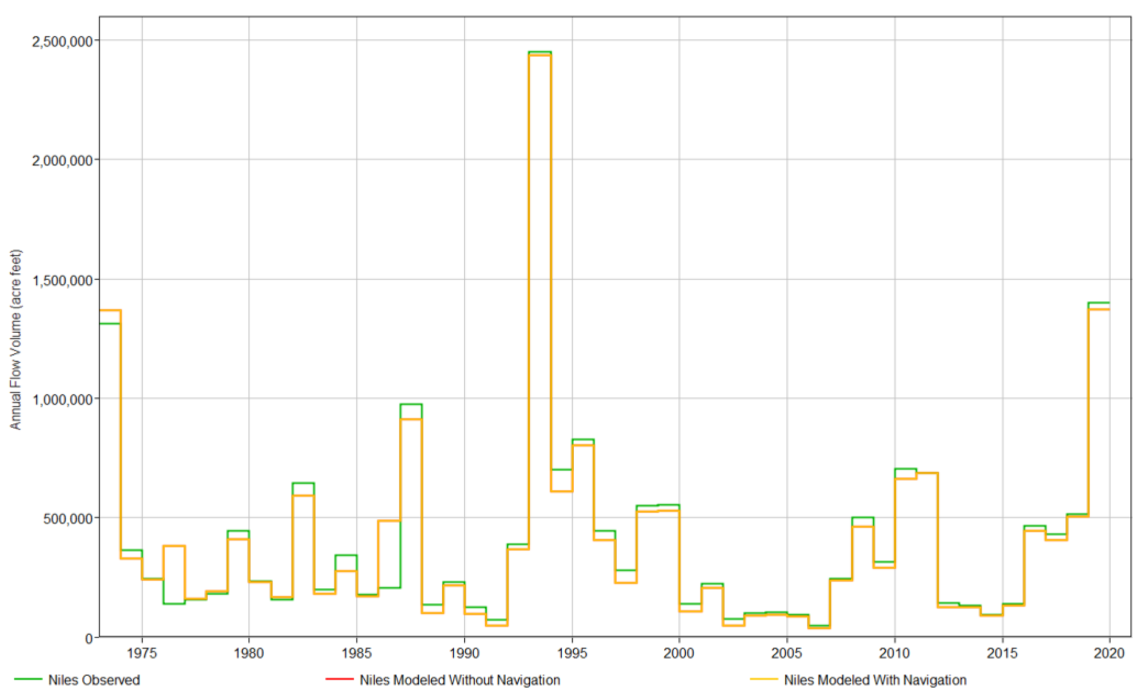


Figure 4-12. Niles Observed and Modeled Annual Flow Volume for 1973 through 2019

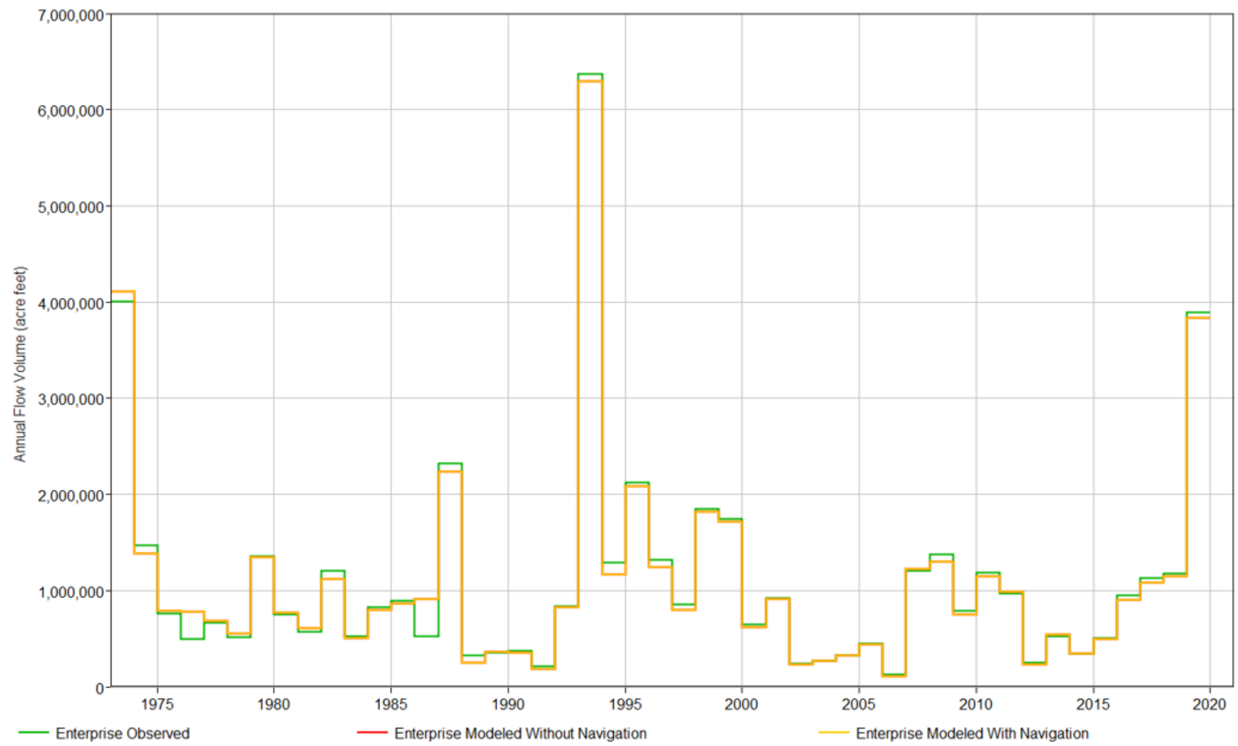


Figure 4-13. Enterprise Observed and Modeled Annual Flow Volume for 1973 through 2019

The Milford Reservoir pool elevation duration plot from 01 Aug 1967 (approximate time of first fill) to 01 Jan 2020 is shown in Figure 4-14. Comparison of the observed and modeled duration indicate that the model tends to have higher pool elevations in the flood control pool. The low pool durations show that the model tends to stay a little higher than observed except when considering navigation. Seasonal water level management plans will allow the lake below the multi-purpose pool during the winter and one foot above the multi-purpose pool during the spring and fall which may be part of the reason for the observed differing from the modeled. The water level management plan was not put into the model since it is discretional and may not be followed depending on the basin conditions. However, the significant rise in the less frequent portions of the duration curve is probably due to the model constraining releases due to downstream control points especially on the Missouri River. Some of the potential reasons for these differences are discussed at the start of section 4.

Navigation flow support impacts to pool elevation and outflow for selected periods of time are shown in Figure 4-15 to Figure 4-18. These are drought years so pools are already low from reduced inflow and water quality support. Navigation support results in lower pool elevations. When large inflows occur, the without navigation scenario will make larger releases if the multi-purpose pool fills.

Figure 4-19 shows the observed and modeled annual flow volume from 1965 (when outflow data started) to the 2019. The observed volumes tend to be slightly higher than modeled. The model scenarios were very similar, but navigation flow support resulted is small differences for a few years. The large difference in 2019 is due to modeled storage being carried over into 2020. In the observed data set, water was emptied from flood storage before the end of 2019 by using a deviation for higher flow targets on the Missouri River, benefitting flood control operations at Milford, Tuttle Creek and Perry, as well as Clinton.

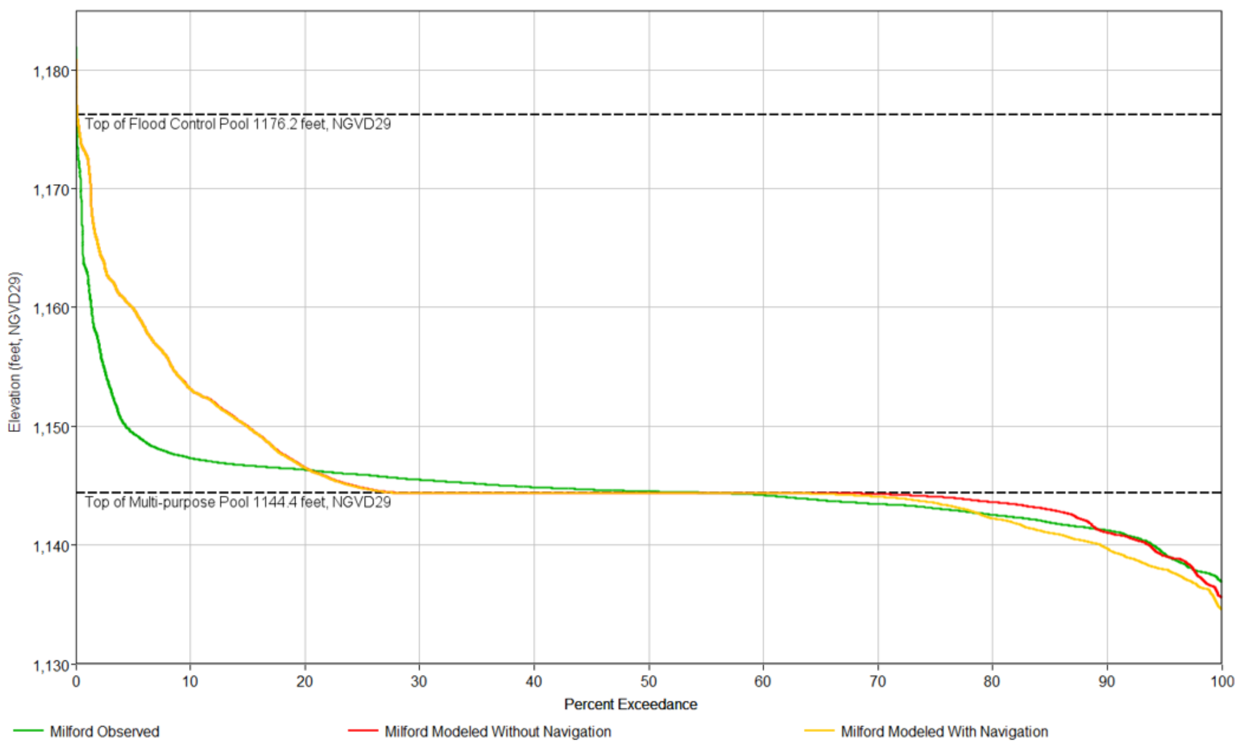


Figure 4-14. Milford observed and modeled pool elevation duration from 01Jul1967 to 01Jan2020

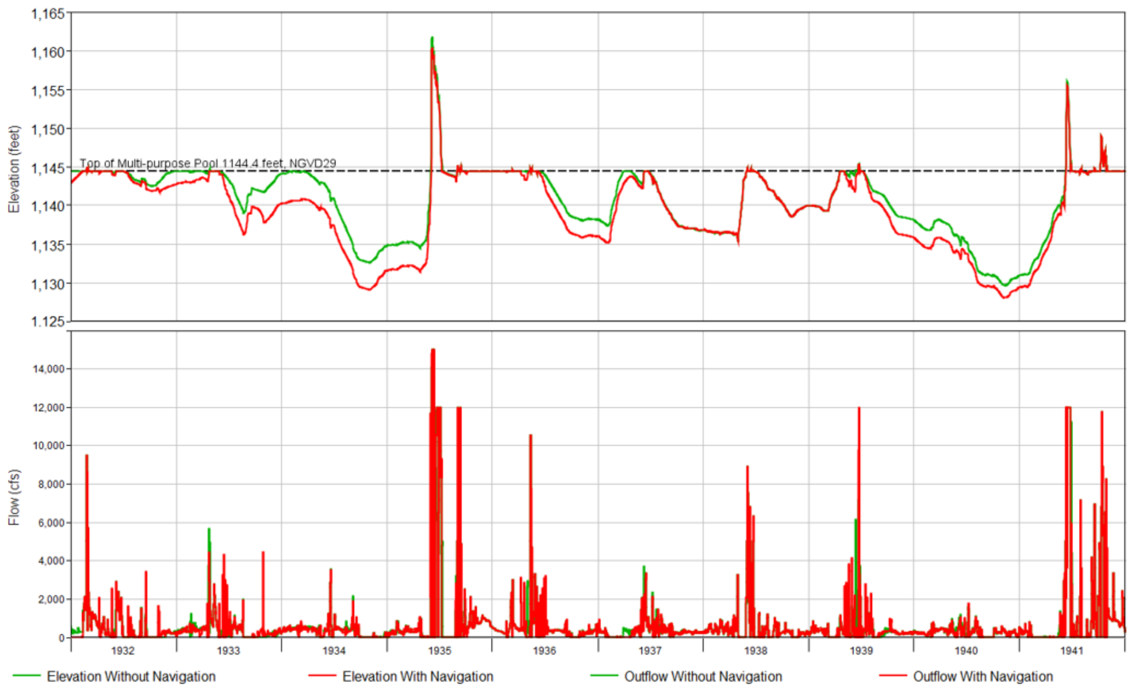


Figure 4-15. Milford pool elevation modeled with and without navigation flow support for the years 1932 through 1941

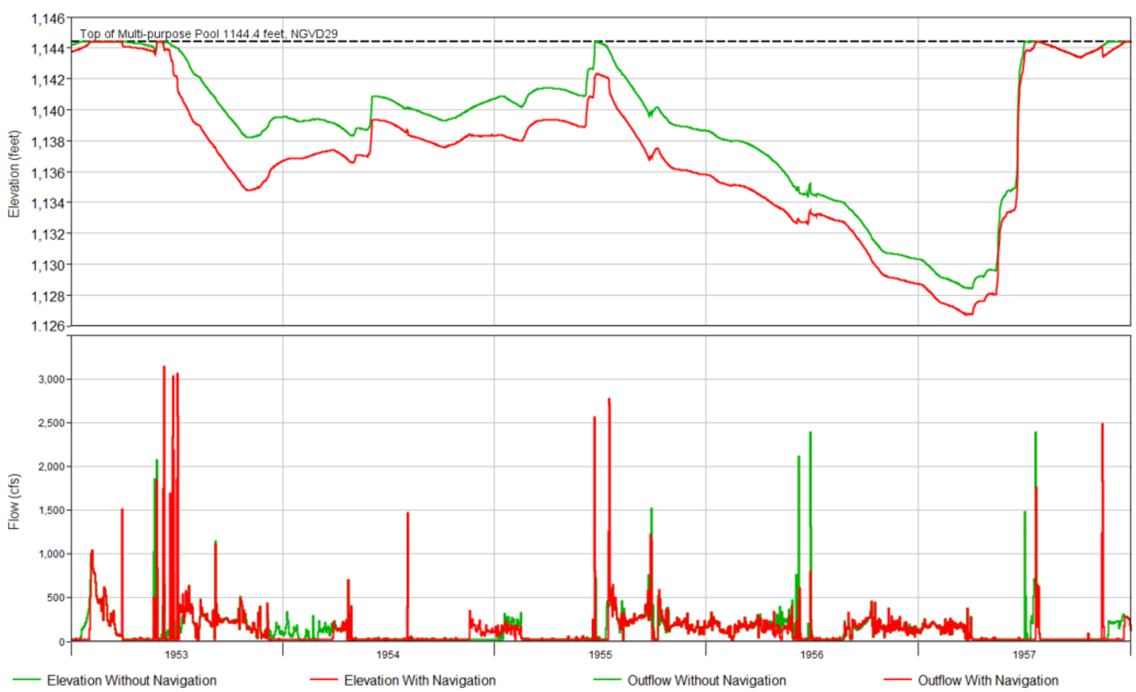


Figure 4-16. Milford pool elevation modeled with and without navigation flow support for the years 1955 through 1958

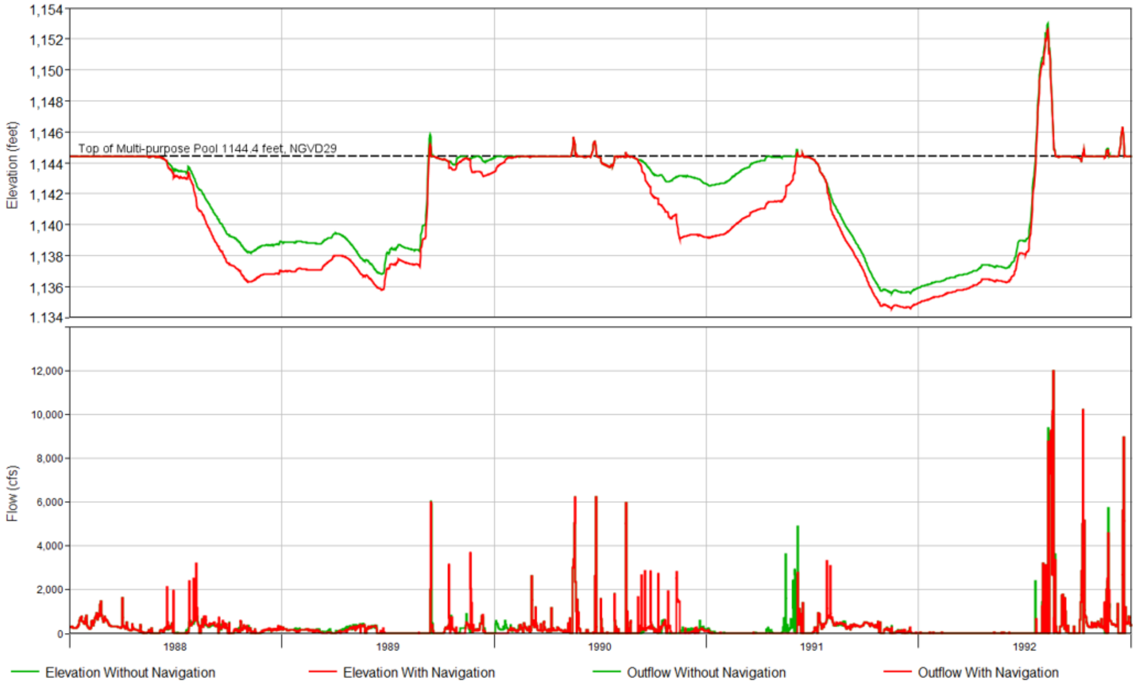


Figure 4-17. Milford pool elevation modeled with and without navigation flow support for the years 1989 through 1991

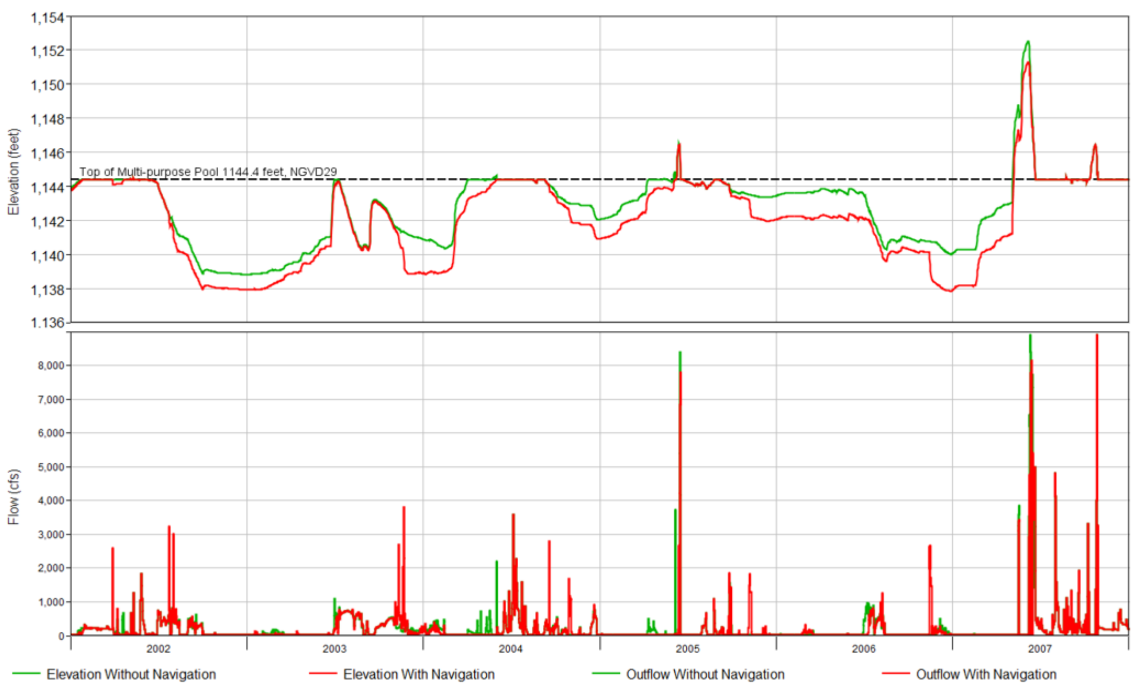


Figure 4-18. Milford pool elevation modeled with and without navigation flow support for the years 2002 through 2007

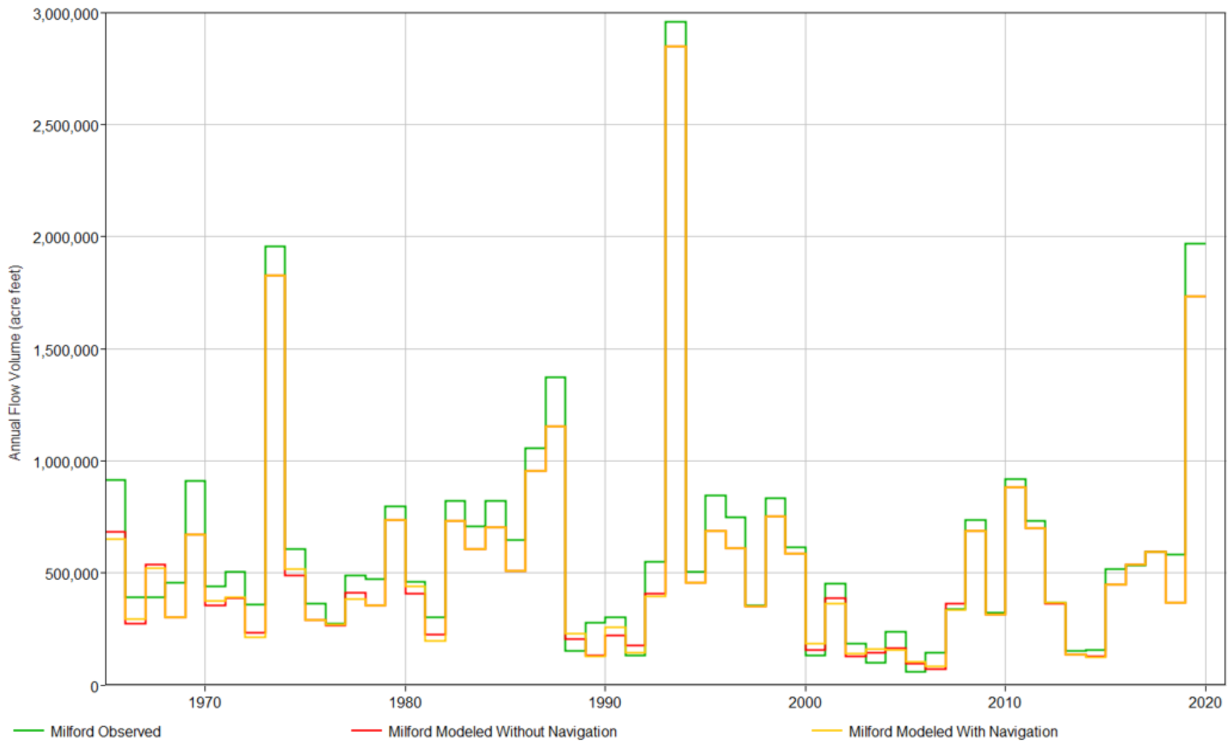


Figure 4-19. Milford Observed and Modeled Annual Flow Volume for 1965 through 2019

Downstream of Milford the Kansas River at Fort Riley (impacted by regulation from all three Smoky Hill reservoirs and Milford Reservoir) annual flow volume is compared in Figure 4-20. This plot starts in 1973 which is about when the impacts of the regulation of all reservoirs began at these gages allowing a comparison of regulated observed and modeled. The observed volume continues to be slightly higher than modeled at this gage.

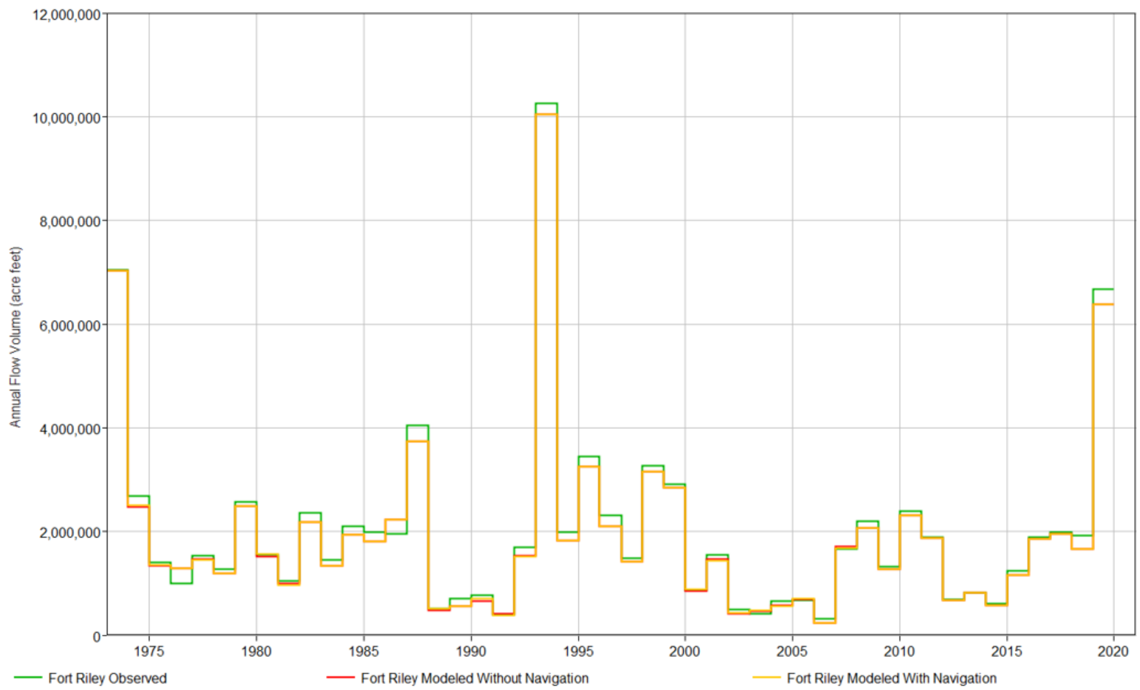


Figure 4-20. Fort Riley Observed and Modeled Annual Flow Volume for 1973 through 2019

The Tuttle Creek Reservoir pool elevation duration plot from 01May1963 (approximate time of first fill) to 01Jan2020 is shown in Figure 4-21. Comparison of the observed and modeled duration indicate that the model tends to have higher pool elevations in the flood control pool. Seasonal water level management plans will allow the lake below the multi-purpose pool during the winter and five feet above the multi-purpose pool during the spring and fall which may be part of the reason for the observed differing from the modeled. The water level management plan was not put into the model since it is discretional and may not be followed depending on the basin conditions. Navigation results in pool elevations dropping below the multi-purpose pool slightly more often. Like Milford, the significant rise in the less frequent portions of the duration curve is probably due to the model constraining releases due to downstream control points especially on the Missouri River. Some of the potential reasons for these differences are discussed at the start of section 4.

Navigation flow support impacts to pool elevation and outflow for selected periods of time are shown in Figure 4-22 to Figure 4-25. These are drought years so pools are already low from reduced inflow and water quality support. Navigation support results in lower pool elevations. When large inflows occur, the without navigation scenario will make larger releases if the multi-purpose pool fills. Larger encroachments into the flood control pool were very similar for both scenarios.

Figure 4-26 shows the observed and modeled annual flow volume from 1960 (when outflow data started) to the 2019. The observed volumes match modeled closely except during high flow years. Navigation flow support only results in small differences a few years. Small differences between observed and modeled are probably due to estimated modeled evaporation. The large difference in 2019 is due to modeled storage being carried over into 2020. In the observed data set, water was emptied from flood storage before the end of 2019 by using a deviation for higher flow targets on the Missouri River, benefitting flood control operations at Milford, Tuttle Creek and Perry, as well as Clinton.

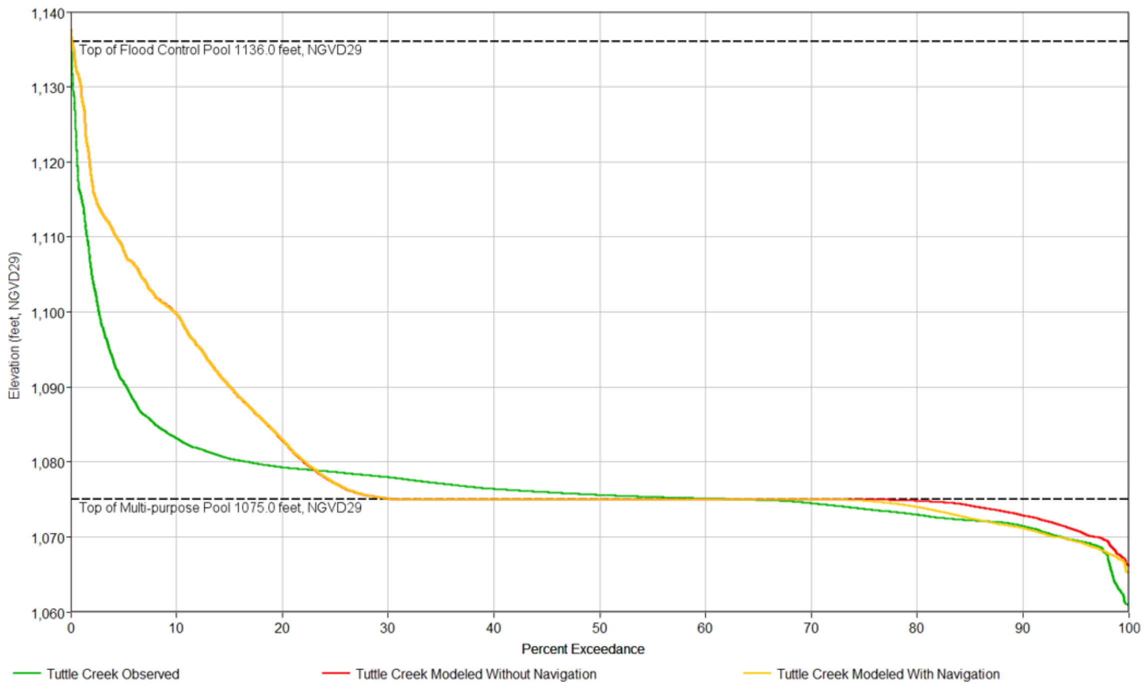


Figure 4-21. Tuttle Creek observed and modeled pool elevation duration from 01Apr1963 to 01Jan2020

Figure 4-22. Tuttle Creek pool elevation modeled with and without navigation flow support for the years 1932 through 1941

Figure 4-23. Tuttle Creek pool elevation modeled with and without navigation flow support for the years 1955 through 1959

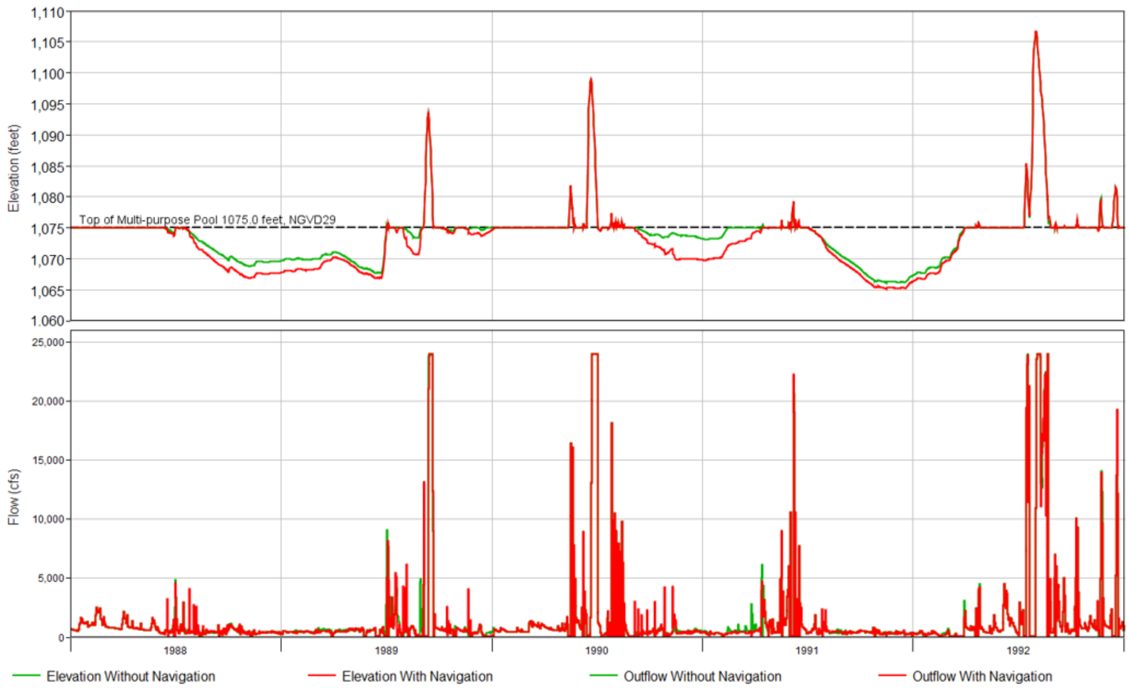


Figure 4-24. Tuttle Creek pool elevation modeled with and without navigation flow support for the years 1989 through 1991

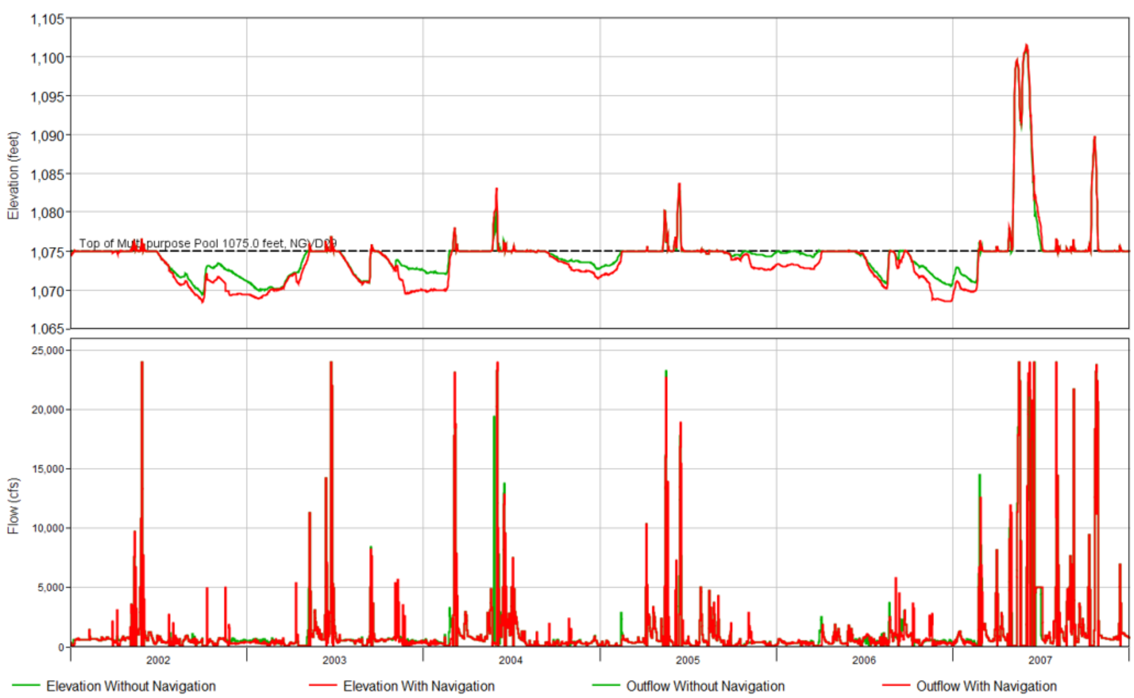


Figure 4-25. Tuttle Creek pool elevation modeled with and without navigation flow support for the years 2002 through 2007

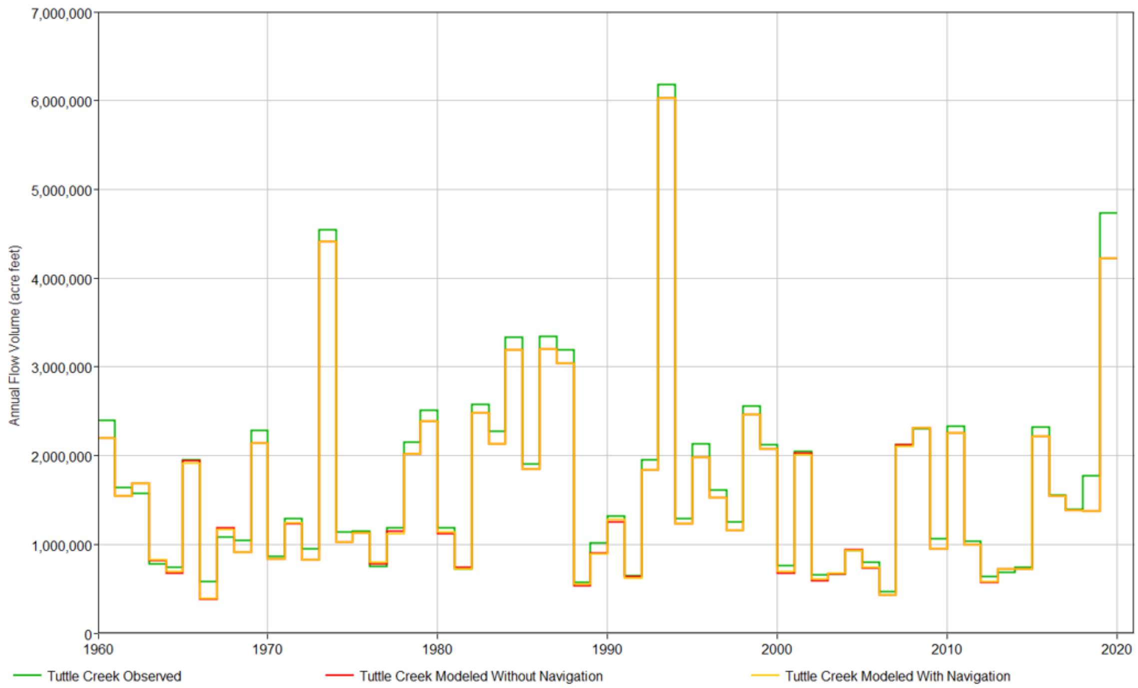


Figure 4-26. Tuttle Creek Observed and Modeled Annual Flow Volume for 1960 through 2019

Downstream of Tuttle Creek the Kansas River at Wamego and Topeka (impacted by regulation from all three Smoky Hill reservoirs and Milford and Tuttle Creek reservoirs) annual flow volumes are compared in Figure 4-27 and Figure 4-28. These plots start in 1973 which is about when the impacts of the regulation of all reservoirs began at these gages allowing a comparison of regulated observed and modeled. The observed volume continues to be slightly higher than modeled at these gages especially during the larger flow years.

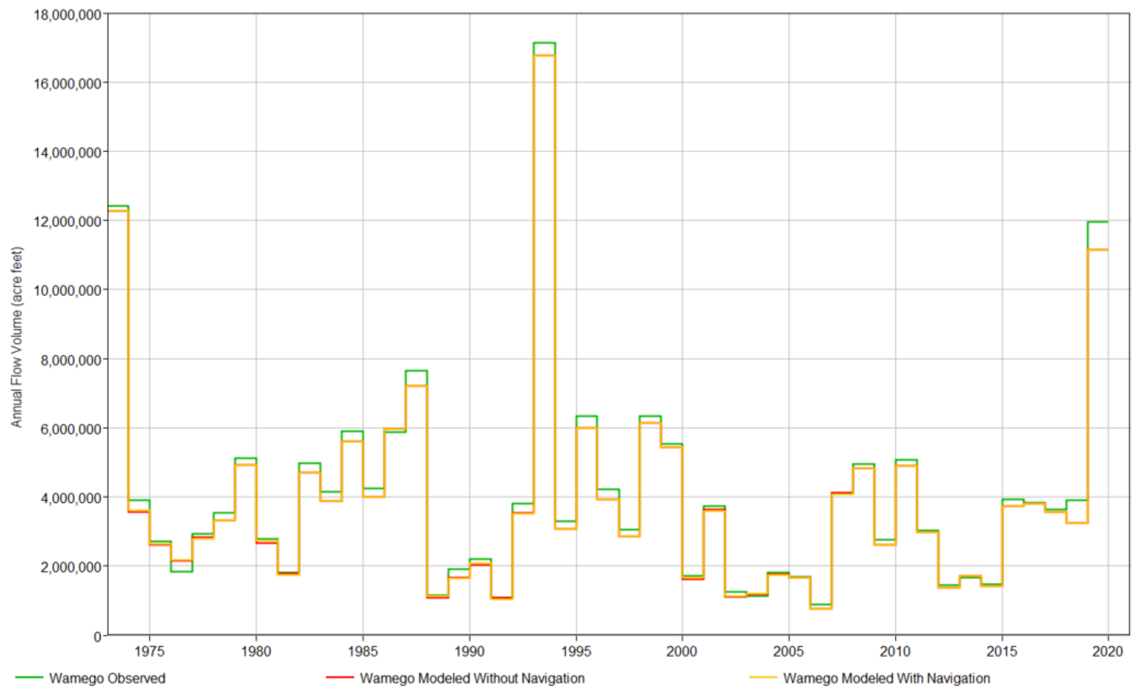


Figure 4-27. Wamego Observed and Modeled Annual Flow Volume for 1973 through 2019.

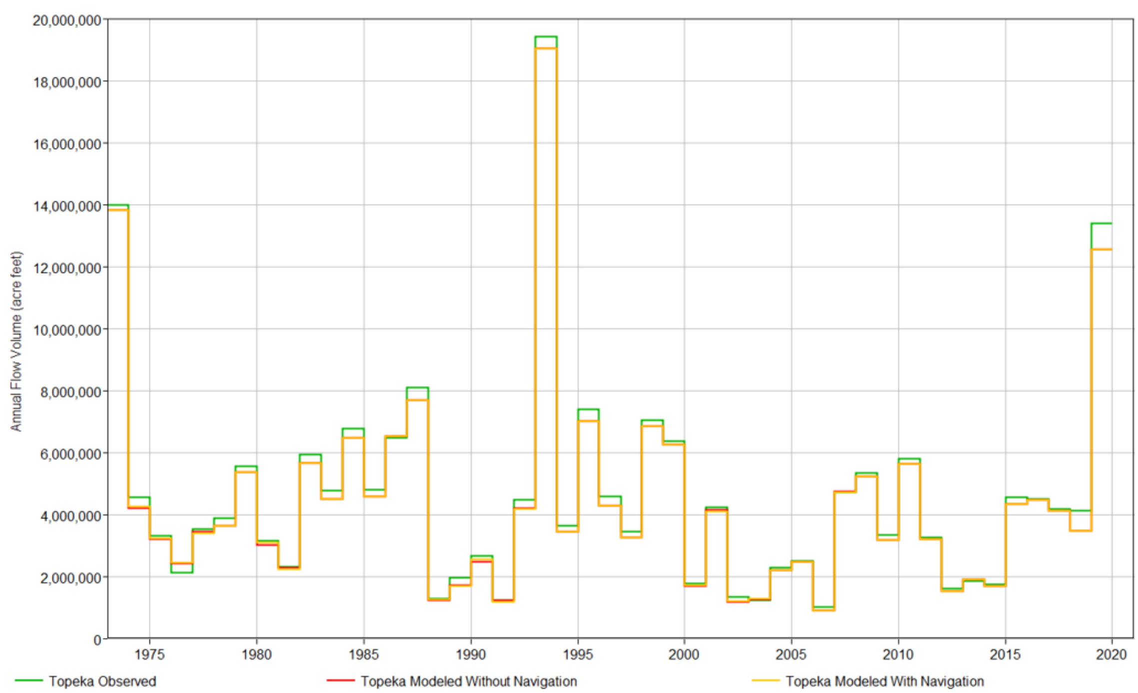


Figure 4-28. Topeka Observed and Modeled Annual Flow Volume for 1973 through 2019.

The Perry Reservoir pool elevation duration plot from 01April1971 (approximate time of first fill) to 01Jan2020 is shown in Figure 4-29. Comparison of the observed and modeled duration indicate that the model tends to be in the flood control pool for longer amounts of time. Seasonal water level management plans will allow the lake below the multi-purpose pool during the winter and 2 to 2.5 feet above the multi-purpose pool during the spring and fall which may be part of the reason for the observed differing from the modeled. The water level management plan was not put into the model since it is discretional and may not be followed depending on the basin conditions. The navigation scenario results in more common pool elevations below multi-purpose pool. Additional model analysis was conducted to see how much of an impact was made by the water level management plans. This analysis is shown in section 2.1 of "Attachment 1 Supporting Plots". Like Milford and Tuttle Creek, the significant rise in the less frequent portions of the duration curve is probably due to the model constraining releases due to downstream control points especially on the Missouri River. Some of the potential reasons for these differences are discussed at the start of section 4.

Navigation flow support impacts to pool elevation and outflow for selected periods of time are shown in Figure 4-30 to Figure 4-33. These are drought years so pools are already low from reduced inflow and water quality support. Navigation support results in lower pool elevations. When large inflows occur, the without navigation scenario will make larger releases if the multi-purpose pool fills. Larger encroachments into the flood control pool were very similar for both scenarios.

Figure 4-34 shows the observed and modeled annual flow volume from 1967 (when outflow data started) to the 2019. The observed volumes match modeled closely except during high flow years. Navigation flow support only results in small differences a few years. Small differences between observed and modeled are probably due to estimated modeled evaporation. The large difference in 2019 is due to modeled storage being carried over into 2020. In the observed data set, water was emptied from flood storage before the end of 2019 by using a deviation for higher flow targets on the Missouri River, benefitting flood control operations at Milford, Tuttle Creek and Perry, as well as Clinton.

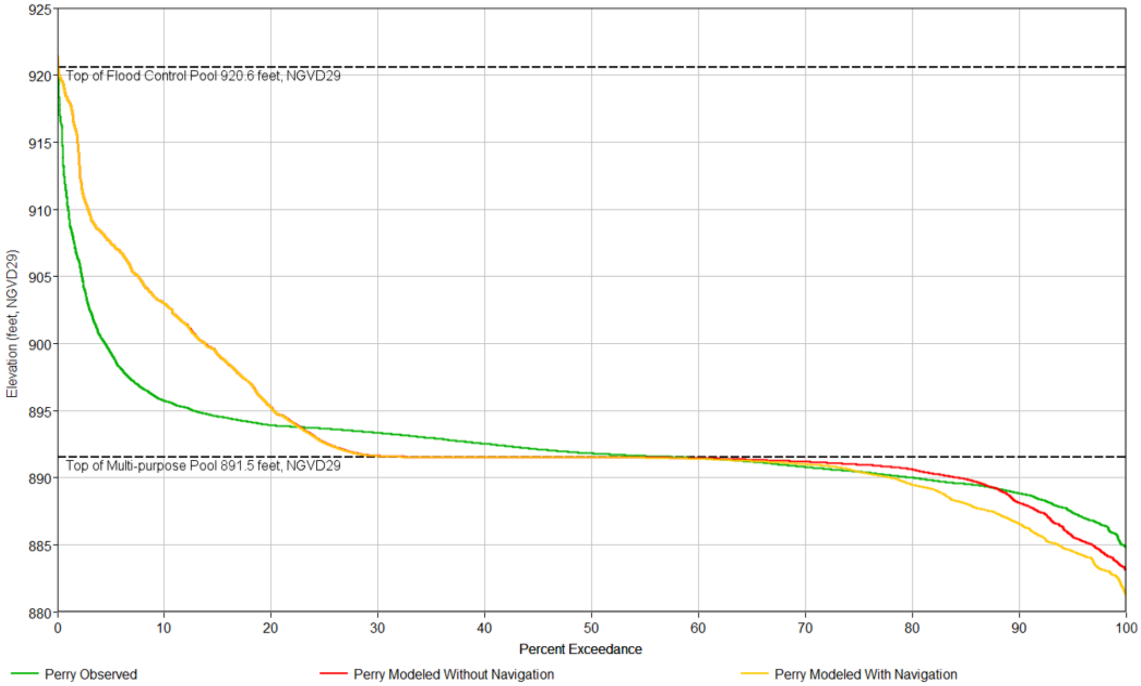


Figure 4-29. Perry observed and modeled pool elevation duration from 01Jun1970 to 01Jan2020.

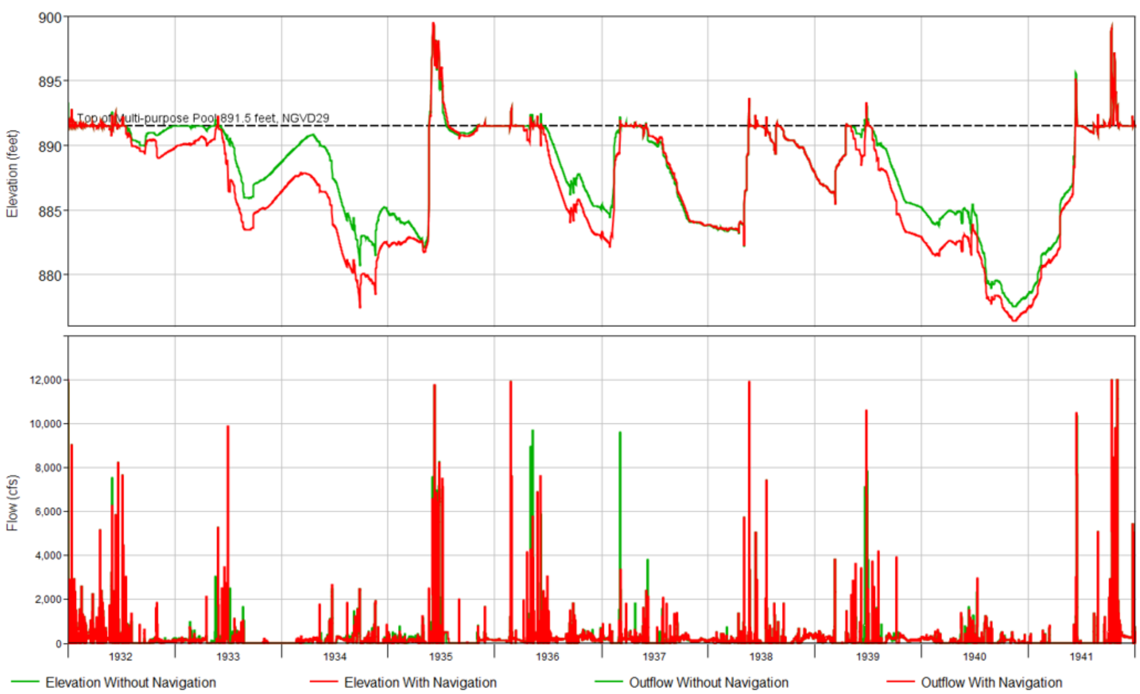


Figure 4-30. Perry pool elevation modeled with and without navigation flow support for the years 1932 through 1941.

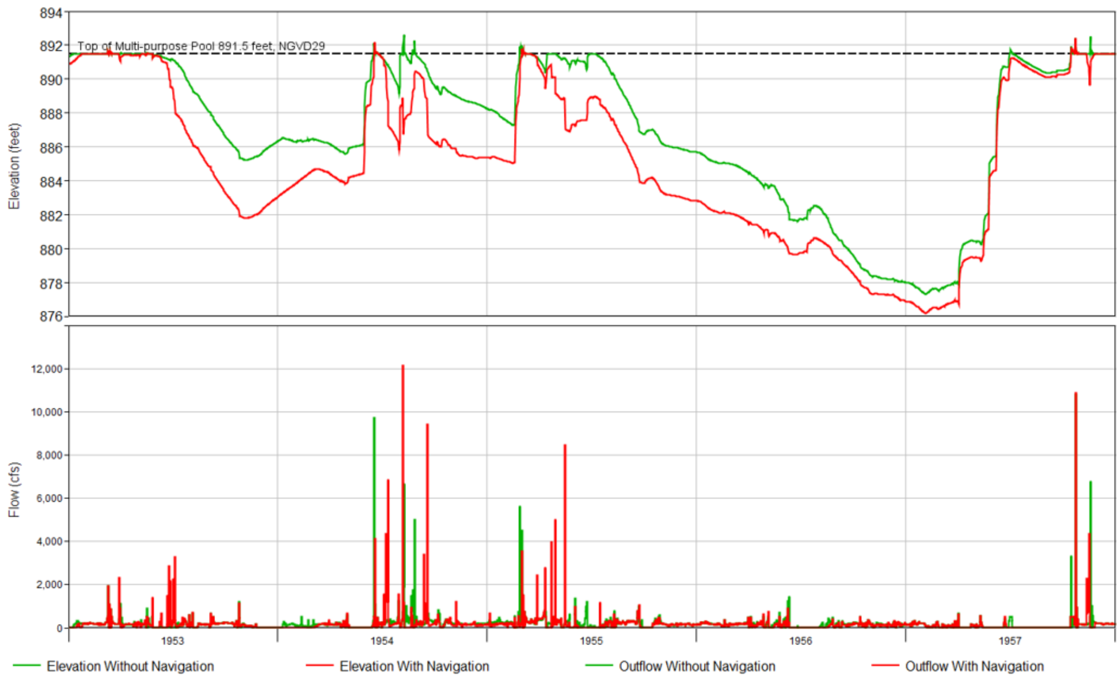


Figure 4-31. Perry pool elevation modeled with and without navigation flow support for the years 1955 through 1958

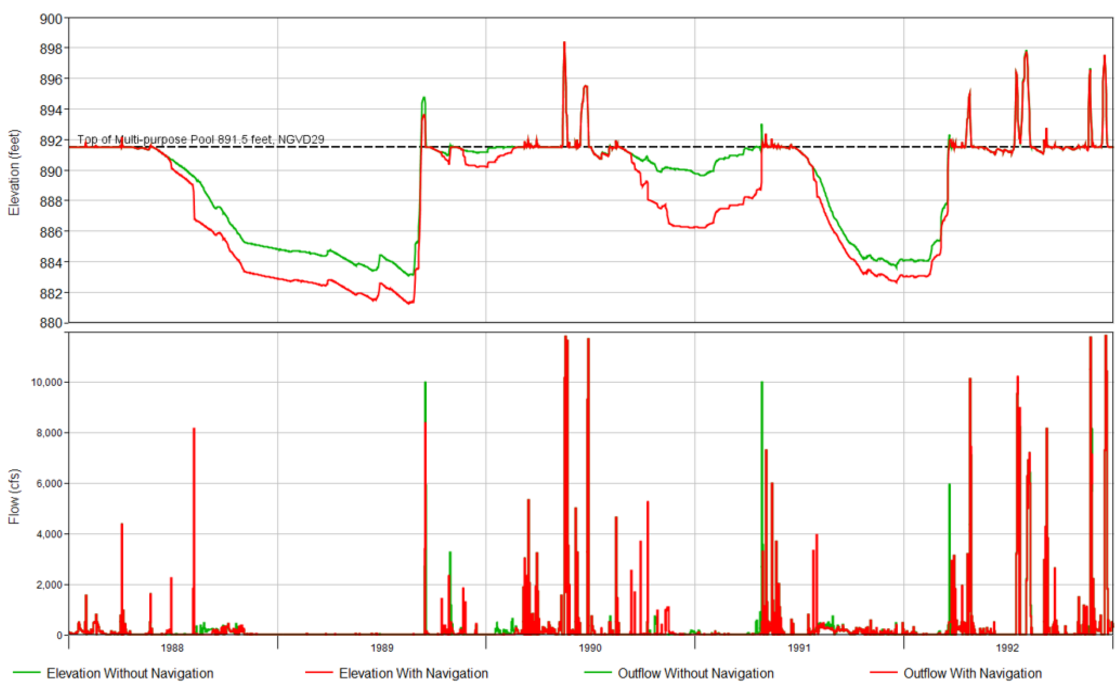


Figure 4-32. Perry pool elevation modeled with and without navigation flow support for the years 1989 through 1991

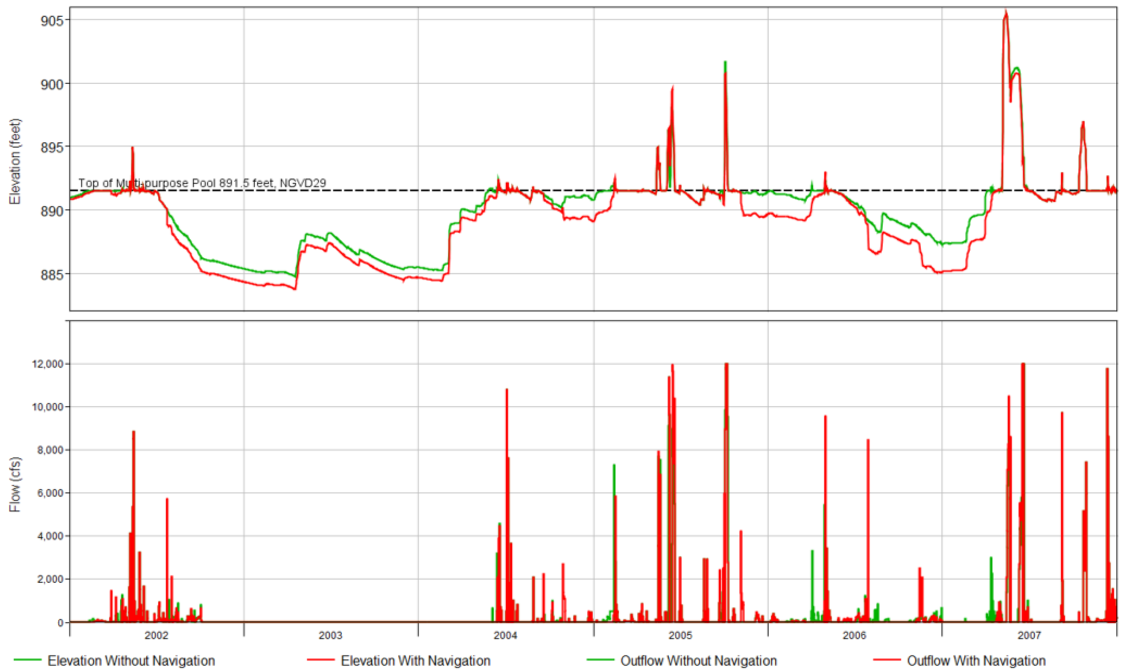


Figure 4-33. Perry pool elevation modeled with and without navigation flow support for the years 2002 through 2007

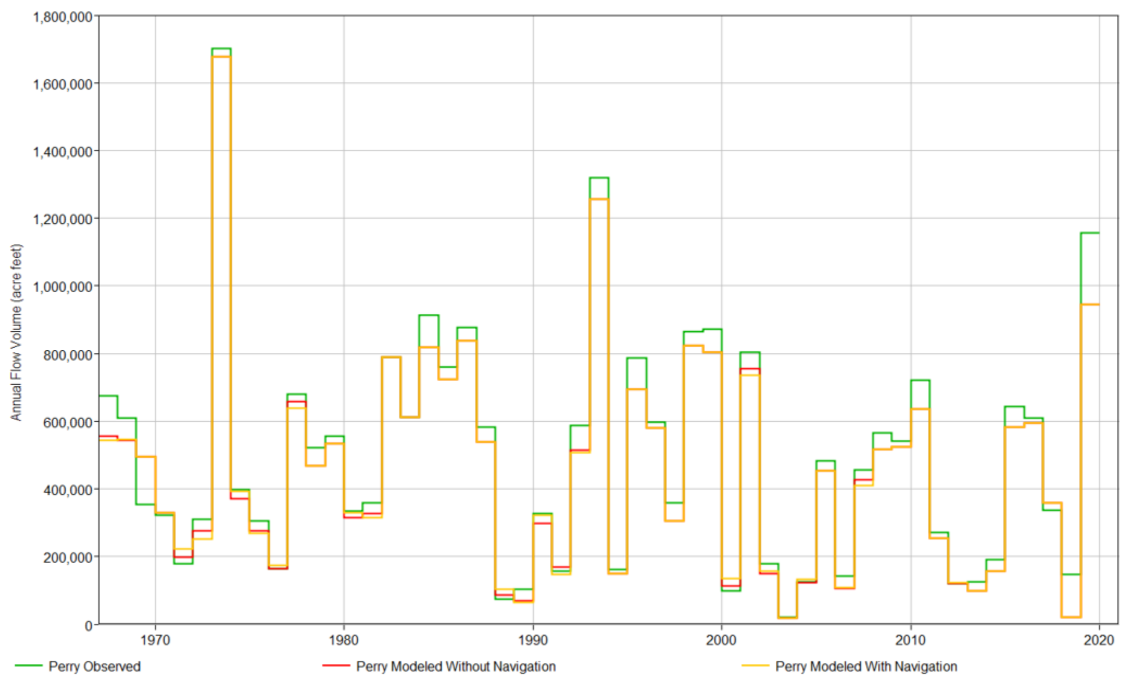


Figure 4-34. Perry Observed and Modeled Annual Flow Volume for 1967 through 2019

Downstream of Perry the Kansas River at Lecompton (impacted by regulation from all three Smoky Hill reservoirs and Milford, Tuttle Creek, and Perry reservoirs) annual flow volumes are compared in Figure 4-35. This plot starts in 1973 which is about when the impacts of the regulation of all reservoirs began at these gages allowing a comparison of regulated observed and modeled. The observed volume continues to be slightly higher than modeled at these gages especially during the larger flow years.

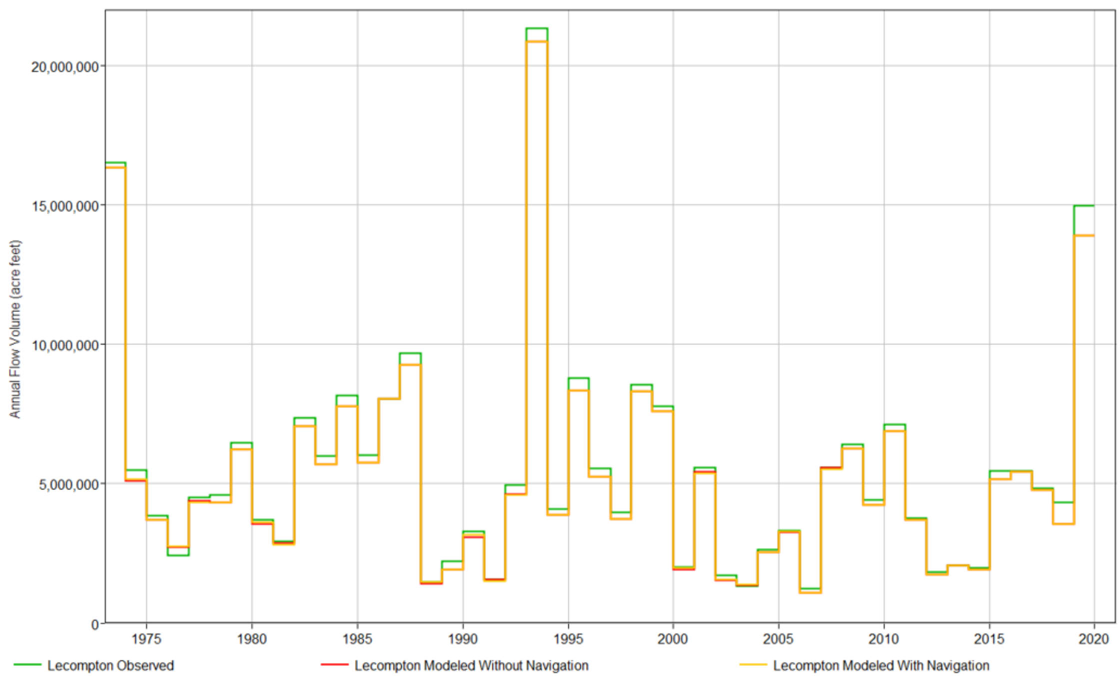


Figure 4-35. Lecompton Observed and Modeled Annual Flow Volume for 1973 through 2019

The Clinton Reservoir pool elevation duration plot from 01April1980 (approximate time of first fill) to 01Jan2020 is shown in Figure 4-36. Both model scenarios result in the same pool duration since navigation flow is not supported from Clinton. Comparison of the observed and modeled duration indicate that the model tends to be in the flood control pool for longer amounts of time. Seasonal water level management plans will allow the lake below the multi-purpose pool during the winter and two feet above the multi-purpose pool during the spring and fall which may be part of the reason for the observed differing from the modeled. The water level management plan was not put into the model since it is discretional and may not be followed depending on the basin conditions. Like Milford, Tuttle Creek, and Perry, there is a rise in the less frequent portions of the duration curve which are probably due to the model constraining releases due to downstream control points especially on the Missouri River. Some of the potential reasons for these differences are discussed at the start of section 4. These impacts do not appear to be as large as the other lakes. Figure 4-37 shows the observed and modeled annual flow volume from 1978 (when outflow data started) to the 2019. The modeled scenarios with and without navigation are identical. The observed volumes tend to be higher than modeled. Small differences are probably due to estimated modeled evaporation. The large difference in 2019 is due to modeled storage being carried over into 2020. In the observed data set, water was emptied from flood storage before the end of 2019 by using a deviation for higher flow targets on the Missouri River, benefitting flood control operations at Milford, Tuttle Creek and Perry, as well as Clinton.

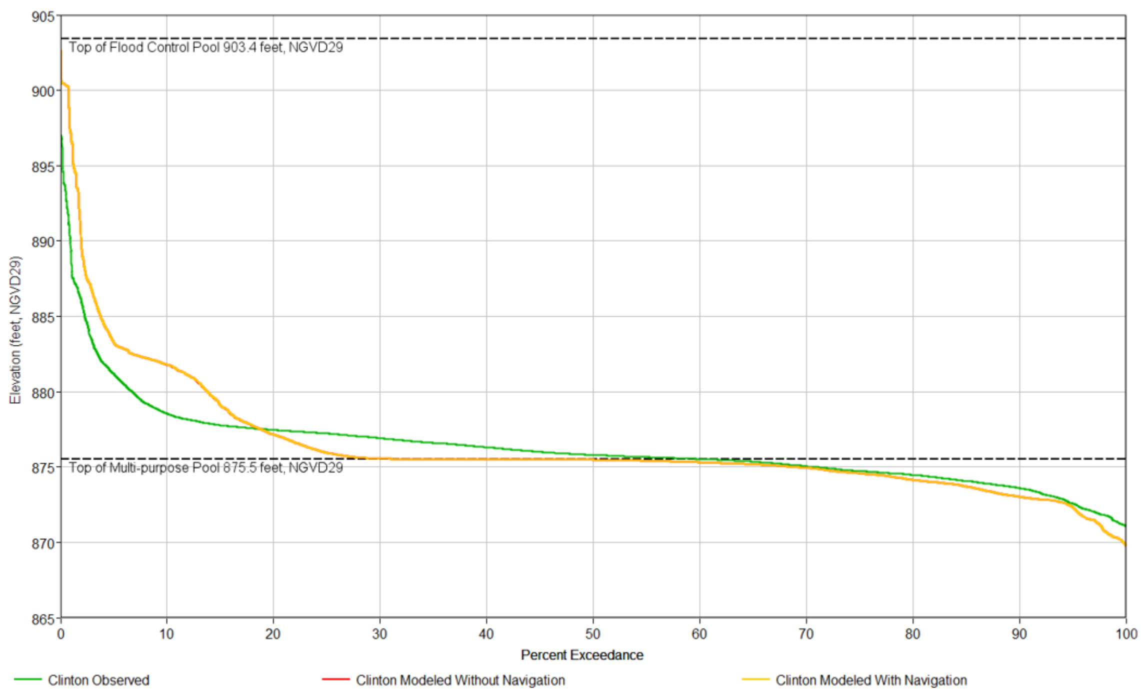


Figure 4-36. Clinton observed and modeled pool elevation duration from 01Apr1980 to 01Jan2020

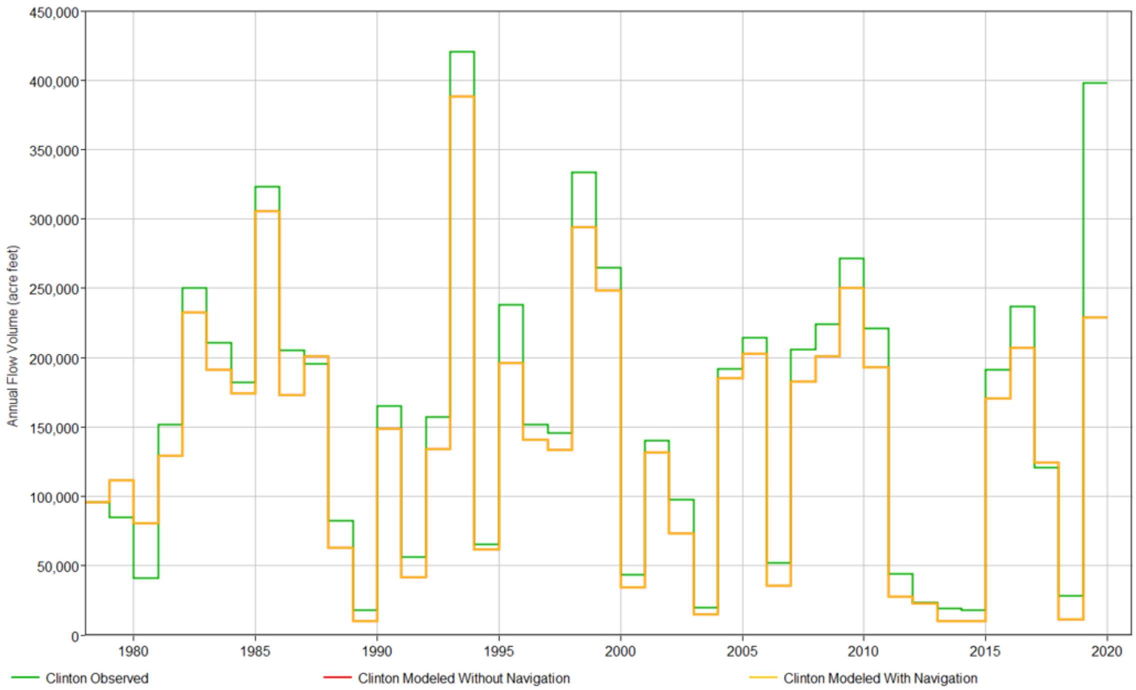


Figure 4-37. Clinton Observed and Modeled Annual Flow Volume for 1978 through 2019

Downstream of Clinton the Wakarusa River at Lawrence (impacted by regulation from Clinton), Kansas River at Desoto (impacted by regulation from all the Kansas Basin Reservoirs) and the Missouri River at Kansas City and Waverly (impacted by regulation from all the Upper Missouri River and Kansas River reservoirs) annual flow volumes are compared in Figure 4-38, Figure 4-39, Figure 4-44, and Figure 4-45. These plots start in 1980 which is about when the impacts of the regulation of all reservoirs began at these gages allowing a comparison of regulated observed and modeled. Navigation flow support has very little impact to the annual flow volumes as most of the releases are for a short duration. The observed volume continues to be higher than modeled at the Lawrence gage, consistent with the actual passage of flood water in 2019. Desoto modeled is very similar to observed except during the flood years. 2019 observed volume is higher due to modeled flood storage being carried over to 2020 and follows the trend witnessed at Lawrence, potentially diminished somewhat by the much larger flows in the Kansas and Missouri River gages. The Missouri River gages observed flow volume tend to be slightly lower than modeled and do not share the trends observed on the Kansas River. This is probably due to the modeled mainstem Missouri River regulated flows and local inflows overwhelming contributions from the Kansas River.

The effect on the Kansas River at Desoto flow of reservoir releases for navigation flow support is shown in Figure 4-40 to Figure 4-43. Navigation support was provided up to 4000 cfs and the releases are generally made late in the year when the Missouri River dropped. Annual peak flows are generally the same with and without navigation, but some of the dryer years released larger peak flows in the without navigation scenario.

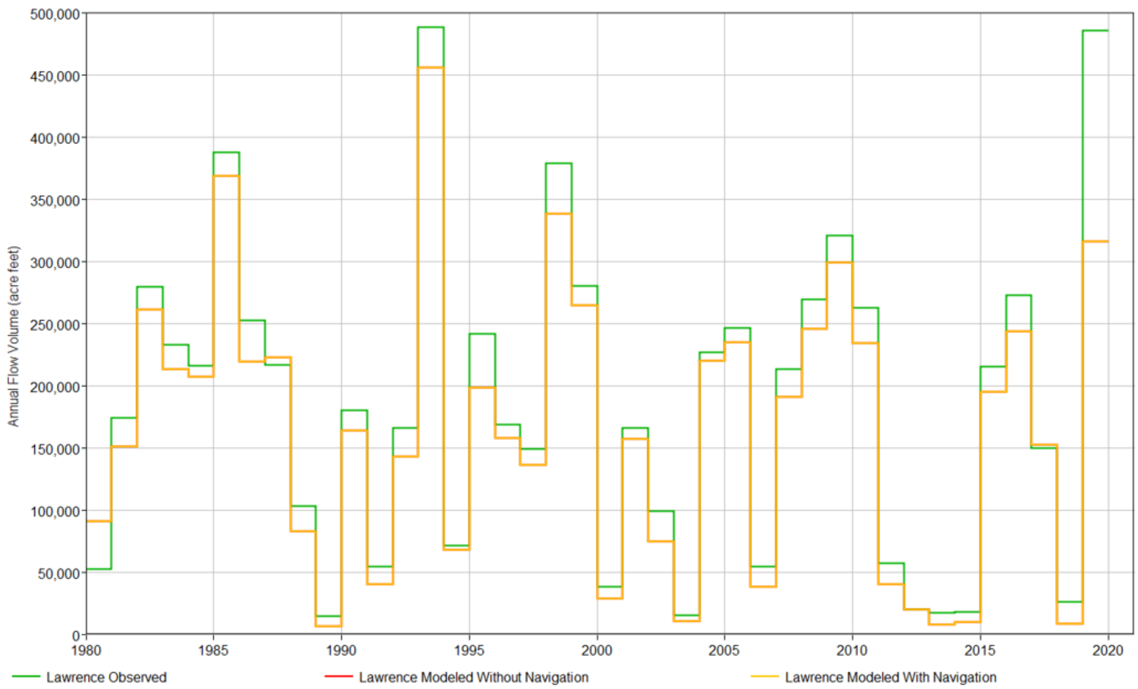


Figure 4-39. Lawrence Observed and Modeled Annual Flow Volume for 1980 through 2019

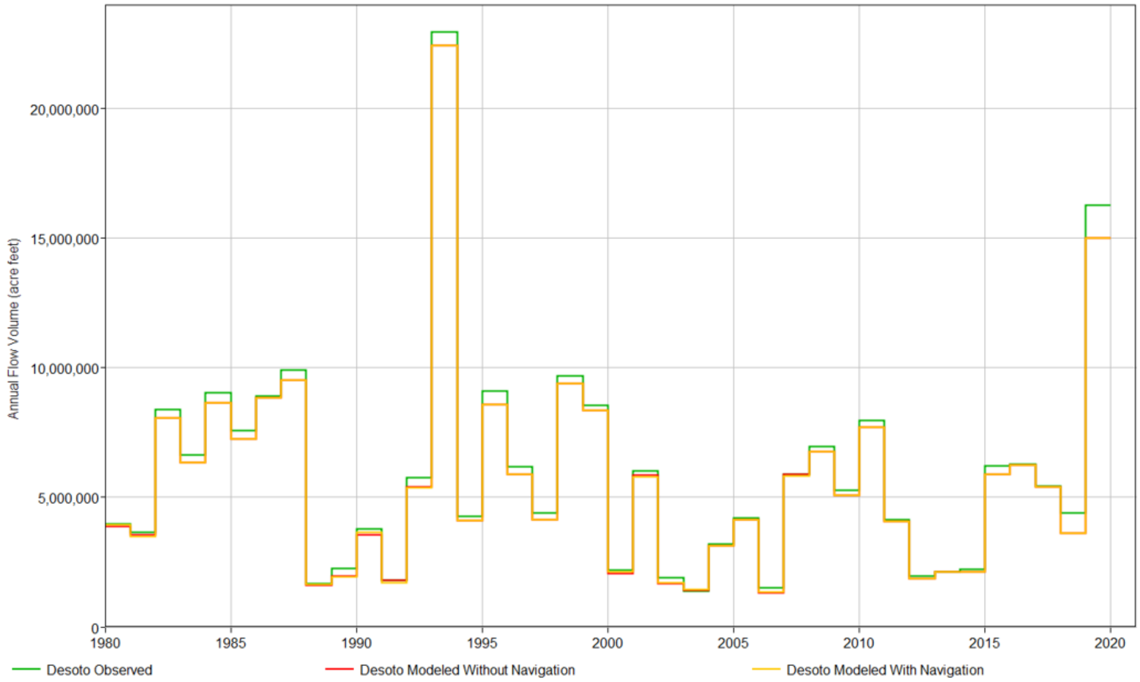


Figure 4-39. Desoto Observed and Modeled Annual Flow Volume for 1980 through 2019

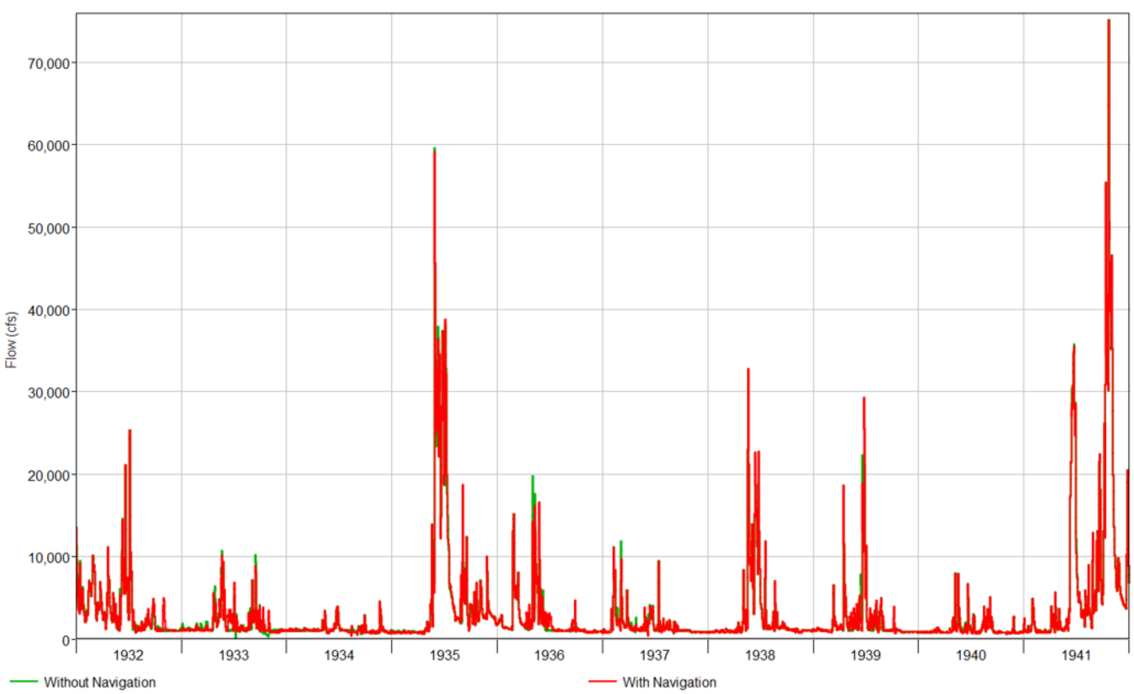


Figure 4-40. Desoto flow modeled with and without navigation flow support for the years 1932 through 1941

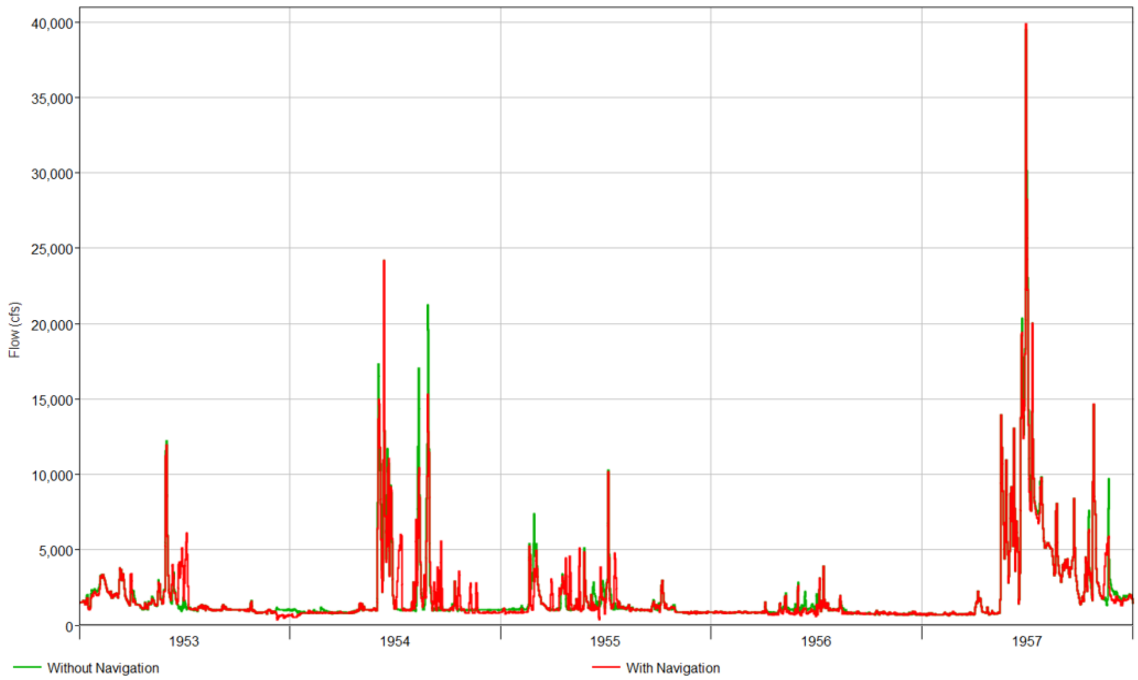


Figure 4-41. Desoto flow modeled with and without navigation flow support for the years 1955 through 1958

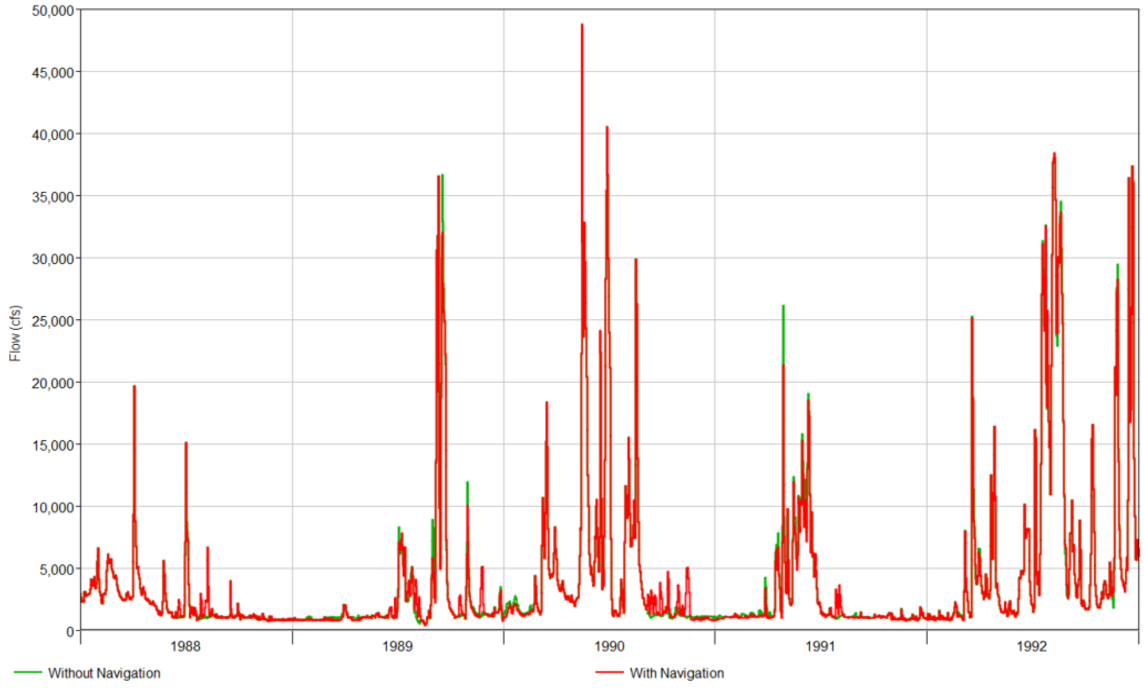


Figure 4-42. Desoto flow modeled with and without navigation flow support for the years 1989 through 1991.

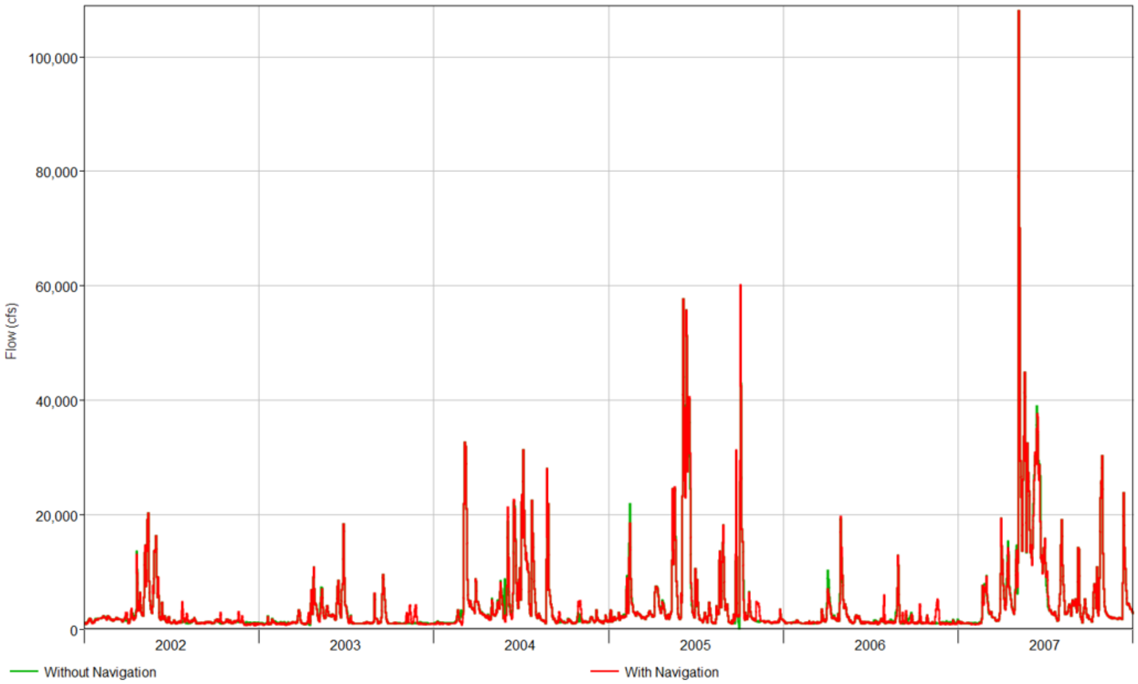


Figure 4-43. Desoto flow modeled with and without navigation flow support for the years 2002 through 2006

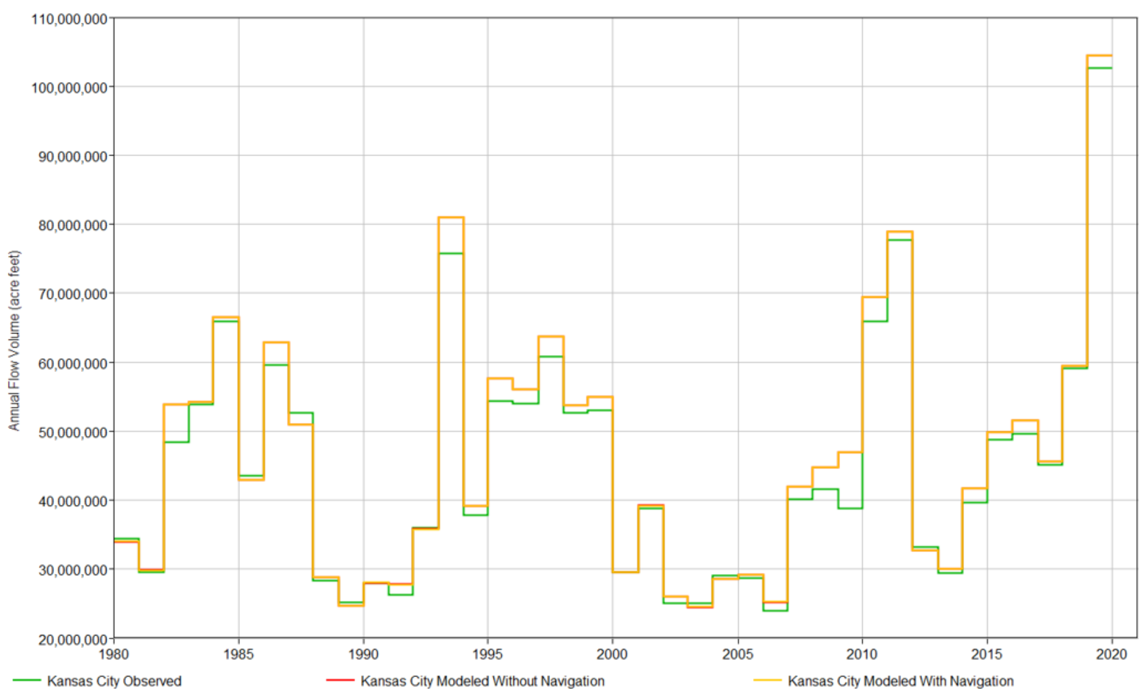


Figure 4-44. Kansas City Observed and Modeled Annual Flow Volume for 1980 through 2019

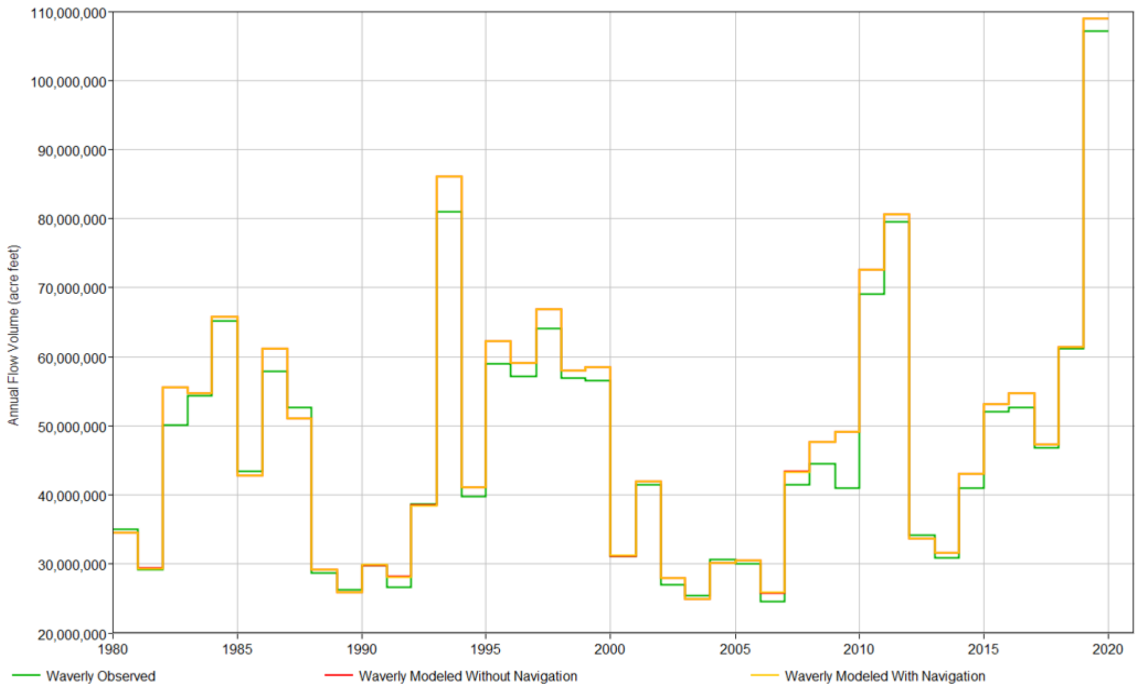


Figure 4-45. Waverly Observed and Modeled Annual Flow Volume for 1980 through 2019

5. Conclusions

A full set of data was developed for the Kansas River HEC-ResSim model. Data was extended using observed gage data and regression between gages as necessary. When no other methods were available data was extended using watershed ratios. Local flow data sets were developed by routing observed/extended flows from the upstream gages and using a spreadsheet process to smooth negative flows all the while conserving flow volume totals. Some uncertainties exist in the extended gage data, but the data set appears to be a reasonable estimate.

The Lower Kansas River CWMS model was utilized as a start for the KRRFSS HEC-ResSim model. Several adjustments were made to this model, as necessary, including routing methods, input data sets, and reservoir rules.

The reservoir elevation duration curves indicated that the modeled regulation adequately models the actual conditions. Milford, Perry, Tuttle Creek and Clinton model results accumulate water in the flood control pool for longer durations than in the actual data set. Some of these differences may be due to seasonal water level management plans. Some years actual operations have been impacted by formal deviations that allowed higher flow targets on the Missouri River permitting the pool elevations to be maintained at lower levels.

Navigation flow support model scenarios estimate the impact of navigation flows on the reservoirs and downstream gages. Navigation flow support can result in significant reductions in pool elevations, but there is minimal change in the peak flows even for years when navigation releases were made.

Observed and modeled annual flow volumes were compared for all the reservoir outflows and the key gages in the basin. The observed flow volumes tended to be a little higher than modeled. Reservoir evaporation estimates in the model and present incremental depletions are the primary reasons for lower annual flow volume. Also, the modeled 2019 flow volume had flood storage carried over into the following year when actual was able to empty the flood storage because of a deviation. Annual peak flows were less impacted than the flow volume comparison.

The KRRFSS HEC-ResSim model results in a reasonable assumption of basin regulated flows for 1920 to 2019. The existing condition model can be used for ongoing study analysis of future without project and proposed alternative reservoir regulation and flows.

Attachment 1
KRRFSS Water Management Documentation—Supporting Plots

1. Unregulated Reservoir Inflow Analysis

1.1 Background

Calculations are conducted annually to determine unregulated flow if the dams were not in place. From the difference between the observed (regulated) flow and the calculated unregulated flow flood damages prevented in dollars are computed. The unregulated flow is also referred to as natural flow. Although the calculations are made annually, the historical record of natural flows was only calculated for peak annual events. This project undertook calculating the natural flow in the Kansas City District (NWK) from the inception of the reservoir through 2019 using a daily time step.

Stage and flow on the Kansas River are impacted by seven reservoirs owned by the US Army Corps of Engineers (USACE) and eleven flood control reservoirs owned by the U.S. Bureau of Reclamation (USBR). These USBR reservoirs are operated by USACE when they are in flood control operations.

Stage and flow at the Missouri River at Kansas City, MO are impacted by all the Omaha District (NWO) reservoirs including the mainstem Missouri River reservoirs which are operated by the Missouri River Basin Water Management (MRBWM) office. MRBWM calculates unregulated flow for the Missouri River at Saint Joseph, MO which accounts for the impact of all the reservoirs in NWO. The Saint Joseph unregulated flow is then routed to Kansas City for use in the NWK unregulated flow calculations.

This study is interested in unregulated flows in NWK upstream of the Missouri River at Waverly, MO. In addition to the NWO and Kansas River reservoirs, Smithville Reservoir impacts flows at Kansas City and Waverly, and Longview and Blue Springs Reservoirs impact the flow at Waverly. Table 1.1-1 shows all the NWK reservoirs that impact flow at the Missouri River at Waverly.

Table 1.1-1. Kansas City District Reservoirs that impact flow at the Missouri River at Waverly and above.

Reservoir	Ownership	Downstream Reservoir
Bonny	USBR	Trenton
Trenton (Swanson Lake)	USBR	Harlan County
Enders	USBR	Harlan County
Red Willow (Hugh Butler Lake)	USBR	Harlan County
Medicine Creek (Harry Strunk Lake)	USBR	Harlan County
Norton (Keith Sebelius Lake)	USBR	Harlan County
Harlan County	USACE	Milford
Lovewell	USBR	Milford
Milford	USACE	
Cedar Bluff	USBR	Kanopolis
Kanopolis	USACE	
Wilson	USACE	
Kirwin	USBR	Glen Elder
Webster	USBR	Glen Elder
Glen Elder Dam (Waconda Lake)	USBR	
Tuttle Creek	USACE	
Perry	USACE	
Clinton	USACE	
Smithville	USACE	
Longview	USACE	
Blue Springs	USACE	

1.2 Data Preparation

Period of record daily reservoir inflow and outflow was obtained from the USACE database for all the Corps-owned reservoirs. Daily inflow and outflow for all the USBR projects are available in the USACE database from 1980 to the present. Five USBR projects (Cedar Bluff, Glen Elder, Kirwin, Lovewell, and Webster) used USACE data for the full period of record. The rest of the USBR projects had outflow records from USBR for prior to 1980. Inflows for these USBR projects were calculated using USBR storage and inflow data for prior to 1980. Calculated inflows resulted in some unreasonable data spikes that were screened out in the Unregulated_v6.dss file prior to use in calculating the unregulated flow.

Daily, period of record flow for the river gages were obtained from the U.S Geological Survey (USGS).

1.3 Natural Flow Calculation Process

Data calculations were made using the "Benefits_48to2020.xlsx" excel spreadsheet. Reservoir inflows and outflows were loaded into the spreadsheet. These were then used to calculate reservoir holdouts which measure how much water the reservoir stored or added to the river. The holdout is calculated by the following equation:

$$\text{Holdout} = (\text{Inflow} - 0.1 * \text{Evaporation}) - \text{Outflow}$$

Evaporation is the flow evaporation from the reservoir in cfs. A portion of the evaporation is removed from the inflow since it was used in the originally calculation of inflow. If the reservoir were not on the river, the evaporation would be lower from the river channel. If the reservoir is storing water, inflows are greater than the outflow and the holdout is positive. If the reservoir is evacuating storage, the outflow is greater than the inflow and the holdout is negative.

During a typical rain event, the holdouts will be positive while rainfall runoff is occurring. This will also result in the regulated flow at the downstream gages being much lower than in the unregulated situation. After the rainfall runoff subsides, reservoir releases often begin to draw the lake back down at which time the holdouts become negative. This will result in the unregulated flow being higher than the regulated in the downstream gages. This typical reservoir operation results in removing the really large unregulated flows with the tradeoff (and sometimes the benefit) of higher flows after an event.

The calculated holdouts at the Missouri River at Saint Joseph were calculated by the MRBWM office and loaded into the USACE database. This data set was also loaded into the spreadsheet.

All the holdouts are then routed to the downstream gages using coefficient routing parameters. A separate worksheet is set up to show calculations for each gage. Routing coefficient parameters are shown in Table 1.3-1. In each worksheet the reservoir holdouts are routed to the gage. The observed flow is then added to the routed holdouts to determine the unregulated flow. There are also calculations to determine the percent of flow reduction provided by each reservoir.

This approach is based simply on observed flow and routed holdouts. Water depletions in the basin are not part of the calculation; although, any depletions that impacted the observed flow will intrinsically be accounted. During times of low flow and large irrigation use, the calculated unregulated flows can become negative because of the uncertainty associated with the depletions and routing parameters. There is also some uncertainty with the observed flow even though the approved USGS flow was used.

Table 1.3-1. Routing parameters used to calculate unregulated follows

From	To	Day 0	Day 1	Day 2	Day 3	Day 4
Bonny Reservoir	Republican River at Stratton, NE	0.0	0.3	0.7		
Republican River at Stratton, NE	Swanson Reservoir	1.0				
Enders Reservoir	Frenchman Creek at Palisade, NE	0.0	0.6	0.4		
Frenchman Creek at Palisade, NE	Republican River at Cambridge, NE	0.0	0.1	0.5	0.4	
Swanson Reservoir	Republican River at Cambridge, NE	0.0	0.1	0.5	0.4	
Hugh Butler Reservoir	Republican River at Cambridge, NE	0.0	0.4	0.6		
Harry Strunk Reservoir	Republican River at Cambridge, NE	0.4	0.6			
Republican River at Cambridge, NE	Republican River at Orleans, NE	0.0	0.3	0.6	0.1	
Keith Sebelius Reservoir	Prairie Dog Creek near Woodruff, KS	0.0	0.6	0.4		
Republican River at Orleans, NE	Harlan County Reservoir	1.0				
Prairie Dog Creek near Woodruff, KS	Harlan County Reservoir	1.0				
Harlan County Reservoir	Republican River at Concordia, KS				0.5	0.5
Lovewell Reservoir	Republican River at Concordia, KS		0.4	0.6		
Republican River at Concordia, KS	Republican River at Clay Center, KS		0.4	0.6		
Republican River at Clay Center, KS	Milford Reservoir	1.0				
Cedar Bluff Reservoir	Smoky Hill River at Ellsworth, KS				0.3	0.7
Smoky Hill River at Ellsworth, KS	Kanopolis Reservoir	1.0				
Kanopolis Reservoir	Smoky Hill River near Mentor, KS	0.0	0.4	0.6		
Wilson Reservoir	Saline River at Tescott, KS	0.1	0.2	0.3	0.4	
Saline River at Tescott, KS	Smoky Hill River at New Cambria, KS	0.2	0.3	0.5		
Smoky Hill River near Mentor, KS	Smoky Hill River at New Cambria, KS	0.4	0.6			
Kirwin Reservoir	Waconda Reservoir	0.5	0.5			
Webster Reservoir	Waconda Reservoir	0.5	0.5			
Waconda Reservoir	Solomon River at Niles, KS	0.2	0.7	0.1		
Smoky Hill River at New Cambria, KS	Smoky Hill River at Enterprise, KS	0.0	0.7	0.3		
Solomon River at Niles, KS	Smoky Hill River at Enterprise, KS	0.2	0.7	0.1		

From	To	Day 0	Day 1	Day 2	Day 3	Day 4
Smoky Hill River at Enterprise, KS	Kansas River at Fort Riley, KS	0.3	0.7			
Milford Reservoir	Kansas River at Fort Riley, KS	0.7	0.3			
Kansas River at Fort Riley, KS	Kansas River at Wamego, KS	0.4	0.6			
Tuttle Creek Reservoir	Kansas River at Wamego, KS	0.8	0.2			
Kansas River at Wamego, KS	Kansas River at Topeka, KS	0.4	0.6			
Kansas River at Topeka, KS	Kansas River at Lecompton, KS	0.8	0.2			
Perry Reservoir	Kansas River at Lecompton, KS	0.8	0.2			
Kansas River at Lecompton, KS	Kansas River at Desoto, KS	0.5	0.5			
Clinton Reservoir	Kansas River at Desoto, KS	0.5	0.5			
Smithville Reservoir	Little Platte River at Smithville, MO	1.0				
Little Platte River at Smithville, MO	Missouri River at Kansas City, MO	0.5	0.5			
Kansas River at Desoto, KS	Missouri River at Kansas City, MO	0.8	0.2			
Missouri River at Saint Joseph, MO	Missouri River at Kansas City, MO	0.1	0.8	0.1		
Blue Springs and Longview Reservoirs	Missouri River at Waverly, MO		1.0			
Missouri River at Kansas City, MO	Missouri River at Waverly, MO	0.1	0.8	0.1		

1.4 Reservoir Inflow Plots

Several historic flood events were evaluated at Kanopolis, Waconda, and Milford to compare regulated and unregulated flow for these reservoirs since they all have reservoir systems above them. Even though many of the upstream reservoirs are in traditionally arid portions of the basin, they can have a large impact on floods depending on where the rain falls. In addition to capturing a peak inflow, releases are often small as much of the inflow goes into filling the often-depleted multi-purpose pool and eventually to supplying irrigation flows that do not reach downstream.

Figure 1.4-1, Figure 1.4-2, and Figure 1.4-3 show Kanopolis inflow plots for 1951, 1993, and 2019, respectively. Cedar Bluff provided a significant amount of flow reduction in 1951. It was newly constructed at the time and filled for the first time. They did reach flood pool and began making releases later in the event as shown by the observed flow being higher than the natural flow from mid-July through September. In 1993, Cedar Bluff stored all its inflow in its conservation pool and did not release throughout the event. The 2019 event had almost all the rainfall downstream of Cedar Bluff. Cedar Bluff did not release for the entire year.

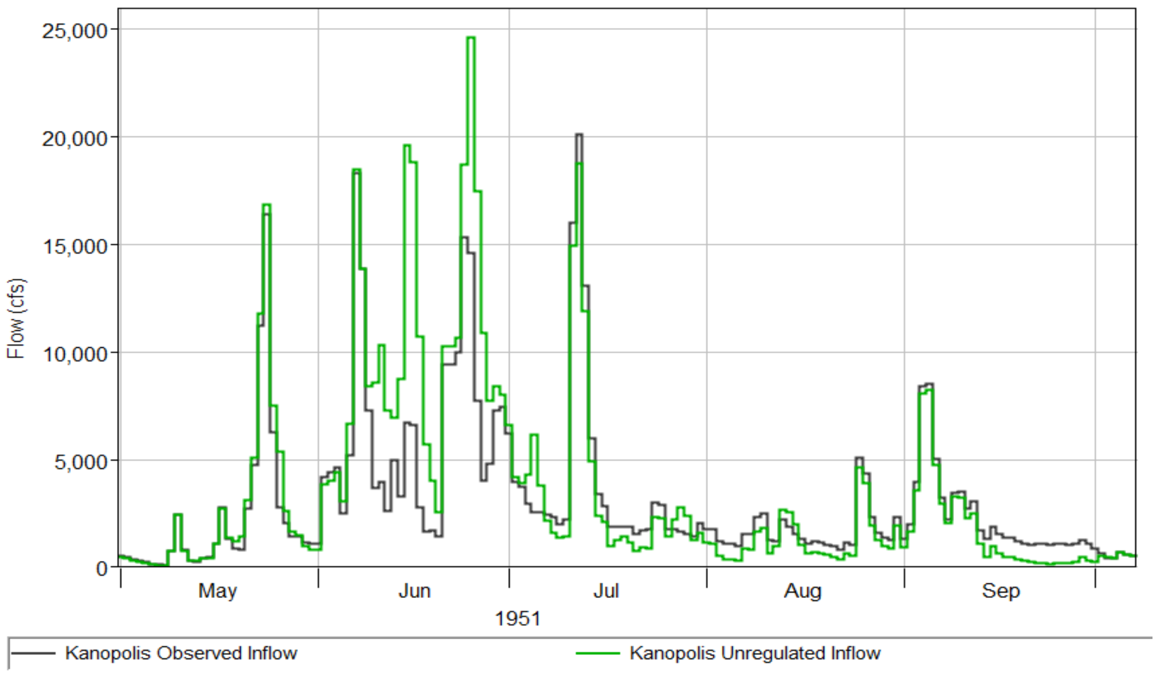


Figure 1.4-1. Kanopolis Reservoir observed and unregulated inflow for the 1951 flood event

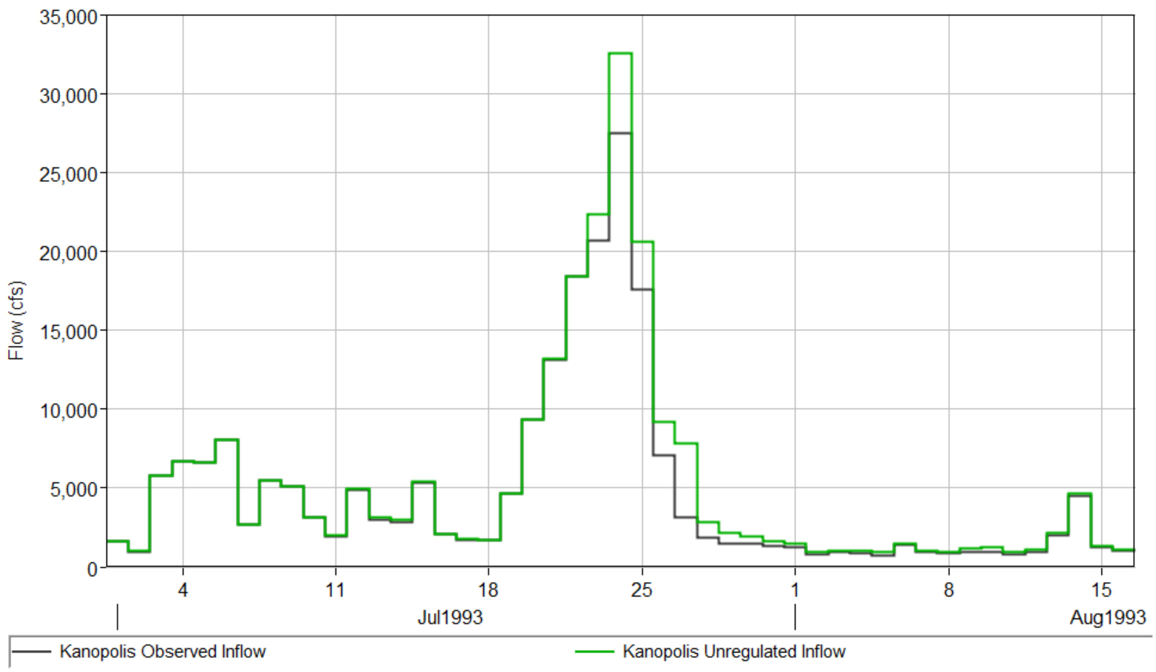


Figure 1.4-2. Kanopolis Reservoir observed and unregulated inflow for the 1993 flood event.

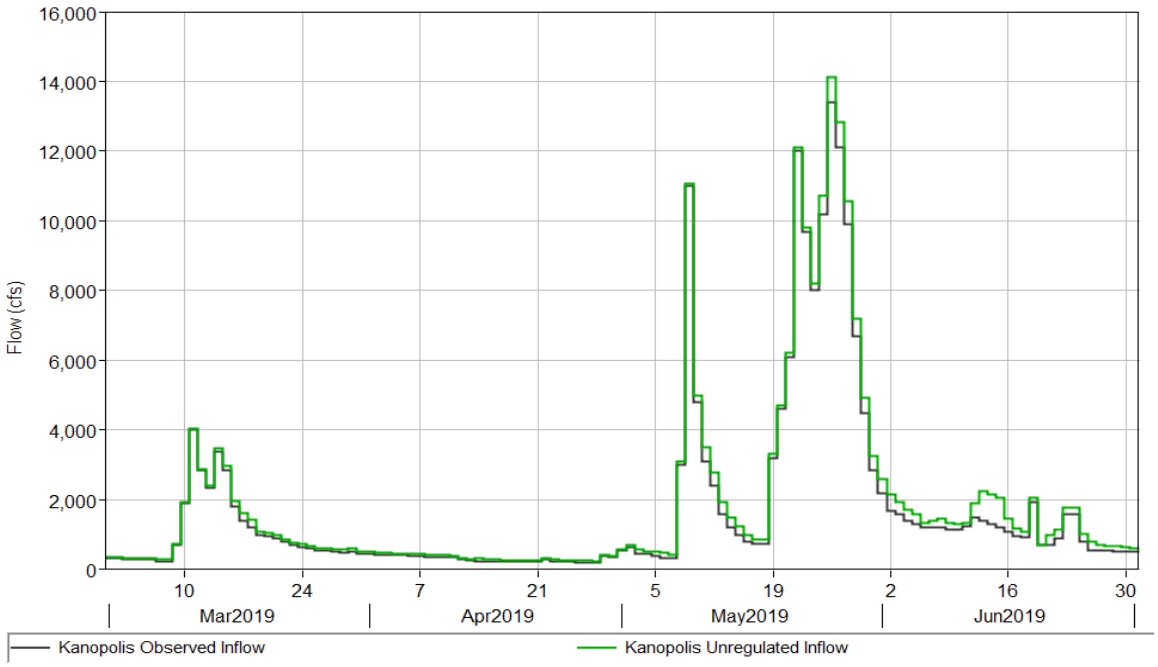


Figure 1.4-3. Kanopolis Reservoir observed and unregulated inflow for the 2019 flood event

Waconda data collection began in 1967, and unregulated data was also calculated from that time forward. Figure 1.4-4 and Figure 1.4-5 show Waconda inflow plots for 1993 and 2019, respectively. In 1993, the upstream projects both made some releases during this event and entered the flood pool in mid to late summer; however, they were able to provide significant reduction in flow for Waconda. In 2019, Kirwin and Webster both began the event with full multi-purpose pools. All flood storage was passed to Waconda, but peak inflow into Wacanda was reduced during the inflow events because of the time the water was routing through the reservoir. The 2019 inflow was smaller magnitude than many historic events, but the wet period lasted for a long time leading to significant volume passing through the reservoir system.

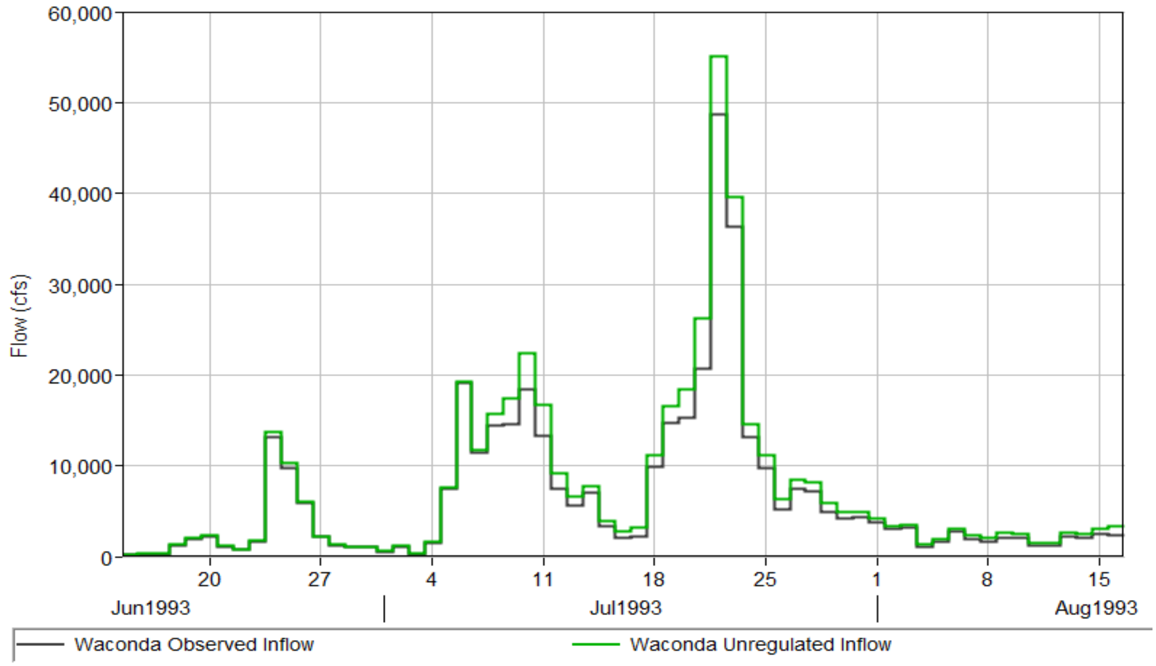


Figure 1.4-4. **Waconda Reservoir observed and unregulated inflow for the 1993 flood event**

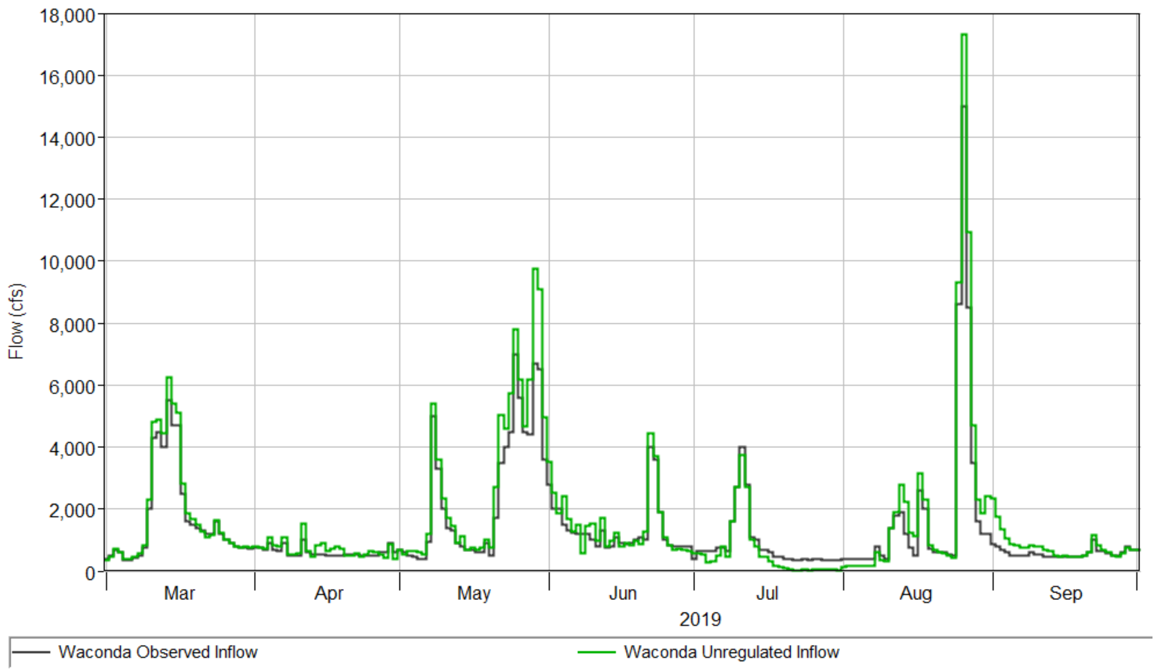


Figure 1.4-5. **Waconda Reservoir observed and unregulated inflow for the 2019 flood event**

Milford data collection began in 1964, and unregulated data was also calculated from that time forward. Figure 1.4-6 and Figure 1.4-7 show Milford inflow plots for 1993 and 2019, respectively. In 1993, Lovewell made some large releases of over 4500 cfs in July. Harlan County made minimal releases until late summer. Milford received a lot of local runoff as well. In 2019, Harlan County and Lovewell only made small releases until late July. Some significant reduction of inflow was observed depending on the rainfall location. The reservoirs above Harlan County also provided holdouts that were routed downstream. In general, those reservoirs were ready to store if they got inflow.

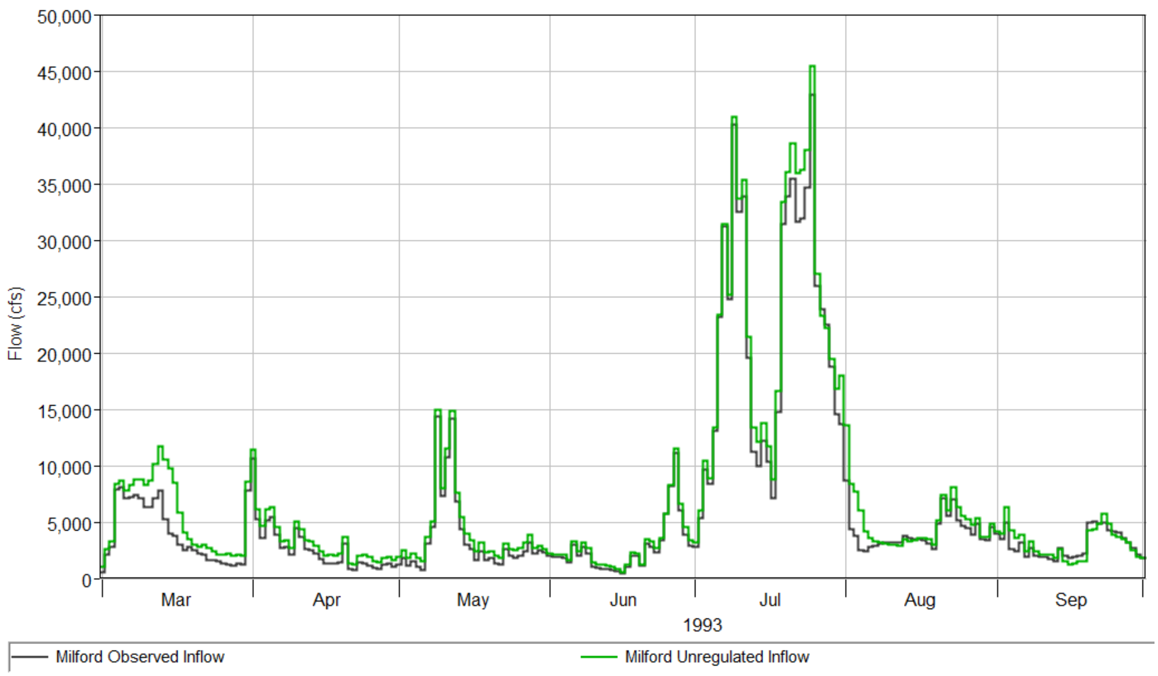


Figure 1.4-6. Milford Reservoir observed and unregulated inflow for the 1993 flood event

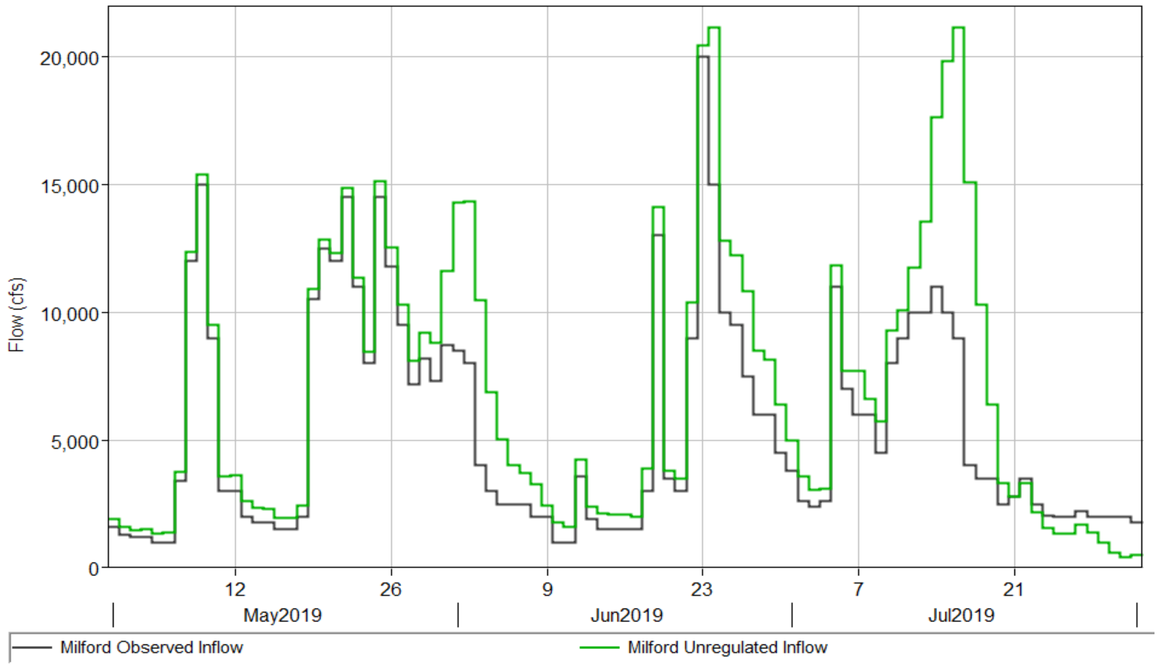


Figure 1.4-7. Milford Reservoir observed and unregulated inflow for the 2019 flood event.

2. Model Results Analysis

2.1 Impact of Water Level Management Plans

To better understand the model results and pool duration analysis that was shown in section 4 of the KRRFSS ResSim Documentation, an additional model simulation was conducted with the typical water level management plan (WLMP) pool elevations used as the guide curve instead of using the top of the multi-purpose pool. This defines how much discrepancy between modeled and observed pool duration can be attributed to the water level management plan. This analysis was conducted before depletions were added into the model; however, it provides insights into the impacts of the water level management plans. Water level management plans are updated annually, so using one plan for the period of analysis in not fully accurate, but the plans do not always have large changes from year to year, so it does give an idea of the impact.

All the model simulations result in different reservoir releases especially centered around the Missouri River downstream control points. The model adheres more strictly to the 90,000 cfs limit at Waverly as opposed to real-time operations that has increased uncertainty about future rainfall conditions.

The Milford water level management plan has changed in recent years to target low pool elevations with the hope of mitigating harmful algal blooms. When the WLMP was included, it resulted in pool elevation durations that were lower than the observed for the more frequent pool elevations. The WLMP only had small impacts for the less frequent events that are more a function of how the model handles releases and the Missouri River at Waverly downstream control point. The Milford pool elevation duration plot is shown in Figure 2-1.

There were many flood control events that stayed above the observed. This would lead to the higher pool elevation duration in the flood control zone. Examples of this are shown in Figure 2-2 and Figure 2-4. Figure 2-3 and Figure 2-5 show the observed versus the modeled Milford outflow for these same flood years. These plots confirm that the model releases nearly the same amount as the observed data; however, the timing is different. Some small differences in the volume can be attributed to differences evaporation.

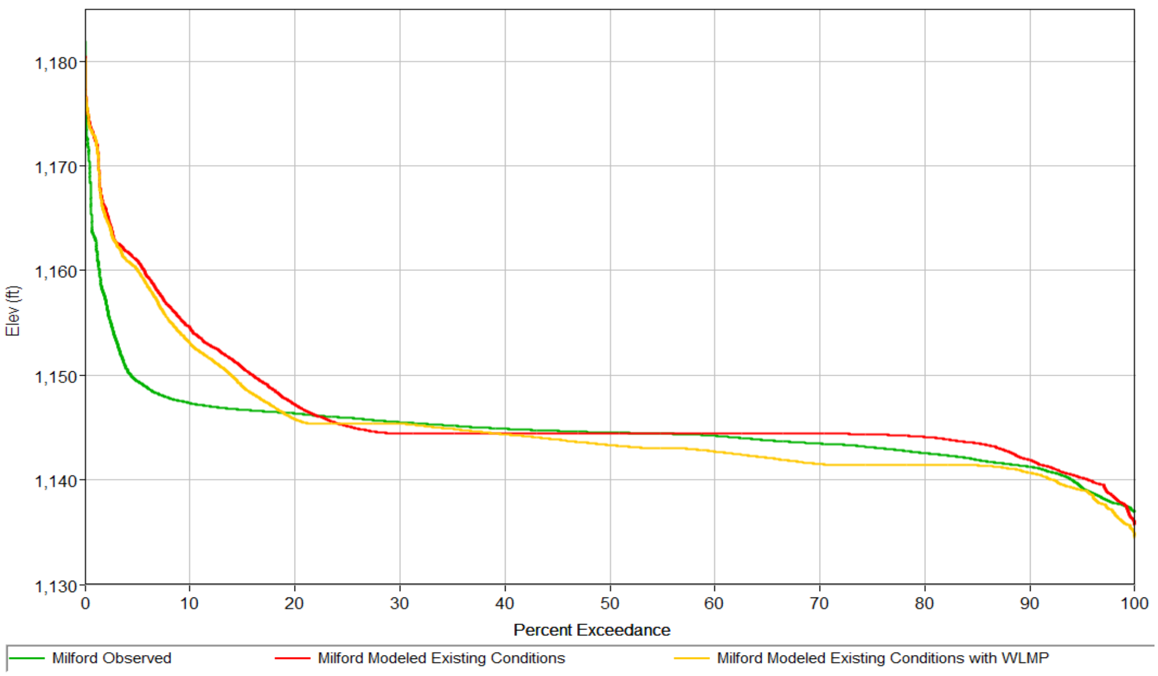


Figure 2-1. Milford observed and modeled pool elevation duration from 01Aug1967 to 01Jan2020.

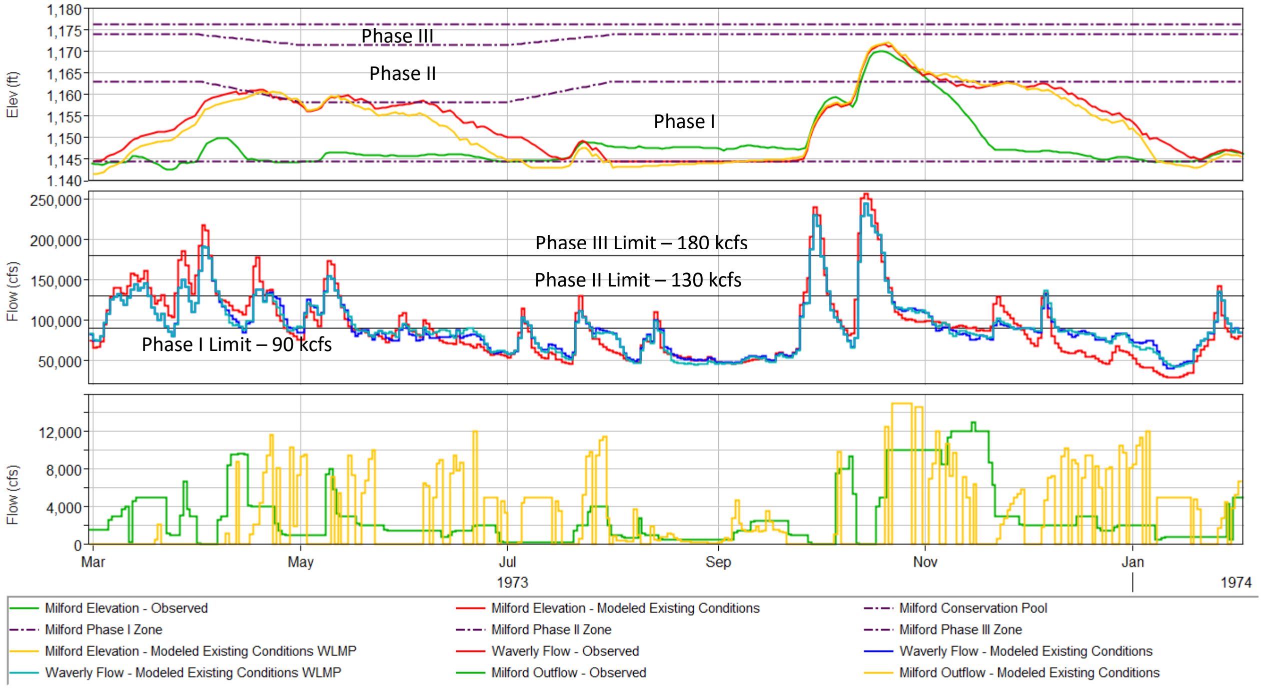


Figure 2-2. Milford 1973 pool elevation compared to the Waverly flow

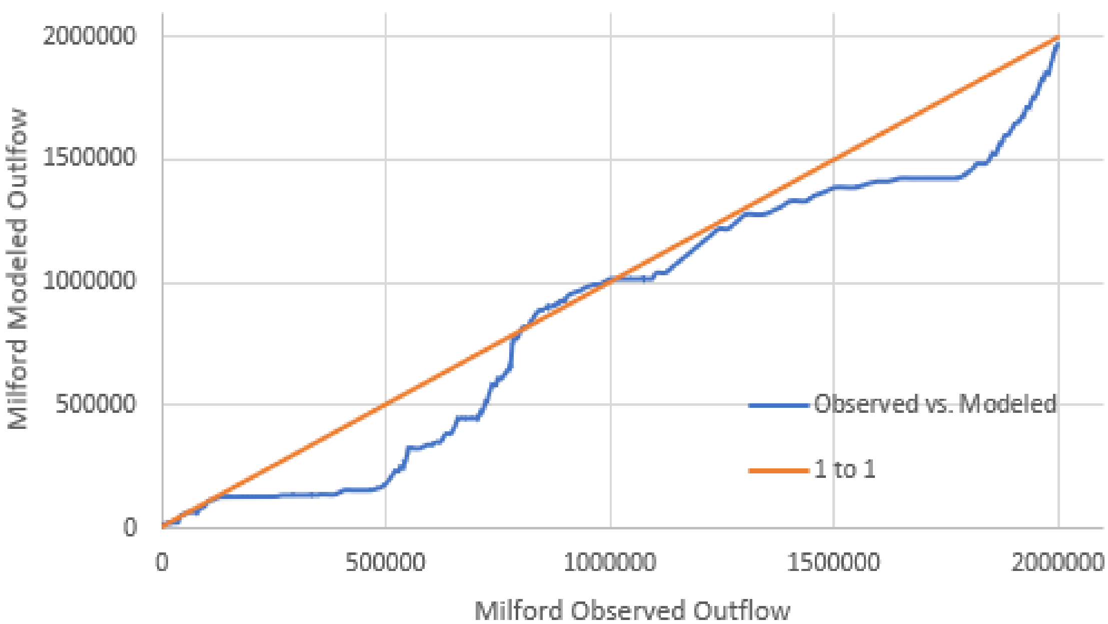


Figure 2-3. Observed versus modeled outflow compared to a 1 on 1 line for 1973

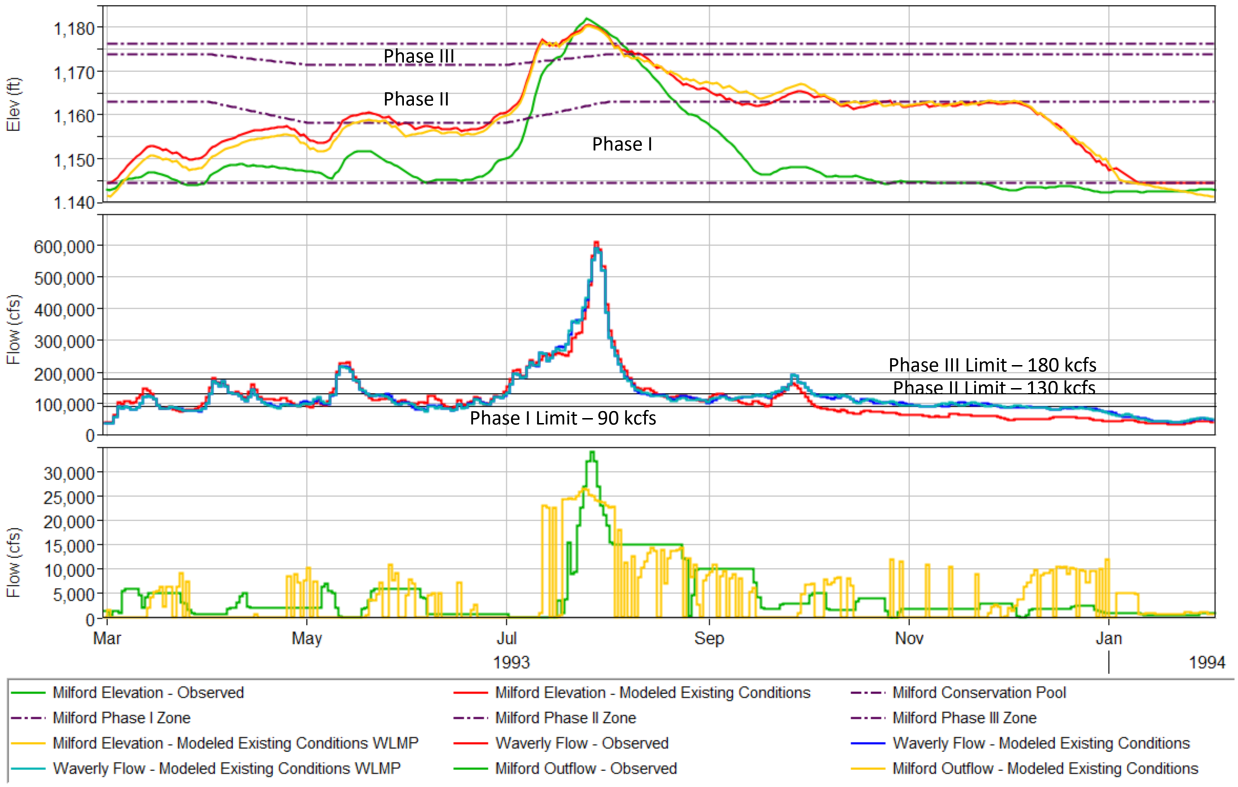


Figure 2-4. Milford 1993 pool elevation compared to the Waverly flow

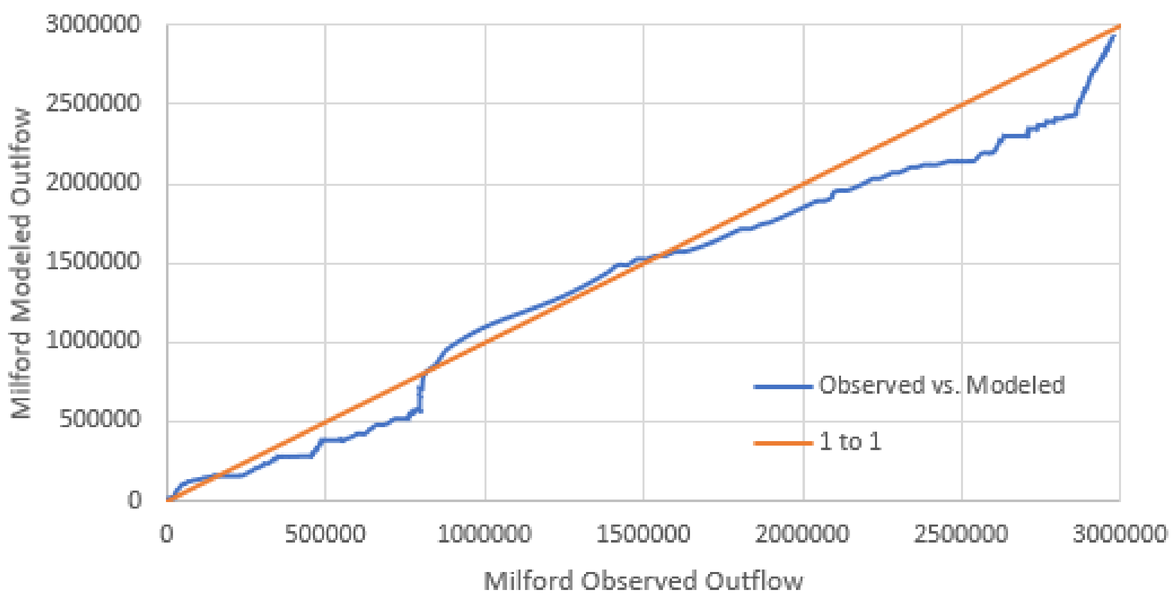


Figure 2-5. Observed versus modeled outflow compared to a 1 on 1 line for 1993

The Tuttle Creek water level management plan has been mostly unchanged for several years. When the WLMP was included, it resulted in pool elevation durations that were very similar to observed except for the highest and lowest pool elevations. The WLMP only had small impacts for the less frequent events that are more a function of how the model handles releases and the Missouri River at Waverly downstream control point. The lowest observed pool elevations may be a function of navigation flow support coupled with maintaining downstream water quality targets. The Tuttle Creek pool elevation duration plot is shown in Figure 2-6.

There were many flood control events that modeled the pool elevation higher than the observed. This would lead to the higher pool elevation duration in the flood control zone. Examples of this are shown in Figure 2-7 and Figure 2-9. Figure 2-8 and Figure 2-10 show the observed versus the modeled Tuttle Creek outflow for these same flood years. These plots confirm that the model releases nearly the same amount as the observed data; however, the timing is different. Some small differences in the volume can be attributed to differences evaporation.

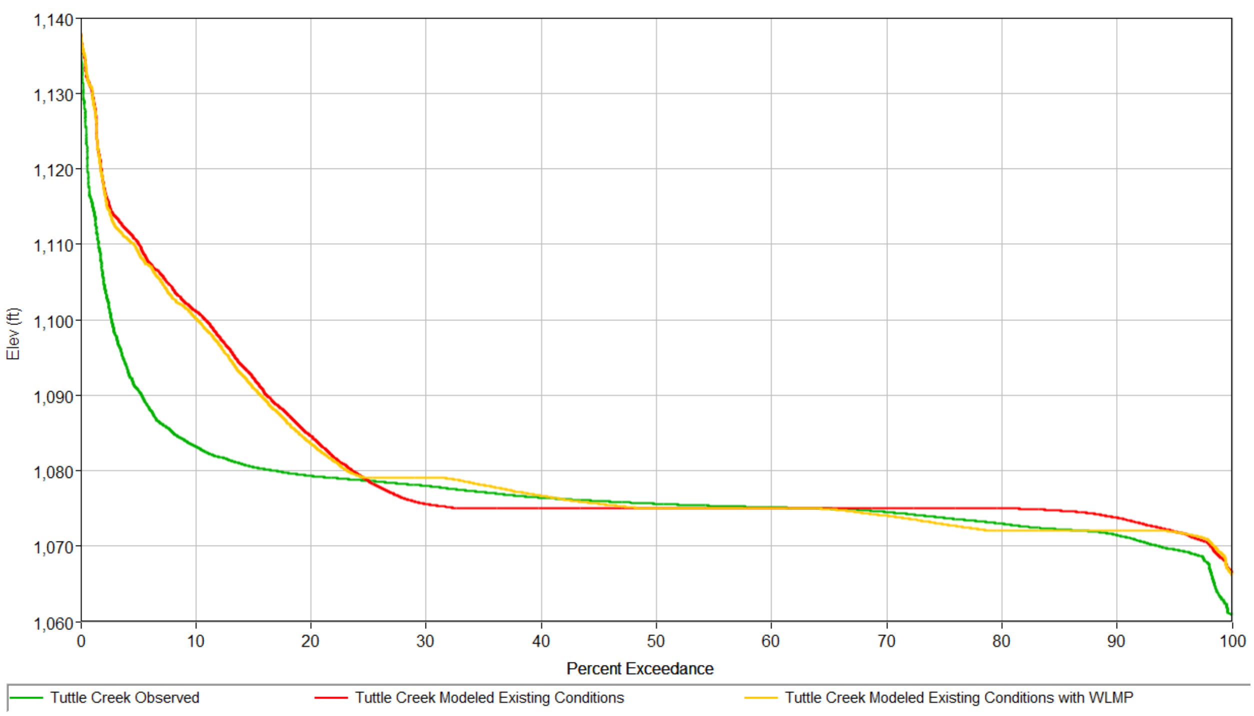


Figure 2-6. Tuttle Creek observed and modeled pool elevation duration from 01May1963 to 01Jan2020

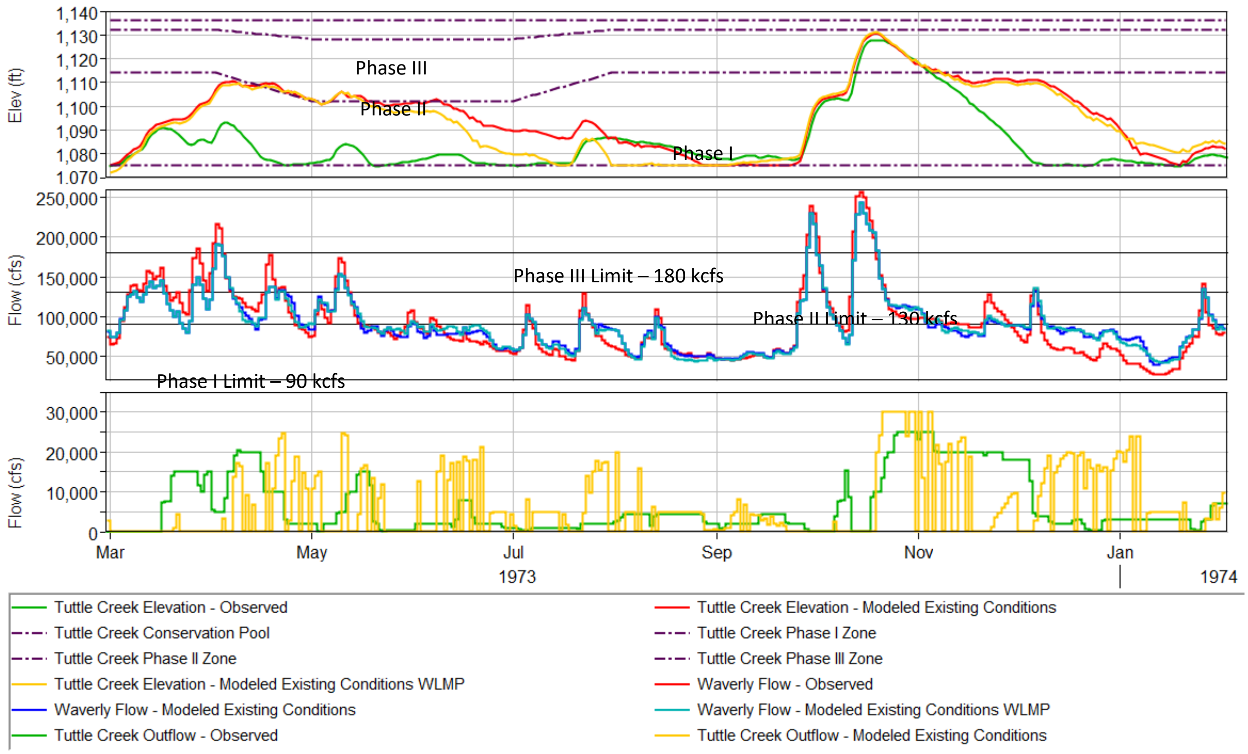


Figure 2-7. Tuttle Creek 1973 pool elevation compared to the Waverly flow

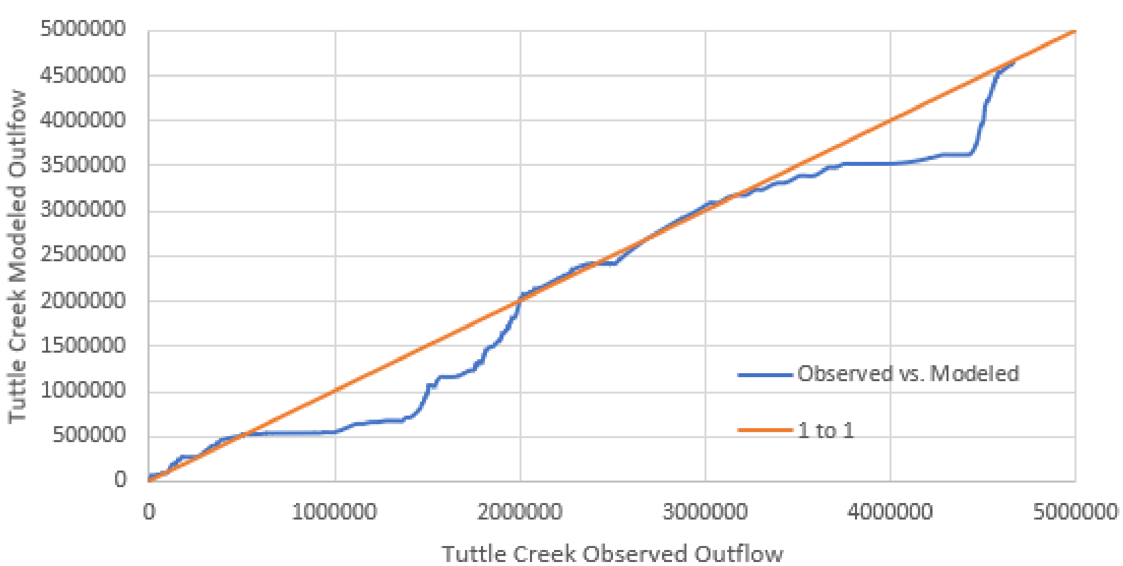


Figure 2-8. Observed versus modeled outflow compared to a 1 on 1 line for 1973

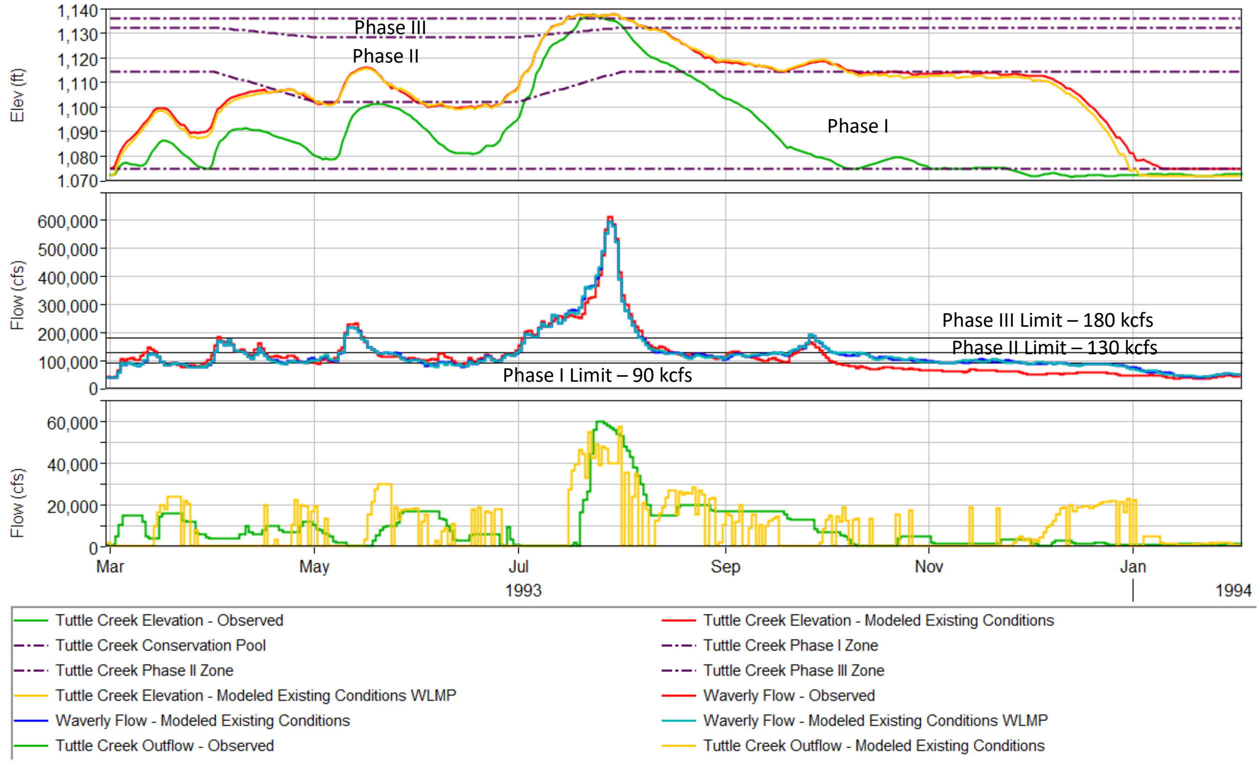


Figure 2-9. Tuttle Creek 1993 pool elevation compared to the Waverly flow

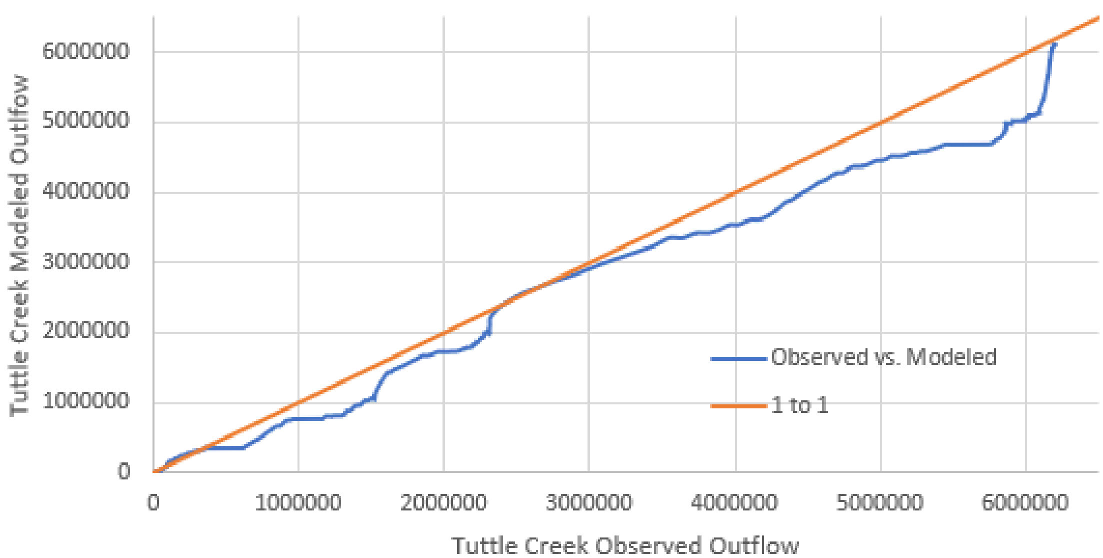


Figure 2-10. Observed versus modeled outflow compared to a 1 on 1 line for 1993

The Perry water level management plan has been mostly unchanged for several years. When the WLMP was included, it resulted in pool elevation durations that were very similar to observed except for the higher pool elevations. The WLMP only had small impacts for the less frequent events that are more a function of how the model handles releases and the Missouri River at Waverly downstream control point. The Perry pool elevation duration plot is shown in Figure 2-11.

There were many flood control events that modeled the pool elevation higher than the observed. This would lead to the higher pool elevation duration in the flood control zone. Examples of this are shown in Figure 2-12 and Figure 2-14. Figure 2-13 and Figure 2-15 show the observed versus the modeled Perry outflow for these same flood years. These plots confirm that the model does release the same amount as the observed data; however, the timing is different. Some small differences in the volume can be attributed to differences evaporation.

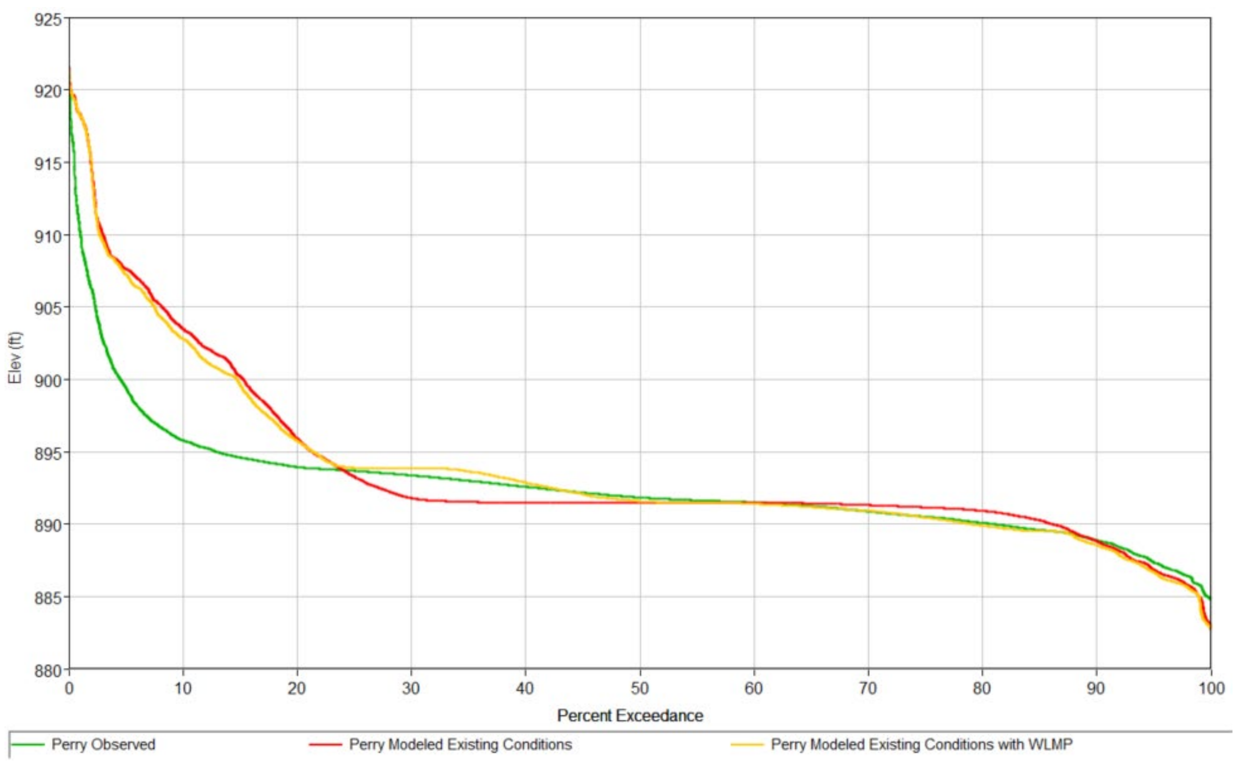


Figure 2-11. **Perry observed and modeled pool elevation duration from 01Apr1971 to 01Jan2020**

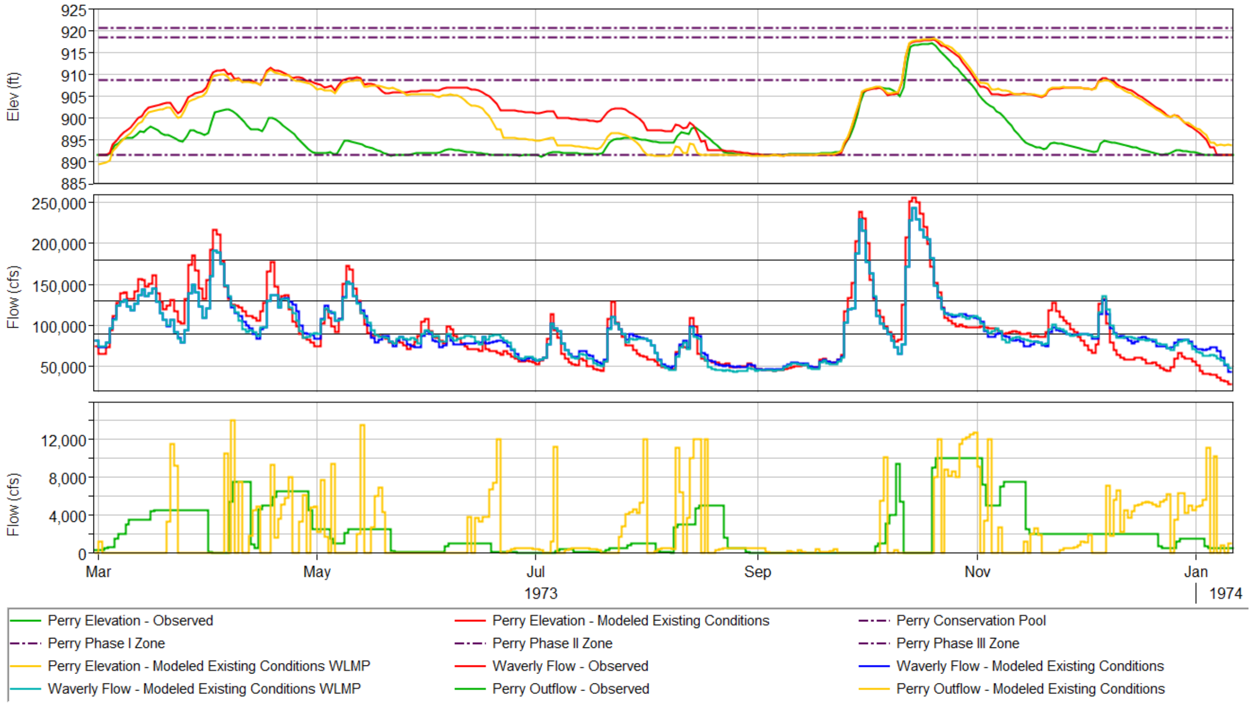


Figure 2-12. Perry 1973 pool elevation compared to the Waverly flow

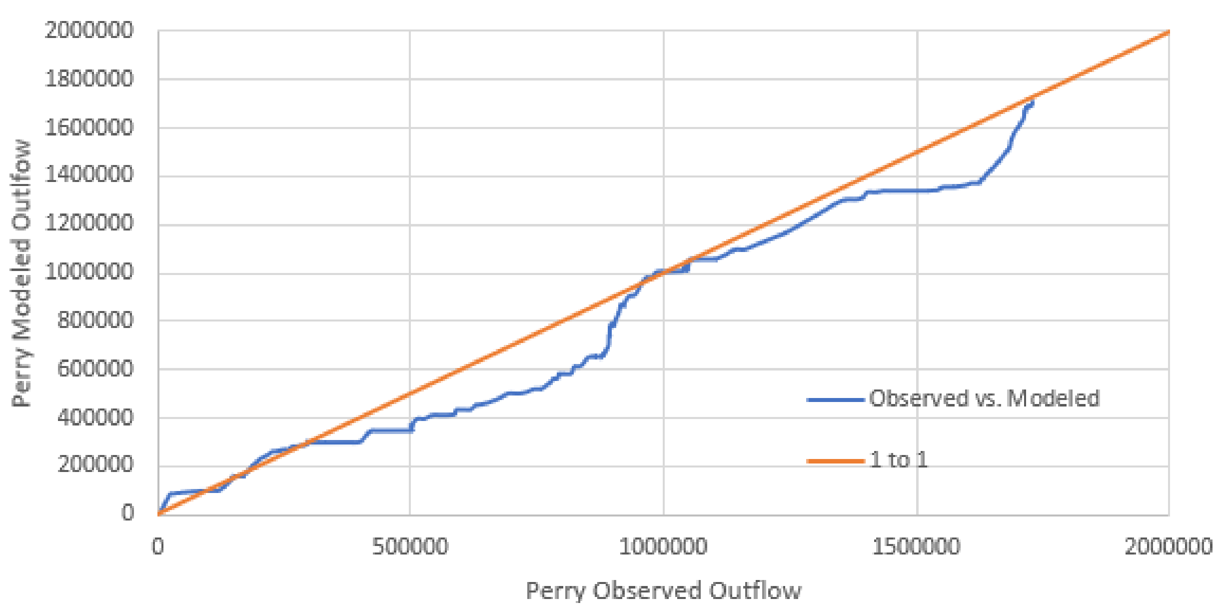


Figure 2-13. Observed versus modeled outflow compared to a 1 on 1 line for 1973.

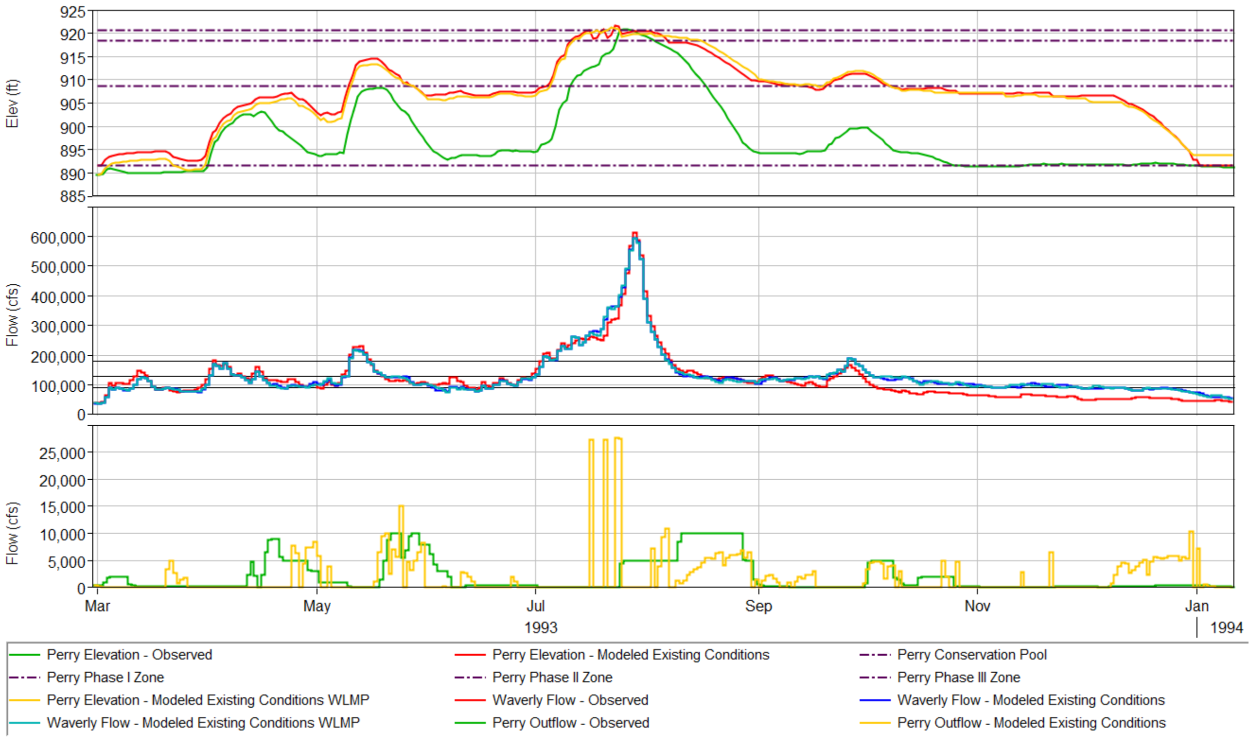


Figure 2-14. Perry 1993 pool elevation compared to the Waverly flow.

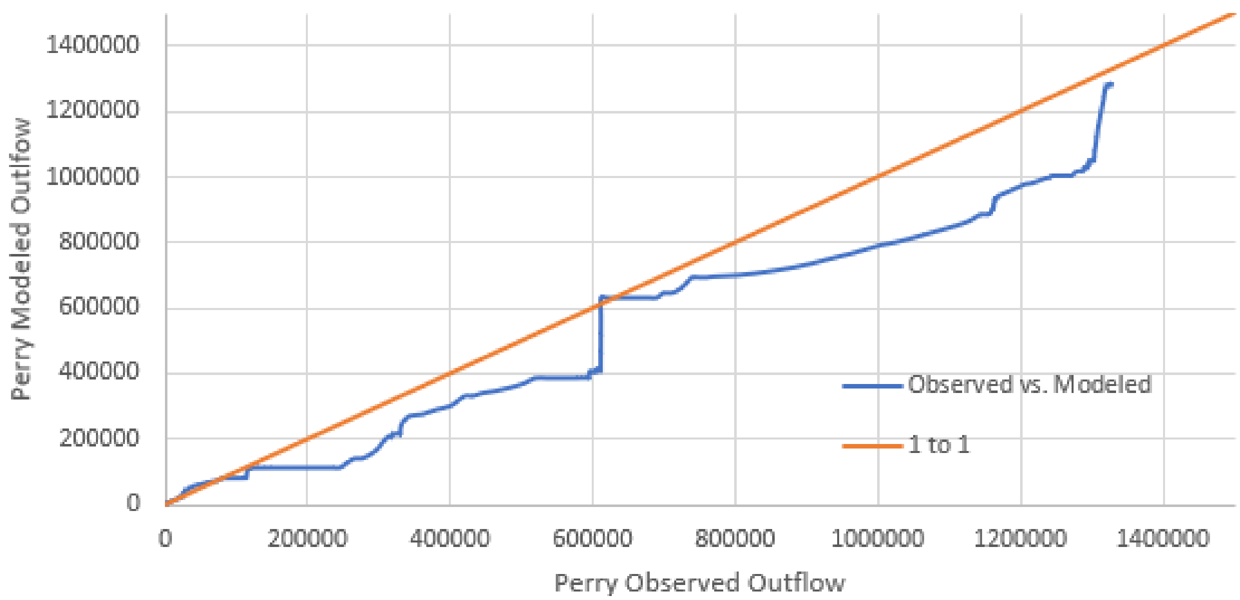


Figure 2-15. Observed versus modeled outflow compared to a 1 on 1 line for 1993.

2.2 Mass Balance Analysis

To ensure mass balance is consistent within ResSim, the sum of all annual reservoir outflow volumes was compared to the inflow volume. The modeled volumes were also compared to the observed data record. This analysis was conducted at Wilson and Tuttle Creek from 1980 to 2019 as a spot-check of the model. Observed flow-evaporation is consistently available starting in 1980 which is why the analysis was started then.

Modeled and observed inflow, outflow, and flow-evaporation were converted to annual flow volumes in acre-feet. Modeled and observed inflow is identical since the reservoirs are used as boundary condition in the ResSim model setup. Modeled and observed end-of-year storage was also tabulated and the annual change in storage was calculated. Reservoir outflow, evaporation, and the change in storage was summed to account for the water balance in a given year. The percent difference between inflow and the total outflow was calculated. The model had no difference between the inflow and the sum of the outflows showing that the model has consistent mass balance. There are some notable differences in the observed data set which are due to large shifts in pool elevation for a gage correction. There were two years where Wilson had a gage correction that impacted the calculation and three years at Tuttle Creek. All other years were less than 1% off mass balance for the observed data set. A deeper analysis can be made on the observed data process, but for the purposes of this study, the model is performing appropriately. All discrepancies between modeled and observed can be attributed to the observed data set.

Table 2.2-1 and Table 2.2-2 show the Wilson and Tuttle Creek analysis, respectively.

Table 2.2-1. Wilson mass balance annual volume comparison.

	Observed							Modeled—Existing Conditions with no Navigation							
Year	Inflow (AF)	Outflow (AF)	Evap (AF)	31Dec Storage (AF)	ΔStorage (AF)	O+E+ΔS (AF)	Inflow / Outflow (%)	Inflow (AF)	Outflow (AF)	Evap (AF)	31Dec Storage (AF)	ΔStorage (AF)	O+E+ΔS (AF)	Inflow / Outflow (%)	Observed/ Modeled (%)
1980	48,159	11,385	42,507	233,248				48,159	7,260	46,183	213,325				
1981	35,193	7,876	32,333	228,069	-5,179	35,031	-0.46%	35,193	7,250	44,922	196,347	-16,978	35,193	0.00%	0.46%
1982	68,768	23,572	33,149	240,209	12,140	68,861	0.13%	68,768	7,250	45,433	212,432	16,085	68,768	0.00%	-0.14%
1983	31,661	8,261	37,869	225,993	-14,216	31,915	0.80%	31,661	7,250	44,921	191,922	-20,510	31,661	0.00%	-0.80%
1984	59,908	11,500	35,463	238,526	12,533	59,496	-0.69%	59,908	7,260	44,862	199,708	7,786	59,908	0.00%	0.69%
1985	71,436	36,588	33,365	233,390	-5,136	64,818	-10.21%	71,436	7,250	45,251	218,643	18,935	71,435	0.00%	9.26%
1986	37,865	7,841	33,016	230,361	-3,029	37,828	-0.10%	37,865	7,250	45,367	203,892	-14,751	37,865	0.00%	0.10%
1987	285,227	229,122	37,899	248,531	18,170	285,191	-0.01%	285,227	203,711	49,235	236,173	32,282	285,227	0.00%	0.01%
1988	28,648	17,475	40,456	219,287	-29,245	28,687	0.14%	28,648	14,106	46,386	204,329	-31,845	28,648	0.00%	-0.13%
1989	29,741	8,166	34,343	206,583	-12,704	29,805	0.22%	29,741	7,250	43,732	183,088	-21,241	29,741	0.00%	-0.22%
1990	36,786	7,176	33,773	201,589	-4,994	35,955	-2.31%	36,786	7,250	41,770	170,854	-12,234	36,786	0.00%	2.26%
1991	31,040	7,147	33,751	191,600	-9,989	30,909	-0.42%	31,040	7,250	39,412	155,233	-15,621	31,040	0.00%	0.42%
1992	75,264	7,208	28,395	231,368	39,769	75,371	0.14%	75,264	7,260	39,160	184,076	28,844	75,263	0.00%	-0.14%
1993	737,445	598,552	43,893	326,295	94,927	737,371	-0.01%	737,445	551,357	65,651	304,511	120,435	737,444	0.00%	0.01%
1994	128,761	176,521	35,381	243,063	-83,232	128,670	-0.07%	128,761	149,981	47,670	235,623	-68,889	128,762	0.00%	0.07%
1995	266,089	225,205	35,787	248,441	5,378	266,370	0.11%	266,089	212,658	52,865	236,188	565	266,089	0.00%	-0.11%
1996	106,813	83,284	33,247	238,524	-9,917	106,615	-0.19%	106,813	59,135	47,679	236,188	0	106,813	0.00%	0.19%
1997	97,971	61,205	33,974	241,338	2,814	97,993	0.02%	97,971	50,347	47,624	236,188	0	97,971	0.00%	-0.02%
1998	170,990	139,620	34,884	237,938	-3,400	171,103	0.07%	170,990	123,146	47,844	236,188	0	170,990	0.00%	-0.07%
1999	145,807	106,277	35,067	242,398	4,460	145,804	0.00%	145,807	98,092	47,715	236,188	0	145,807	0.00%	0.00%
2000	71,555	44,160	39,351	230,508	-11,890	71,621	0.09%	71,555	36,238	47,264	224,242	-11,946	71,555	0.00%	-0.09%
2001	130,088	78,501	38,316	243,731	13,223	130,040	-0.04%	130,088	70,368	47,773	236,188	11,946	130,088	0.00%	0.04%
2002	39,136	18,292	38,291	226,311	-17,421	39,163	0.07%	39,136	14,683	46,680	213,962	-22,226	39,137	0.00%	-0.07%
2003	31,893	7,248	36,326	214,764	-11,547	32,027	0.42%	31,893	7,250	44,924	193,682	-20,280	31,893	0.00%	-0.42%
2004	45,630	7,168	33,587	219,472	4,708	45,462	-0.37%	45,630	7,260	43,855	188,198	-5,484	45,631	0.00%	0.37%

	Observed							Modeled—Existing Conditions with no Navigation							
Year	**Inflow (AF)**	**Outflow (AF)**	**Evap (AF)**	**31Dec Storage (AF)**	**ΔStorage (AF)**	**O+E+ΔS (AF)**	**Inflow / Outflow (%)**	**Inflow (AF)**	**Outflow (AF)**	**Evap (AF)**	**31Dec Storage (AF)**	**ΔStorage (AF)**	**O+E+ΔS (AF)**	**Inflow / Outflow (%)**	**Observed/ Modeled (%)**
2005	30,193	7,210	34,958	207,597	-11,875	30,294	0.33%	30,193	7,250	42,391	168,750	-19,448	30,193	0.00%	-0.33%
2006	21,148	7,289	36,703	184,688	-22,910	21,083	-0.31%	21,148	7,250	37,770	144,878	-23,872	21,148	0.00%	0.31%
2007	74,681	7,313	35,827	216,108	31,421	74,561	-0.16%	74,681	7,250	39,837	172,472	27,594	74,680	0.00%	0.16%
2008	163,323	100,604	34,952	243,407	27,299	162,855	-0.29%	163,323	55,975	43,632	236,188	63,716	163,322	0.00%	0.29%
2009	80,372	42,203	34,688	247,467	4,060	80,951	0.71%	80,371	32,827	47,545	236,188	0	80,371	0.00%	-0.72%
2010	75,353	50,563	36,940	235,104	-12,363	75,140	-0.28%	75,349	40,763	47,171	223,603	-12,585	75,349	0.00%	0.28%
2011	50,407	8,432	38,817	238,507	3,403	50,651	0.48%	50,407	8,681	46,571	218,757	-4,846	50,407	0.00%	-0.48%
2012	19,268	7,143	39,003	205,105	-33,402	12,744	-51.19%	19,268	7,260	44,858	185,908	-32,849	19,268	0.00%	33.86%
2013	27,715	7,211	37,078	188,648	-16,457	27,831	0.42%	27,715	7,250	41,054	165,320	-20,588	27,716	0.00%	-0.42%
2014	20,944	7,160	31,690	170,773	-17,875	20,975	0.15%	20,946	7,250	37,304	141,713	-23,608	20,946	0.00%	-0.14%
2015	22,898	7,218	29,603	156,953	-13,820	23,001	0.45%	22,898	7,250	34,410	122,951	-18,762	22,898	0.00%	-0.45%
2016	166,660	46,905	32,460	244,095	87,142	166,508	-0.09%	166,660	14,919	38,502	236,188	113,237	166,658	0.00%	0.09%
2017	146,547	114,127	38,225	238,288	-5,808	146,545	0.00%	146,547	98,650	47,897	236,188	0	146,547	0.00%	0.00%
2018	190,013	150,827	36,182	240,924	2,636	189,645	-0.19%	190,011	141,298	47,865	237,036	848	190,011	0.00%	0.19%

Table 2.2-2. Tuttle Creek mass balance annual volume comparison

	Observed							Modeled—Existing Conditions with no Navigation							
Year	**Inflow (AF)**	**Outflow (AF)**	**Evap (AF)**	**31Dec Storage (AF)**	**ΔStorage (AF)**	**O+E+ΔS (AF)**	**Inflow/ Outflow (%)**	**Inflow (AF)**	**Outflow (AF)**	**Evap (AF)**	**31Dec Storage (AF)**	**ΔStorage (AF)**	**O+E+ΔS (AF)**	**Inflow/ Outflow (%)**	**Observed/ Modeled (%)**
1980	1,213,854	1,190,009	68,482	352,343				1,213,854	1,159,155	54,773	256,940				
1981	864,181	726,332	50,446	440,449	88,106	864,884	0.08%	864,181	812,515	51,593	257,014	74	864,181	0.00%	-0.08%
1982	2,621,969	2,575,402	52,412	433,092	-7,357	2,620,457	-0.06%	2,621,969	2,540,191	81,778	257,014	0	2,621,969	0.00%	0.06%
1983	2,295,713	2,279,492	59,569	350,277	-82,815	2,256,246	-1.75%	2,295,713	2,220,189	75,523	257,014	0	2,295,713	0.00%	1.72%
1984	3,422,113	3,332,060	57,387	352,916	2,640	3,392,086	-0.89%	3,422,113	3,305,380	116,732	257,014	0	3,422,113	0.00%	0.88%
1985	1,962,515	1,906,816	42,235	366,328	13,412	1,962,463	0.00%	1,962,515	1,909,146	53,368	257,014	0	1,962,515	0.00%	0.00%
1986	3,360,513	3,341,152	48,905	336,422	-29,907	3,360,151	-0.01%	3,360,513	3,264,529	95,984	257,014	0	3,360,513	0.00%	0.01%
1987	3,199,812	3,191,811	49,735	297,698	-38,724	3,202,822	0.09%	3,199,812	3,122,197	77,615	257,014	0	3,199,812	0.00%	-0.09%
1988	590,895	573,698	48,672	266,222	-31,476	590,894	0.00%	590,895	577,662	50,334	219,912	-37,102	590,895	0.00%	0.00%
1989	1,072,123	1,014,449	44,482	279,833	13,612	1,072,543	0.04%	1,072,123	985,002	50,019	257,014	37,102	1,072,123	0.00%	-0.04%
1990	1,373,990	1,319,748	45,903	288,103	8,270	1,373,921	-0.01%	1,373,990	1,329,737	55,533	245,734	-11,280	1,373,990	0.00%	0.01%
1991	670,740	646,252	46,941	265,261	-22,842	670,351	-0.06%	670,740	669,458	49,038	197,979	-47,756	670,741	0.00%	0.06%
1992	2,030,753	1,950,185	45,148	300,442	35,181	2,030,514	-0.01%	2,030,753	1,910,577	61,140	257,014	59,035	2,030,752	0.00%	0.01%
1993	6,251,189	6,179,354	70,702	301,238	796	6,250,852	-0.01%	6,251,189	6,067,068	166,718	274,417	17,403	6,251,189	0.00%	0.01%
1994	1,326,178	1,286,819	44,248	296,733	-4,505	1,326,563	0.03%	1,326,178	1,292,135	51,446	257,014	-17,403	1,326,178	0.00%	-0.03%
1995	2,180,065	2,134,171	45,525	297,279	546	2,180,242	0.01%	2,180,065	2,062,248	117,817	257,014	0	2,180,065	0.00%	-0.01%
1996	1,671,743	1,616,268	45,060	307,808	10,529	1,671,857	0.01%	1,671,743	1,584,792	86,952	257,014	0	1,671,743	0.00%	-0.01%
1997	1,310,915	1,257,223	45,114	315,822	8,015	1,310,351	-0.04%	1,310,915	1,199,599	111,316	257,014	0	1,310,915	0.00%	0.04%
1998	2,582,775	2,554,712	45,405	298,674	-17,149	2,582,969	0.01%	2,582,775	2,510,508	72,267	257,014	0	2,582,775	0.00%	-0.01%
1999	2,221,800	2,122,752	48,037	313,751	15,078	2,185,866	-1.64%	2,221,800	2,126,279	95,521	257,014	0	2,221,800	0.00%	1.62%
2000	727,697	756,886	51,844	232,863	-80,889	727,841	0.02%	727,697	709,205	50,449	225,057	-31,957	727,697	0.00%	-0.02%
2001	2,153,526	2,051,652	51,886	282,561	49,698	2,153,237	-0.01%	2,153,526	2,068,098	59,285	251,199	26,142	2,153,525	0.00%	0.01%
2002	624,674	656,478	38,645	212,553	-70,008	625,115	0.07%	624,674	602,567	49,114	224,192	-27,007	624,674	0.00%	-0.07%
2003	746,738	671,371	45,470	242,466	29,913	746,754	0.00%	746,738	690,949	49,061	230,920	6,728	746,738	0.00%	0.00%
2004	1,019,370	928,240	45,527	288,326	45,860	1,019,628	0.03%	1,019,370	966,561	51,458	232,271	1,351	1,019,370	0.00%	-0.03%
2005	823,877	799,128	44,432	268,210	-20,116	823,445	-0.05%	823,877	749,511	52,072	254,564	22,293	823,876	0.00%	0.05%
2006	443,253	464,500	39,184	207,810	-60,400	443,284	0.01%	443,253	434,763	49,452	213,603	-40,961	443,253	0.00%	-0.01%
2007	2,244,320	2,125,773	47,936	277,862	70,052	2,243,760	-0.02%	2,244,320	2,137,838	63,071	257,014	43,411	2,244,320	0.00%	0.02%
2008	2,394,382	2,300,787	45,245	325,784	47,923	2,393,954	-0.02%	2,394,382	2,323,114	71,268	257,014	0	2,394,382	0.00%	0.02%
2009	1,026,630	1,065,987	39,979	247,121	-78,664	1,027,302	0.07%	1,026,630	968,761	57,869	257,014	0	1,026,630	0.00%	-0.07%

Year	Observed							Modeled—Existing Conditions with no Navigation							Observed/ Modeled (%)
	Inflow (AF)	Outflow (AF)	Evap (AF)	31Dec Storage (AF)	ΔStorage (AF)	O+E+ΔS (AF)	Inflow/ Outflow (%)	Inflow (AF)	Outflow (AF)	Evap (AF)	31Dec Storage (AF)	ΔStorage (AF)	O+E+ΔS (AF)	Inflow/ Outflow (%)	
2010	2,399,585	2,332,743	60,106	253,709	6,589	2,399,437	-0.01%	2,399,585	2,266,060	133,525	257,014	0	2,399,585	0.00%	0.01%
2011	1,128,911	1,034,090	63,413	285,574	31,865	1,129,368	0.04%	1,128,911	1,016,074	112,837	257,014	0	1,128,911	0.00%	-0.04%
2012	554,914	636,755	42,489	142,209	-143,365	535,879	-3.55%	554,914	579,595	48,786	183,548	-73,466	554,915	0.00%	3.43%
2013	843,404	687,215	42,961	255,441	113,233	843,408	0.00%	843,404	729,657	51,653	245,641	62,093	843,403	0.00%	0.00%
2014	792,192	743,689	43,236	260,038	4,597	791,521	-0.08%	793,085	727,998	56,590	254,137	8,496	793,084	0.00%	0.20%
2015	2,447,943	2,319,338	44,785	343,942	83,904	2,448,027	0.00%	2,447,943	2,221,027	93,704	387,346	133,209	2,447,940	0.00%	0.00%
2016	1,494,200	1,555,484	45,474	234,838	-109,103	1,491,854	-0.16%	1,494,200	1,552,894	71,640	257,014	-130,332	1,494,202	0.00%	0.16%
2017	1,441,039	1,392,737	46,041	237,414	2,576	1,441,354	0.02%	1,441,039	1,381,491	73,677	242,885	-14,129	1,441,039	0.00%	-0.02%
2018	1,964,258	1,777,969	50,665	369,701	132,287	1,960,921	-0.17%	1,964,258	1,380,074	85,861	741,201	498,316	1,964,251	0.00%	0.17%

September 2021

Osage Basin HEC-ResSim POR Development

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1. Introduction

The following work is included as part of the Missouri River Flow Frequency Study. The overall project entails the update or development of models for the Missouri River and key tributaries.

For the Osage River basin, an existing model was updated to reflect the current operation of the U.S. Army Corps of Engineers (USACE) projects in the Osage River Basin. Existing datasets from 1928 to 2013 were extended to include all of 2019. This section of the report discusses the processes used to develop Osage Basin HEC-ResSim flows from the Marais des Cygnes River near Pomona, KS to the Osage River at St. Thomas, MO from 2013 to 2019.

Necessary output from the model includes a complete regulated set of flows at the U.S. Geological Survey (USGS) stream gage location at the Osage River near St. Thomas, MO and local inflows

2. Time Zone

All time series referenced in this section of the report is in Central Standard Time (CST) unless otherwise specified. CST is equivalent to Coordinated Universal Time (UTC) minus six hours (UTC -6).

3. Methodology

A USACE Hydrologic Engineering Center (HEC) model, HEC Reservoir System Simulation (ResSim) version 3.5, was used to simulate reservoir operations and route water through the basin. HEC-ResSim is a reservoir simulation model which incorporates user-defined rules and data sets to determine reservoir outflow. The model routes those releases using hydrologic routing methods defined by the user. In the case of the Osage River model, coefficient routing or null routing was used for all reaches. A depiction of the model junctions and reaches in the basin is shown in Figure 1 below.

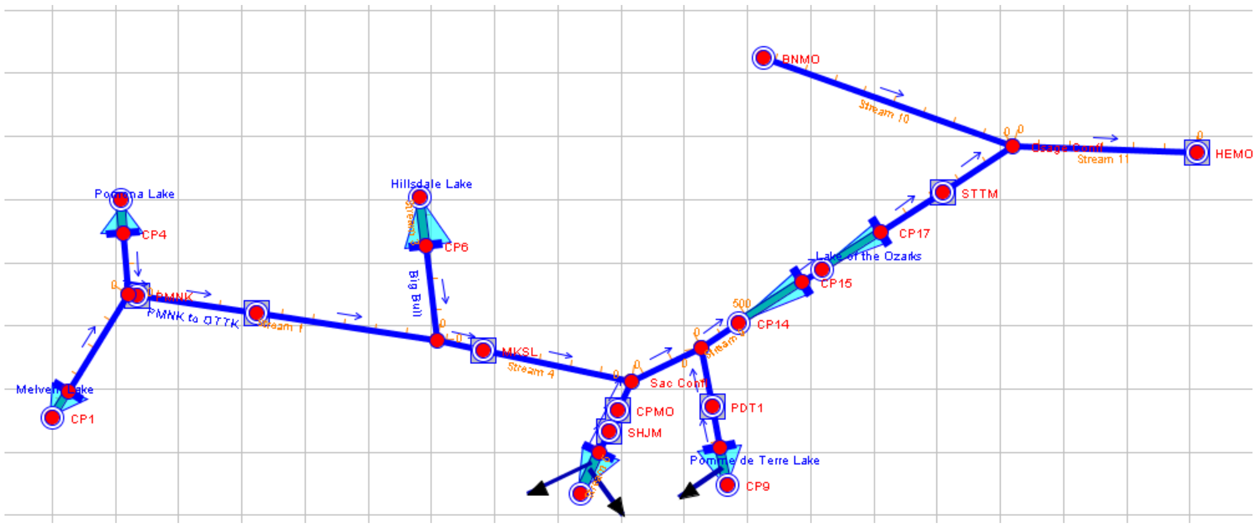


Figure 1. **Figure of Osage ResSim model (with drainage area, rivers, etc.)**

In order to utilize the model, a complete data set for a number of inputs is required. Data sets were collected from observed records and extended, filling in missing and historical data with a variety of methods. Observed records were obtained from the USGS official daily streamflow records, the Corps Water Management Systems (CWMS) database, and from the existing model. The period of record for the model input data was January 1, 1928 through December 310, 2019. The model utilized a daily time step for simulations.

The existing reservoir network "PT_ST-BC" was utilized in simulations for this project. This reservoir network was the final calibrated network utilized in simulations for the 2018 Missouri River Recovery Management Plan and Environmental Impact Statement (Manplan). Additionally, the reservoir network included adjustments for proposed Stockton reallocations included in the 2020 Stockton Reallocation Study. Over the course of this project, hydrologic routing parameters and the reservoir operation rule set were re-evaluated and updated as necessary to improve results.

4. Data Sources and Development

Several data sources were used to develop input time series required for HEC-ResSim simulations. Raw daily data provided by USACE Kansas City District (NWK) Water Management Section (EDH-C), is saved at two different time steps. For the power generating reservoirs (Stockton, Truman, and Lake of the Ozarks), daily data is saved at 2400 and daily data for nonpower generating reservoirs (Melvern, Pomona, Hillsdale, Pomme de Terre) are saved at 0600. The daily data is representative of the daily average of the previous 24 hours. Some time shifts were applied to datasets such that all datasets are recorded at the same time step (0000 or 2400 hours). Specific time shifts are documented in the following sections and are specific for each data type.

In order to create a complete period of record (POR) from 1928 to 2013, time series from 2013 to 2019 were merged with the 1928 to 2013 previously developed datasets. The previous datasets from 1928 to 2019 received higher priority and overwrote any overlapping data within the new time series. Time series development for the 1928 to 2013 datasets are documented in the 2018 USACE "Missouri River Recovery Management Plan Time Series Data Development for Hydrologic Modeling" Report. The 1928 to 2013 time series were not edited to maintain the same methodologies used to develop the 1928 to 2013 time series. As a result, different methods were used to develop the 1928 to 2013 and 2013 to 2019 time series.

4.1 USGS Observed Daily Flows

U.S. Geological Survey (USGS) daily flows from 2013 to 2019 were downloaded using the Hydrologic Engineering Center (HEC) Data Storage System Visual Utility Engine (DSSVue) USGS Web Import tool. The data was imported in local standard time or CST without daylight savings time. Table 1 summarizes the USGS gages downloaded. These datasets were compared to the developed flows to determine how well the developed flow records represented observed flows.

Table 1. USGS Gages

USGS Gage ID	Gage Name	Drainage Area (sq mi)	CWMS ID
06909000	Missouri River at Boonville, MO	500,700	BNMO
06916600	Marais des Cygnes River near KS-MO State Line, KS	3,250	MKSL
06913000	Marais Des Cygnes River near Pomona, KS	1,040	PMNK
06913500	Marais Des Cygnes River near Ottawa, KS	1,250	OTTK
06919020	Sac River at Highway J below Stockton, MO	1,292	SHJM
06919900	Sac River near Caplinger Mills, MO	1,810	CPMO
06921350	Pomme de Terre River near Hermitage, MO	615	PDT1
06926000	Osage River near Bagnell, MO	14,000	CP17
06926510	Osage River below St. Thomas, MO	14,584	STTM
06934500	Missouri River at Hermann, MO	522,500	HEMO

Once downloaded, the USGS flows from 2013 to 2019 were merged with the 1928 to 2013 previously developed datasets. The 1928-2013 datasets received higher priority. Upon comparing the overlapping datasets in 2013, the USGS datasets were consistently lagging by one day (+24 hours) when compared to the 1928-2013 extended POR. No additional time shifts were applied to the USGS data to match the 1928-2013 POR as all USGS data was recorded in CST and is believed to be the best representation of daily data. The developed USGS and historical timeseries are provided in Attachment A.

4.2 Evaporation

Evaporation rates from 1990 to 2013 were computed by multiplying pan evaporation measurements by the pan evaporation coefficients for each month at each reservoir. Thus, the same methodology was used to develop the evaporation rates for the 2013 to 2019 Osage Basin dataset. Pan evaporation rates were provided by USACE NWK EDH-C. Datasets for nonpower generating reservoirs are saved at 0600 each day and are representative of the previous 24 hours. In order to have all datasets recorded at the same time step, evaporation rates for nonpower generating reservoirs were shifted -6 hours in DSSVue such that the measurements were associated with the day that had the majority of the daily value. For example, the 02Jan2014 0600 was shifted -6 hours to 01Jan2014 2400. By doing this, the daily data still represents the original daily average values for 75% of the original 24 hours (0600-2400).

Table 2 displays the monthly pan evaporation rates for each reservoir. The pan evaporation rates were multiplied by the respective monthly pan coefficient in the table below. Then, the data was converted from instantaneous to per-avg. Evaporation rates were unavailable for the Lake of the Ozarks and, as a result, evaporation rates from Truman Lake were also applied to the Lake of the Ozarks.

Table 2. Reservoir Pan Evaporation Rates

Reservoir	CWMS ID	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
Melvern	MELN	0.65	0.46	0.32	0.31	0.38	0.51	0.7	0.91	1.05	1.09	1.00	0.82	0.68
Pomona	POMA	0.65	0.46	0.32	0.31	0.38	0.51	0.7	0.91	1.05	1.09	1.00	0.82	0.68
Hillsdale	HILS	0.65	0.46	0.32	0.31	0.38	0.51	0.7	0.91	1.05	1.09	1.00	0.82	0.68
Pomme de Terre	PODT	1.00	0.64	0.42	0.46	0.53	0.61	0.61	0.78	1.04	1.24	1.79	1.82	0.91
Stockton	STON	1.00	0.64	0.42	0.46	0.53	0.61	0.61	0.78	1.04	1.24	1.79	1.82	0.91
Harry S. Truman	HAST	1.00	0.64	0.42	0.46	0.53	0.61	0.61	0.78	1.04	1.24	1.79	1.82	0.91
Lake of the Ozarks	BAGL	1.00	0.64	0.42	0.46	0.53	0.61	0.61	0.78	1.04	1.24	1.79	1.82	0.91

The previous 1928 to 2013 dataset, labeled as “EVAP-PRECIP”, also accounted for localized precipitation contributions to the reservoir storage. The 1928 to 2013 dataset subtracted the precipitation from the evaporation rates. This methodology was not applied to the 2013 to 2019 time series as the computed reservoir inflows already accounted for lake surface area precipitation contributions. Thus, subtracting the precipitation from the evaporation would double count for the localized precipitation contributions. The 2013 to 2019 average evaporation was then merged with the existing evaporation data series such that the previous 1928 to 2013 dataset received priority if overlapping data occurred, creating a continuous daily time series from 1928 to 2019. Developed evaporation and precipitation time series are provided in Attachment A.

4.3 Reservoir Inflows

Reservoir average daily inflows from 2013 to 2019 were provided by USACE NWK EDH-C and represented all inflow sources including localized runoff and lake surface area precipitation. Again, inflow data recorded at 0600 UTC-6 was advanced 6 hours to move data to 2400, similar to evaporation. Inflow data recorded at 2400 UTC-6 was not shifted in time. Additionally, missing values were interpolated between the two adjacent daily values. The 2013 to 2019 inflows were then merged with the 1928 to 2013 time series where the 1928 to 2013 time series received higher priority for overlapping data. Developed inflow time series were only developed for Melvern, Pomona, Hillsdale, Stockton, and Pomme de Terre reservoirs. The developed reservoir inflow timeseries are provided in Attachment A.

4.4 Reservoir Discharges

Reservoir average daily releases from 2013 to 2019 were provided by USACE NWK EDH-C and represented the total reservoir discharges. Discharges recorded at 0600 UTC-6 were advanced 6 hours to move data to 2400, similarly to the evaporation and reservoir inflow datasets. Discharges recorded at 2400 UTC-6 were not shifted in time. Additionally, missing values were present in all reservoir outflow datasets. The missing data points were interpolated between the two adjacent daily values. The 2013 to 2019 discharges were then merged with the 1928 to 2013 time series where the 1928 to 2013 time series received higher priority for overlapping data. Reservoir discharge time series are provided in Attachment A.

4.5 Power Generation

Power generation datasets were only required for Stockton and Truman lakes in the HEC-ResSim model. Observed datasets were provided by USACE NWK EDH-C and were already recorded at 2400 time intervals. Data was then converted from megawatt-hours (MWh) to megawatt-days (MWd) by dividing by 24. The 2013 to 2019 dataset was then merged with the 1928 to 2013 power generation time series.

5. Ungaged Local Inflow Computations

5.1 Raw Local Flow Calculations

Raw ungaged local inflows were developed at every junction using the Missouri River Recovery Program HEC-ResSim model. Junction locations are provided in Table 3 and Figure 2. In the Osage Basin HEC-ResSim model, all inflow locations and energy outputs were set to zero datasets where each time step data point was set to zero. Additionally, all minimum reservoir releases including the minimum phase, fish, and water supply releases were set to zero. All reservoir monthly evaporation values were set to zero. These parameters were all set to zero in order to reduce the number of inflow sources and calculate the ungaged local inflows using only observed datasets and ResSim routing. Additionally, this methodology eliminated impacts from reservoir releases.

Table 3. Osage HEC-ResSim Junctions where Ungaged Local Inflows were Computed

CWMS ID	Description
PMNK	Pomona, KS
OTTK	Ottawa, KS
MKSL	State Line, KS
SHJM	Highway J Bridge, MO
CPMO	Caplinger Mills, MO
PDT1	Hermitage, MO
CP14	Harry S. Truman Lake Inflow
CP16	Lake of the Ozarks Inflow
STTM	St. Thomas, MO
HEMO	Hermann, MO

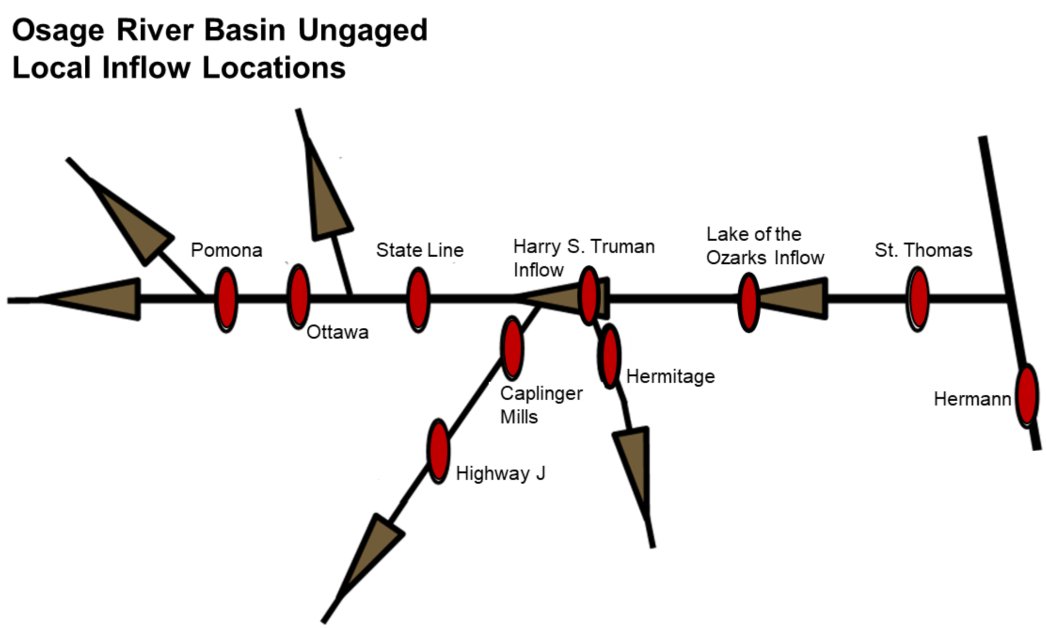


Figure 2. Osage Basin Ungaged Local Inflow Location Schematic

Once the parameters were adjusted to zero to remove additional sources of inflow, a gaged junction location was added to the nearest upstream gage and/or gages if a gaged junction was not already included in the model. For example, when computing the local inflows for Pomona, inflow locations were added at Pomona and Melvern reservoirs. All other upstream and downstream inflow locations utilized the zero flow datasets to prevent any additional inflow from entering the system that may contribute to changing reservoir releases. The nearest upstream inflow locations were then assigned to either the observed USGS datasets or observed reservoir releases.

Once the model inputs were set, the simulations were run, and the modeled inflows at the local inflow locations were extracted from the simulation results. The local flows *(local)* were then computed by subtracting the simulated model flows *(model)* from observed flows *(obs)* as seen in Equation 1. Observed flows could either be USGS observed datasets or the EDH-C provided reservoir inflows.

Equation 1: $$MKSL_{local} = MKSL_{obs} - MKSL_{model}$$

Upon reviewing the computed ungaged local inflows, adjustments were made to the HEC-ResSim routing coefficients to better match observed timing and peak flows. Adjustments for each reach are described in the following sections.

5.1.1 PMNK (110 mile creek and Marias Des Cygnes to Pomona)

A minimal amount of negative local flows were computed in the ungaged local flows at PMNK. USGS and the computed ungaged local time series matched timing well. No routing coefficients were adjusted, and no additional shifts were necessary to match timing.

5.1.2 OTTK (Marias Des Cygnes from Pomona to Ottawa, KS)

A minimal amount of negative local flows were computed in the ungaged local flows at OTTK. USGS and the computed ungaged local time series matched timing well. No routing coefficients were adjusted, and no additional shifts were necessary to match timing.

5.1.3 MKSL (Marias Des Cygnes from Ottawa to Stateline)

A minimal amount of negative local flows were computed in the ungaged local flows at MKSL. USGS and the computed ungaged local time series matched timing. No routing coefficients were adjusted, and no additional shifts were necessary to match timing.

5.1.4 SHJM (Sac River Reach from Stockton Reservoir to Highway J)

The computed ungaged local inflows at SHJM contained several negatives indicating adjustments to routing parameters were needed. The modeled flows at Highway J appear to be about a day (+24 hours) behind the USGS flows. However, since the travel time between Stockton and Highway J is typically less than a day, there were no routing coefficients available within the reach to adjust. As a result, no adjustments to routing coefficients were made. In order to improve the timing of the peak discharges, Pomme de Terre reservoir outflows were shifted a day earlier (-24 hours) to better align with USGS datasets downstream. The resulting local flows had significantly improved timing and fewer negative local flows.

5.1.5 CPMO (Sac River Reach from Highway J to Caplinger Mills)

Several negative ungaged local inflows were present in the CPMO record. The routing coefficients were adjusted to reduce the magnitude of the negative values and improve peak timing. As a result, the routing coefficients were adjusted to 0.60 and 0.40 for time step one and two, respectively. The resulting dataset largely decreased the negative value magnitudes and the timing appeared to match the USGS data.

5.1.6 PDT1 (Pomme de Terre River from Pomme de Terre Reservoir to Hermitage)

The computed ungaged local inflows at PDT1 contained several negatives indicating adjustments to routing parameters were needed. The modeled flows at Hermitage, MO appeared to be about a day (+24 hours) behind the USGS flows. However, since the travel time between Pomme de Terre and Hermitage, MO are usually less than one day, there were not routing coefficients available within the reach to adjust. As a result, no adjustments to routing coefficients were made. In order to improve the timing of the peak discharges, Pomme de Terre reservoir outflows were shifted a day earlier (-24 hours) to better align with USGS datasets downstream. The resulting local flows had significantly improved timing and fewer negative local flows.

5.1.7 CP14 (Reach from Stateline, Caplinger Mills, and Hermitage to Harry S. Truman)

The original parameters produced local flows with minimal negatives. However, the timing of the simulated flows appears to be about a day later (+24 hours) than observed USGS flows. Thus, the routing coefficients were adjusted to improve timing and reduce negative values. Only two routing reaches had parameters available to adjust. Routing coefficients for the reach between MKSL and the Sac River confluence were adjusted to 0.2, 0.4, 0.3, and 0.1 for the four time steps. Routing coefficients for the reach between CPMO and the Sac River confluence were not adjusted. With the adjusted parameters, the flows had smaller magnitude negative values with the exception of the October 2018 event. However, continued routing coefficient adjustment would not prove beneficial as the hydrograph shape was completely different than the simulated shape (Figure 3).

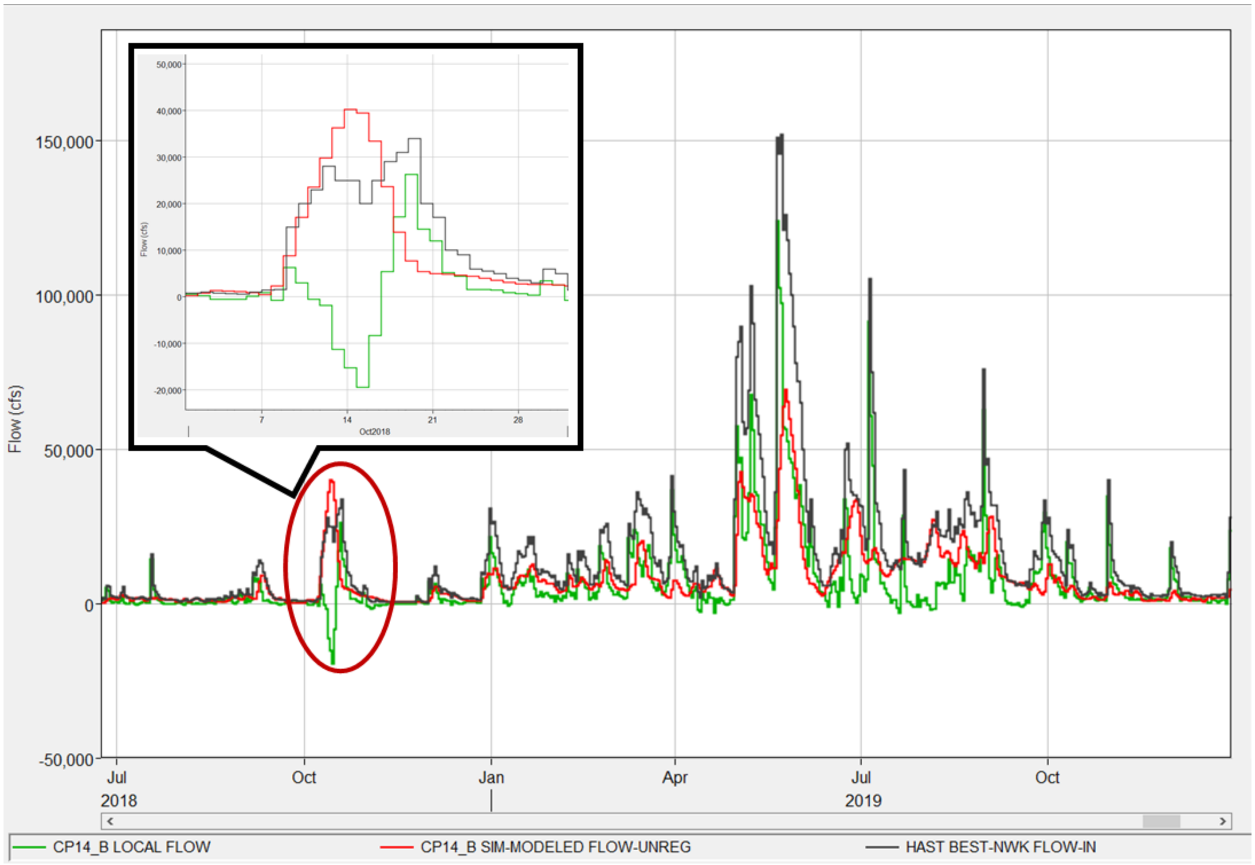


Figure 3. Computed Local Flows at CP14 from July 2018 to December 2019

5.1.8 CP16 (Osage River Reach from Harry S. Truman to Lake of the Ozarks)

The initial default parameters of 0.85 and 0.15 produced several negatives and the timing of the peak flows appeared to be a day later (+24 hours) than the observed peaks. In order to improve timing, the coefficient for the first time step was increased; however, there was no improvement in timing. Further eliminating all routing coefficients still did not improve timing. As a result, the original routing coefficients of 0.85 and 0.15 were maintained. In order to improve the timing of the peak discharges, Pomme de Terre reservoir outflows were shifted a day earlier (-24 hours) to better align with USGS datasets downstream. The resulting local flows had significantly improved timing and fewer negative local flows.

5.1.9 STTM (Osage River Reach from Lake of the Ozarks to St. Thomas)

Instead of using the EDH-C Lake of the Ozarks reservoir releases as the inflow dataset in the model, the USGS gage 06926000 Osage River near Bagnell, MO observed flows were used. This is because the routed flows using the USGS dataset better matched the observed timing of the downstream flows. Missing flows from the Bagnell, MO USGS flows were interpolated. Even with the improved results, the timing still appeared to be delayed. Parameter adjustments of the routing coefficients showed the smallest magnitude negative flows occurred with most of the flow routing occurring on the first day, then the second. As a result, the routing coefficients were adjusted to 0.4 and 0.6.

5.1.10 HEMO (Reach from Boonville and St Thomas to Hermann)

The default routing parameters of 0.1, 0.8, and 0.1 were used for both the Boonville to Osage confluence and the St. Thomas to Osage confluence reaches. With the default parameters, the timing appeared to reflect observed flows at Hermann, MO. However, there appeared to be an issue with one event in 2019 where the observed hydrograph shape was delayed (Figure 4).

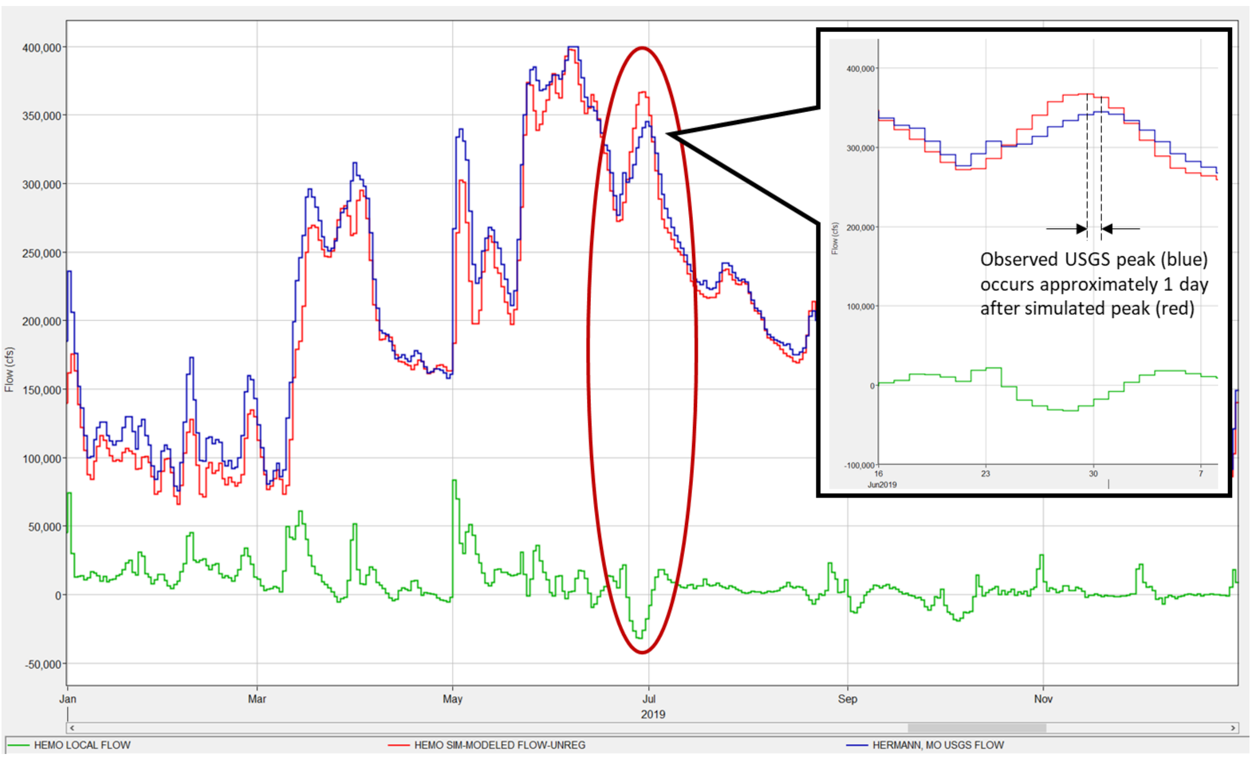


Figure 4. Hermann 2019 USGS, Simulated, and Computed Local Flows

Table 4 displays the final routing coefficients used for different reaches in the Osage HEC-ResSim model.

Table 4. Final Reach Routing Coefficients

Routing Reach	Routing Methodology	Time Step			
		1	2	3	4
Melvern - 110 mi Conf	Coefficient Routing	0.7	0.3	---	---
Pomona - 110 mi Conf	Coefficient Routing	0.98	0.02	---	---
110 mi Conf - PMNK	Null Routing	---	---	---	---
PMNK - OTTK	Coefficient Routing	0.7	0.3	---	---
OTTK - Big Bull Conf	Coefficient Routing	0.0	0.4	0.5	0.1
Hillsdale – Big Bull Conf	Coefficient Routing	0.3	0.3	0.3	0.1
Big Bull Cof - MKSL	Null Routing	---	---	---	---
MKSL - SacConf	Coefficient Routing	0.2	0.4	0.3	0.1
Stockton - SHJM	Null Routing	---	---	---	---
SHJM - CPMO	Coefficient Routing	0.6	0.4	---	---
CPMO - SacConf	Coefficient Routing	0.5	0.5	---	---
SacConf - Pomme Conf	Null Routing	---	---	---	---
Pomme de Terre - PDT1	Null Routing	---	---	---	---
PDT1 - Pomme Conf	Null Routing	---	---	---	---
Pomme Conf - CP14	Null Routing	---	---	---	---
Harry S. Truman - CP16	Coefficient Routing	0.85	0.15	---	---
Lake of the Ozarks - STTM	Coefficient Routing	0.4	0.6	---	---
STTM - Osage Conf	Coefficient Routing	0.1	0.8	0.1	---
BNMO - Osage Conf	Coefficient Routing	0.1	0.8	0.1	---
Osage Conf - HEMO	Null Routing	---	---	---	---

5.2 Ungaged Local Flow Manipulation

After the routing adjustments were made, the raw ungaged local inflow datasets from 2013 to 2019 were entered into an excel spreadsheet to smooth the influence of the negative local flows. The spreadsheet (called "LocalFlow.xlsx") required the raw local flow and the modeled flow after the initial routing at each location (i.e., $MKSL_{local}$ and $MKSL_{model}$ from the raw local flow equation).

5.2.1 Blending

Raw local flow was spit into positive and negative values. Then, the negative values were blended using a running average of between 3 and 7 days. The length of the running average depended on the number and magnitudes of the negative values. Those blended negative values were then summed with the positive values to obtain a blended local flow.

5.2.2 Apportioning

After calculating a blended local flow, that flow could be added to the modeled flow to obtain a blended total flow at each location. A small percentage of flow from positive values could be skimmed from the time series and distributed in the negative values to reduce any remaining negatives further. The percentage of flow was adjusted such that no negative flows remained, and the adjusted volume was within 1% of the original local flow dataset volume. This percentage was very small, with the largest percentage of 1.79% occurring at Hermitage, MO. This is largely attributed to null routing methodology used in the reach between Pomme de Terre Lake and Hermitage. Due to the null routing methodology, routing parameter adjustments could not be used to improve peak timing and reduce negative values. Similar results were observed at Highway J where null routing methodology was applied to the reach between Stockton Lake and Highway J. At Highway J, 1.74% of the positive values were skimmed from the time series and redistributed. At all other gages, less than 0.15% of positive flow was necessary to account for negative flows.

The apportioned and blended flows were added together to create a final local flow time series. Negatives still existed within the local flow datasets; however, negatives should not be present when combined with the routed flows. The developed raw local flow and final local flow time series from 2013 to 2019 are plotted together in Attachment A at Pomona, Ottawa, Stateline, Highway J, Caplinger Mills, Hermitage, CP14 (Truman Inflow), CP16 (Lake of the Ozarks Inflow), St. Thomas, and Hermann.

6. HEC-ResSim POR Simulations

This project utilized the same model parameters that were developed in the Missouri River Recovery Program HEC-ResSim model, with some changes to the rule set and alternatives, and slight changes to the coefficients for some routing reaches. The physical properties of all the Osage Basin dams and outlet works remained unchanged unless otherwise specified.

6.1 Input Parameters

The final POR simulations utilized the observed daily flows, evaporation, reservoir inflows, reservoir discharges, and power generation datasets described under the “Data Sources and Development” section of this report with the exception of Boonville (BNMO) flows. Instead of using USGS observed Missouri River flows at Boonville, the HEC-ResSim routed regulated flows (dated 02 Sep 2021) were used as Missouri River inflows into the Osage HEC-ResSim model. Additionally, the adjusted local flows described in “Ungaged Local Inflow Computations” were added as ungaged local inflows.

6.2 Routing Parameters

The same routing methodology and parameters used to adjust the local flow routings (provided in Table 4) were used in the final POR simulations.

6.3 HEC-ResSim Rules

The rule sets used in developing the regulated flows were copies of the rule set developed in the existing HEC-ResSim model simulation called "PT_ST-BC". The following operation sets were used for Melvern, Pomona, Hillsdale, Stockton, Pomme de Terre, Harry S. Truman, and Lake of the Ozarks reservoirs: Melvern Water Control Manual (WCM), Pomona WCM, Hillsdale WCM, STON-BC, PDT-BC, Harry S. Truman WCM, and Simulated Operation for Melvern, Pomona, Hillsdale, Stockton, Pomme de Terre, Harry S. Truman, and Lake of the Ozarks reservoirs, respectively. A water management evaluation of the rule sets and the WCMs found four discrepancies between the operation sets and the WCMs. As a result, the rules were adjusted. The following sections discuss the rule adjustments in detail.

6.3.1 Stockton

The Stockton rule set appeared to work well. The Springfield water supply was set to a flow of 46.42 cfs which was the maximum release allocated to Springfield; however, the flow is usually much smaller. More accurate simulations should use an average flow. Additionally, the Stockton TriState Outlet was erroneously flowing at times of high pool elevations. As a result, a small change was made to restrict flow from the Stockton TriState Canal that was in the proposal stage as of July 2021. The change adjusted the controlled composite release capacity from 48 cfs to 0 cfs. Additionally, the max capacity of the TriState Outlet was decreased from 48 cfs to 0 cfs.

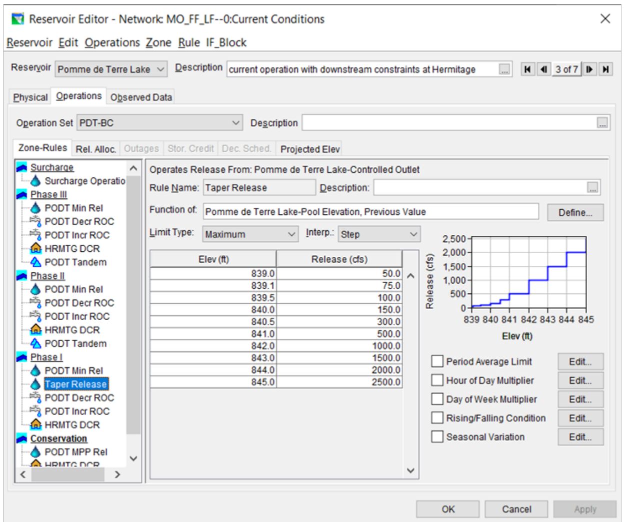
6.3.2 Pomme de Terre

Pomme De Terre Reservoir has a "Taper Release" rule in the Phase I storage zone that was adjusted to allow more release in the lower portions of Phase I. Table and Figure 5 display the rule changes. Additionally, higher releases in the lower portion of the multipurpose pool allowed the flood storage to empty consistent flow was present. Figure 6 displays the impacts of the "Taper Release" rule adjustments on the Pomme de Terre elevations and releases.

Table 5. Adjusted Pomme de Terre Phase I Storage Zone "Taper Release" Rule Steps

Elevation (ft)	Release (cfs)
839	500
841	750
842	1,000
843	1,500
844	2,000
845	2,500

Original Rule Parameters



Adjusted Rule Parameters

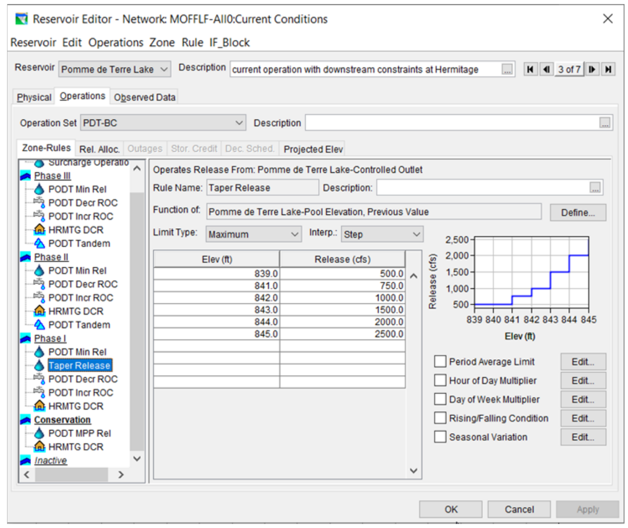


Figure 5. Pomme de Terre "Taper Release" Phase I Rule Adjustments

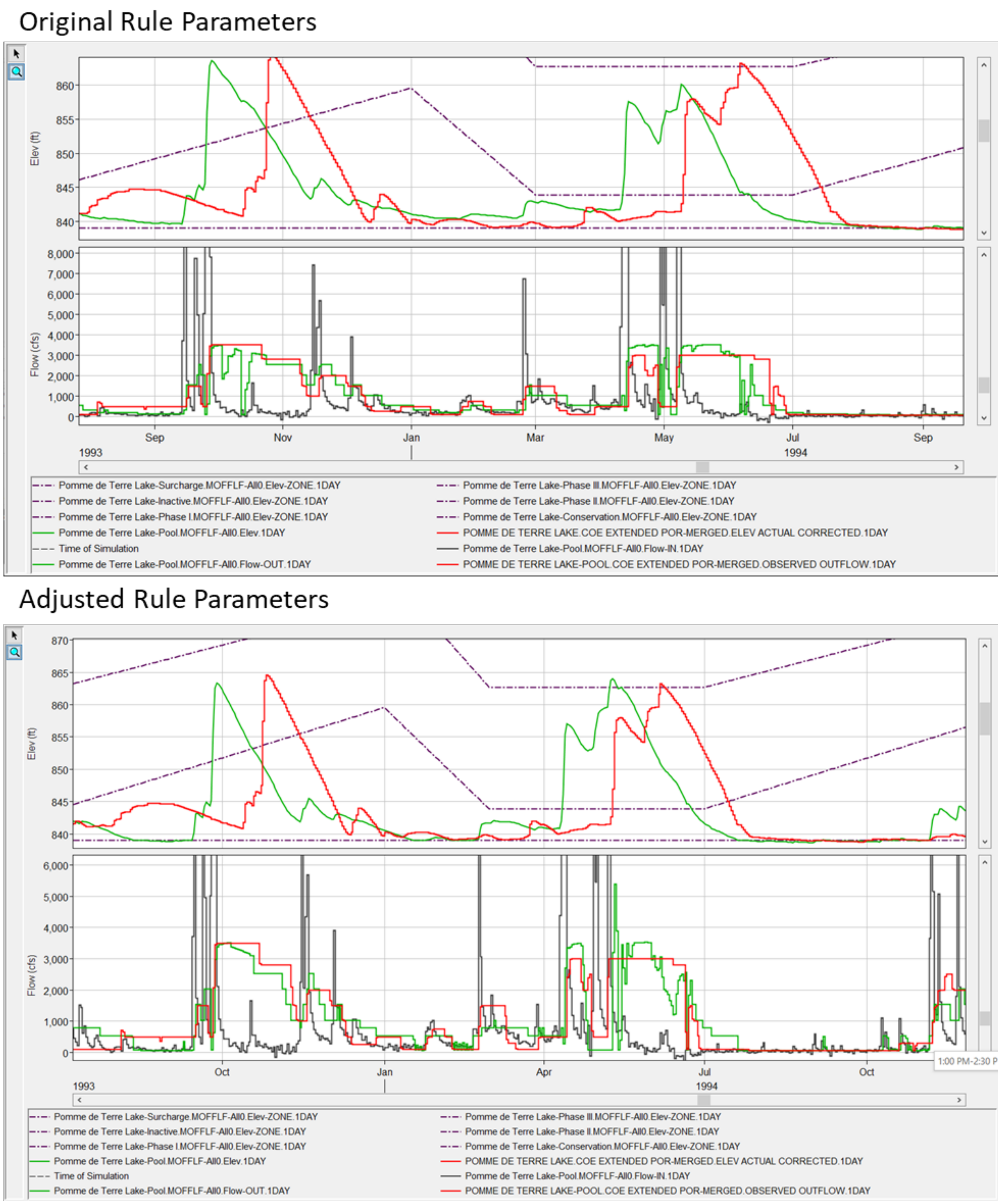


Figure 6. Winter 1994 Pomme de Terre Pool Elevation and Discharge Comparison with "Taper Release" rule adjustments

6.3.3 Harry S. Truman Reservoir

Several rules were adjusted to match the CWMS rules. This was done to improve the STTM criteria exceedance. First, the ranking of the rules under each phased release was adjusted such that the "All Phase STTM" releases received highest priority followed by "All Phase HEMO". All other rankings for Harry S. Truman reservoir remained the same.

Additionally, the maximum flow release in relation to STTM was changed to a maximum limit with step interpolation and the elevation and flows specified in Table 6. This rule applied to the Phase III, Phase II, Phase I, 707 Buffer, and Conservation storage zones.

Table 6. Harry S. Truman WCM Phase III "All Phase STTM" Zone-Rule Elevations and Flows

Elevation (ft)	Flow (cfs)
704.0	34,000
717.1	54,000
735.5	80,000

6.3.4 Lake of the Ozarks

An additional rule titled "BAGL Max" was added to the Top Flood Pool and Above Desired storage zones. This rule specified maximum releases such that during large floods, the Lake of the Ozarks did not release water exceeding the natural flow. The rule capped the release at the maximum inflow to try to approximate the natural flow calculation. The rule specified that Lake of the Ozarks was to release a portion of the inflow to account for some local runoff between Lake of the Ozarks and St. Thomas. Since the local flow drainage areas between Lake of the Ozarks and St. Thomas is approximately 4% of the Osage contributing drainage area at St. Thomas, Lake of the Ozarks was set to release 96% of the inflow. The rule established maximum discharges with linear interpolation. The flows and associated releases are provided in Table . This rule was ranked as the lowest priority with respect to other rules within the same storage zone.

Table 7. Lake of the Ozarks Simulated Operation "BAGL Max" Rule Flows and Releases

Flow (cfs)	Releases (cfs)
0	50,000
50,000	50,000
100,000	95,000
500,000	400,000

Additionally, the "All Phase HEMO" and "Phase II STTM" rules were removed from the Above Desired Zone, Guide Curve, and Below Desired Zone storage zones.

Finally, an additional rule was added to the Guide Curve storage zone. The rule titled "Watch STTM", set maximum releases for different phased releases depending on the downstream conditions at St. Thomas, Harry S. Truman pool elevations, and local flows. Table 8 summarizes the rules for each phase.

Table 8. Lake of the Ozarks "Watch STTM" Rules for Different Release Phases

Phase	Conditions	Max Release
Phase I	HAST pool elevation is greater than or equal to 706 ft and less than 717.1 ft, and Lake of the Ozarks local flows are greater than 10,000 cfs	34,000
Phase II	HAST pool elevation is greater than or equal to 717.1 ft and less than 735.5 ft, and Lake of the Ozarks local flows are less than 10,000 cfs	54,000
Phase III	HAST pool elevation is greater than or equal to 735.5 and Lake of the Ozarks local inflows are less than 10,000 cfs	80,000

6.4 Results and Discussion

With the rule adjustments in place, the HEC-ResSim routing was reviewed once more. It was noted that the adjustments to the reach routing parameters between "SHJM to CPMO" and "BAGL to STTM" sped up the routing process.

The Melvern, Pomona, and Hillsdale rules appeared to operate appropriately. In the rule set, tandem balance was not included in Phase I of the flood pools. This helped to keep normal Truman variations in pool elevation from causing rising pool elevations at the upper lakes. However, a real Phase I event at Truman would also require tandem operations at the upper lakes. Additionally, the PMNK, OTTK, and MKSL downstream control rules appeared to operate well for long term releases. Before an event, reservoirs often did not turn off in time and some water releases added to peak flows. This can occur in real-time operation as well. Figure 7 and Figure 8 provide an example of the operation in May and June of 2015. As seen in the figure, Pomona was in Phase I, approaching Phase II. Pomona then received an inflow event and the releases were increased to 4,000 cfs to pass as much of the inflow as possible. However, OTTK was above criteria and the release added to the peak flow for the event at OTTK (Figure 8). Conversely, in June when the reservoir is drawn down, the criteria was appropriately matched. Additional parameter adjustments could be made in the downstream control rule to better follow the rule such that the model ramps down releases a day earlier. No additional changes were made to the model.

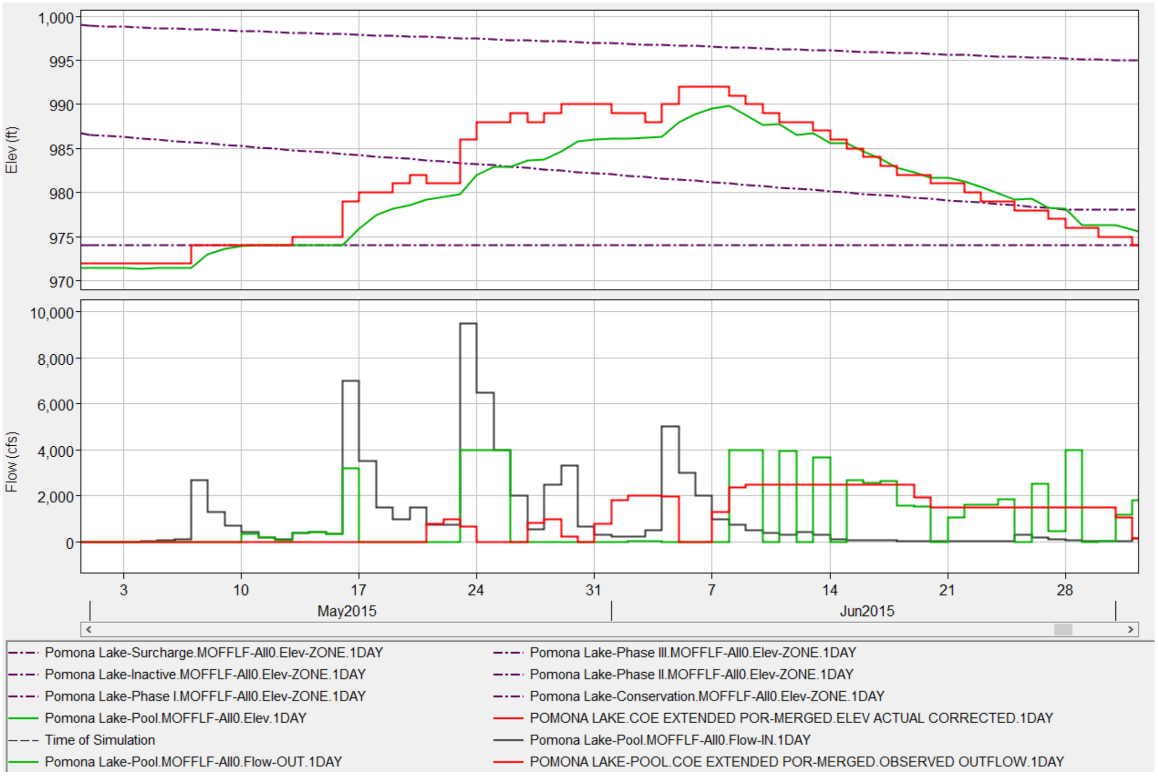


Figure 7. Pomona May and June 2015 Operations

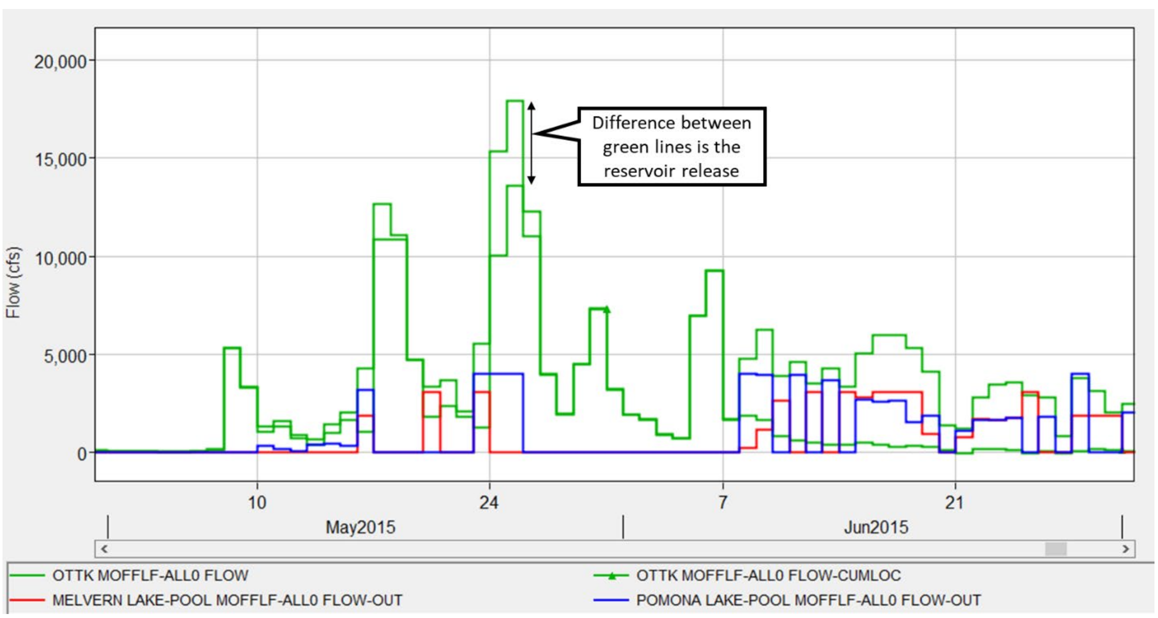


Figure 8. OTTK May and June 2015 Flows

No obvious errors appeared to be evident within the Stockton and Pomme de Terre operations once the rule adjustments described above were implemented.

Truman modeled inflows looked very similar to the CWMS inflows. Additionally, Truman releases appeared to work well in managing the flows at St. Thomas. The rule setup did not appear to allow small amounts of excess flow over criteria in certain situations. However, the rule adjustments discussed above appeared to improve overall simulations and met criteria. The Truman releases were set to keep STTM at target flows. With respect to STTM, Lake of the Ozarks primarily follows USACE targets at STTM. However, in real life, Lake of the Ozarks may make larger releases when they experience larger inflows.

The "All Phase HEMO" rule at Truman also appeared to work well. It appeared to reduce or shut off releases prematurely in order to account for travel time. The only visible error in the resulting time series occurred in 2019, as seen in Figure 9, where the rule shut off for a secondary, lower peak. The shutoff for the secondary peak did not occur as part of the real time operations. However, the error did not appear to impact Missouri River peak flows.

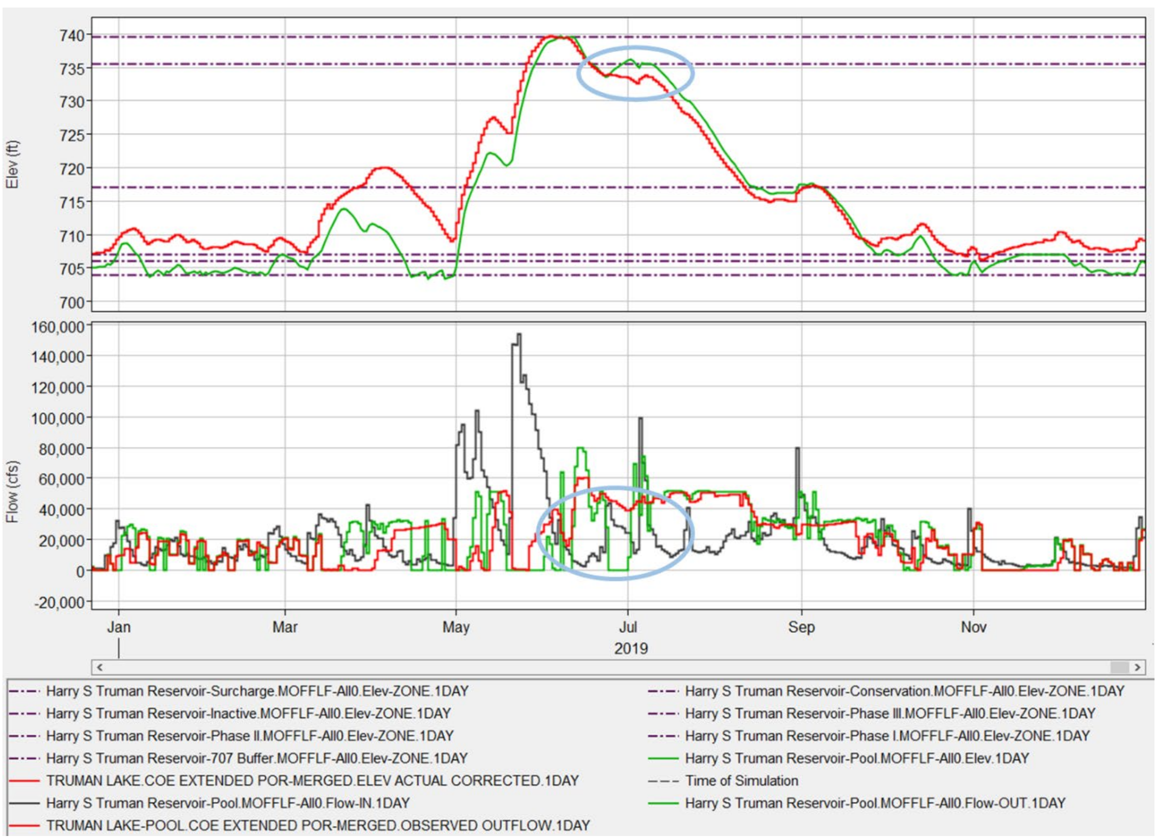


Figure 9. Harry S. Truman Pool Elevations and Flows during 2019

7. Conclusion

An existing HEC-ResSim model for the Osage River Basin from USACE NWK EDH-C was used to perform the analysis. Datasets were extended to run from January 1, 1928 through December 31, 2019 and the local flows were re-calculated with updated data. After a water management evaluation of the model, reservoir routing parameters were updated on two reaches. The reservoir operation sets at Harry S. Truman, Lake of the Ozarks, Pomme de Terre, and Stockton reservoirs were modified to better reflect WCM and CWMS model operations. After these updates, HEC-ResSim output for regulated flow at St. Thomas and ungaged local flows between Boonville, St. Thomas, and Hermann, MO were supplied for use in the Missouri River Flow Frequency Study. A plot of each of these outputs can be found in Attachment A.

Attachment A

1.1 Streamflow Data

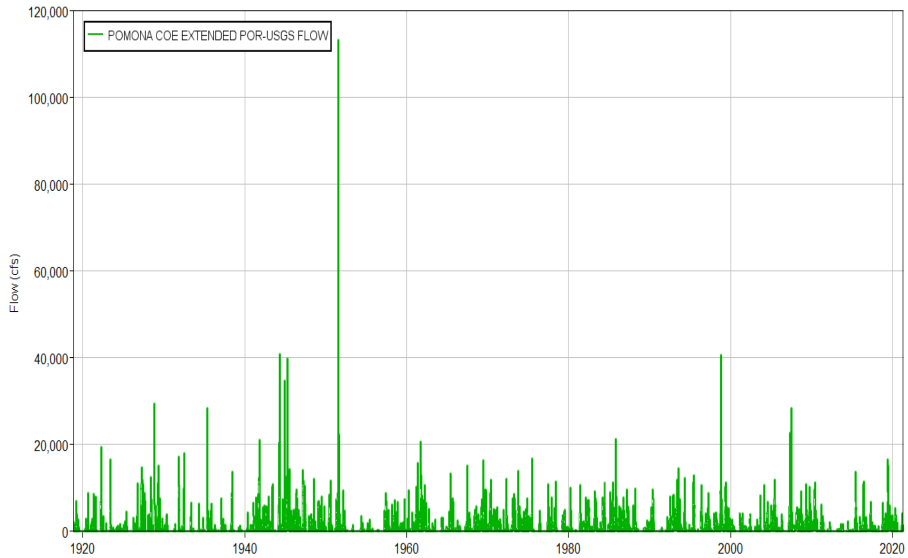


Figure 10. Marais des Cygnes River at Pomona, KS USGS and Historical Streamflow

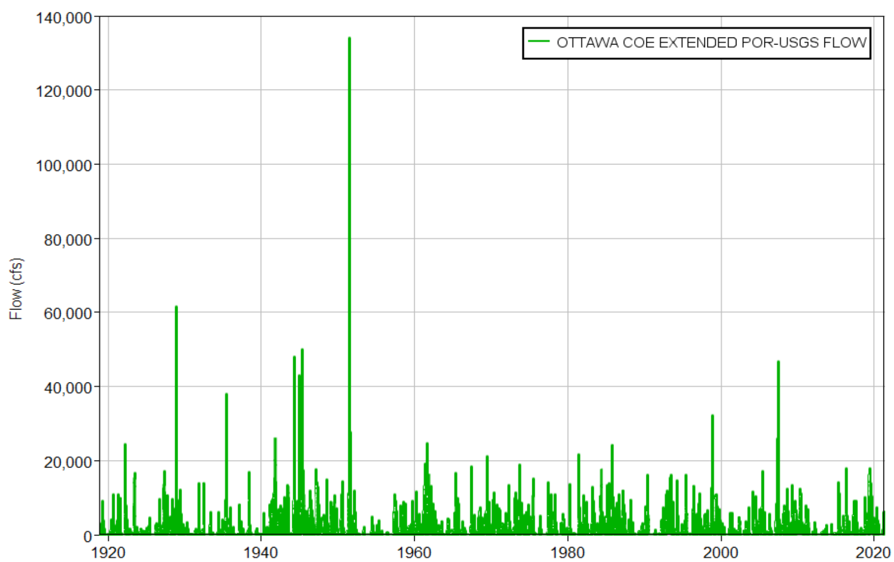


Figure 11. Marais des Cygnes River at Ottawa, KS USGS and Historical Streamflow

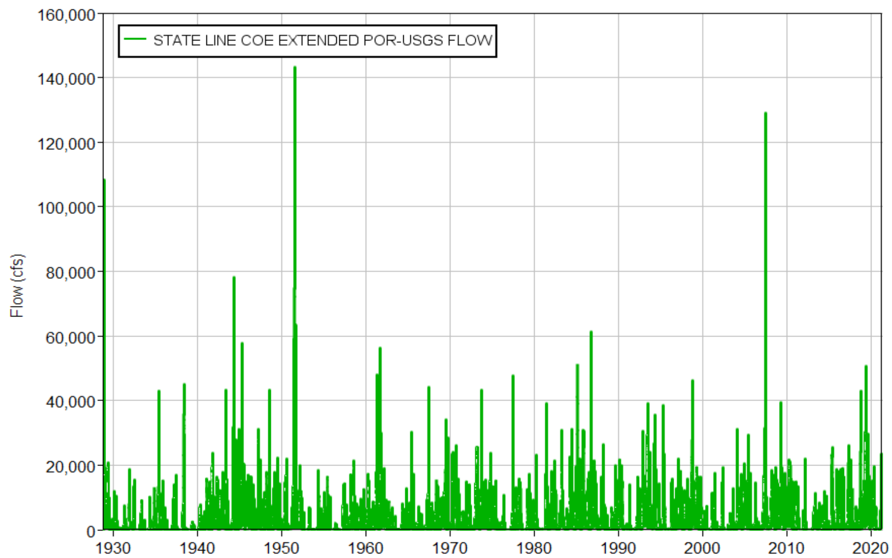


Figure 12. Marais des Cygnes River near the Kansas-Missouri State Line USGS and Historical Streamflow

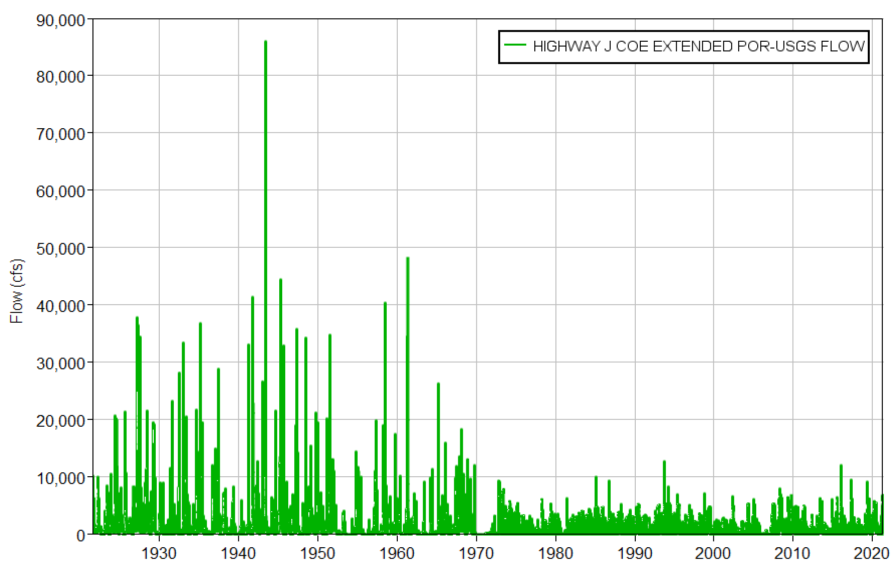


Figure 13. Sac River at Highway J below Stockton, MO USGS and Historical Streamflow

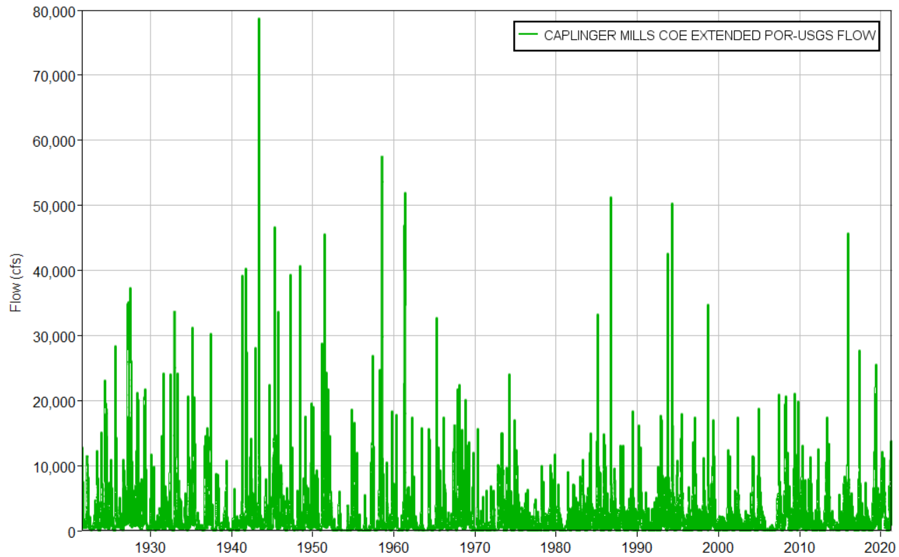


Figure 14. Sac River at Caplinger Mills, MO USGS and Historical Streamflow

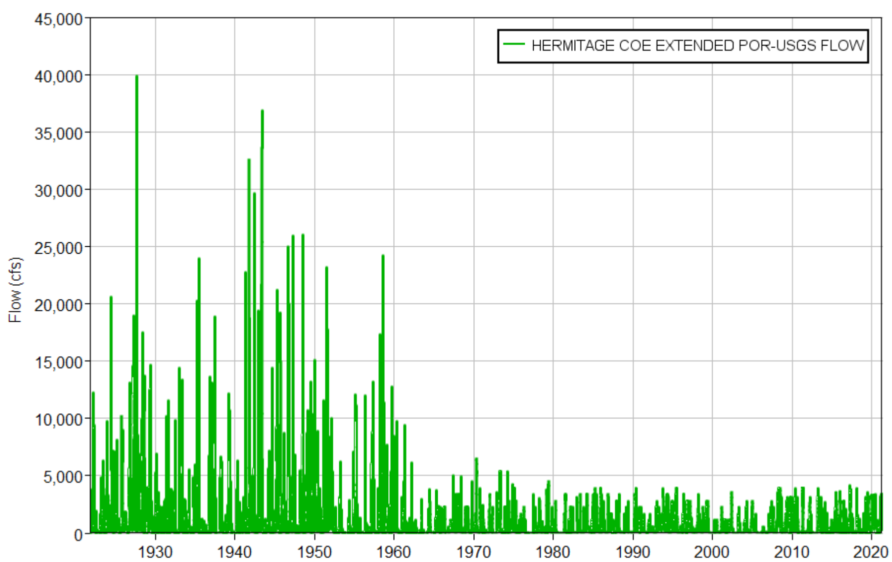


Figure 15. Pomme de Terre River near Hermitage, MO USGS and Historical Streamflow

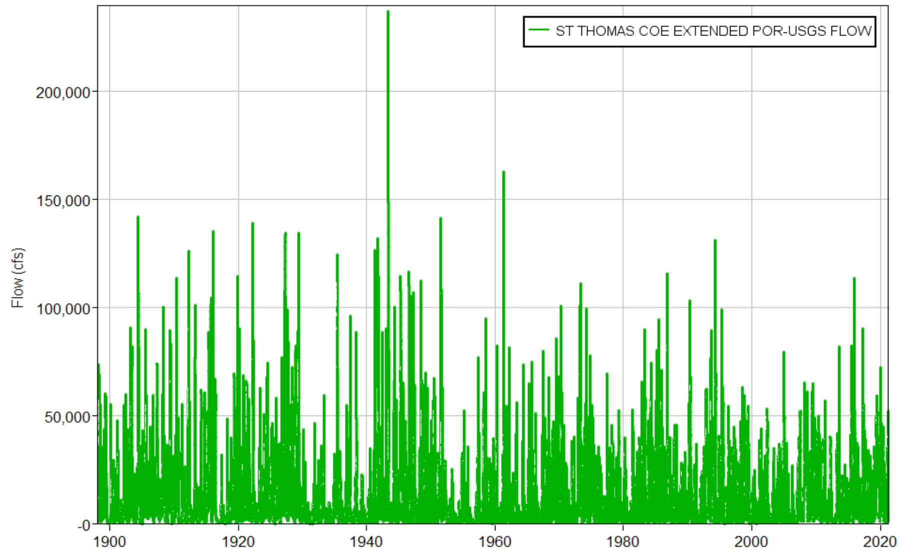


Figure 16. Osage River near St. Thomas, MO USGS and Historical Streamflow

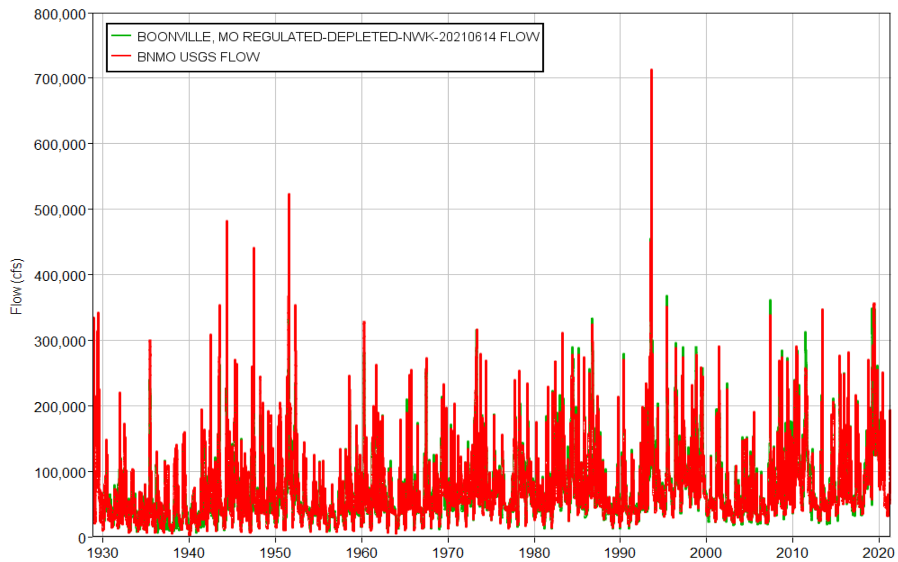


Figure 17. Missouri River at Boonville, MO NWK Simulated Streamflow with Depletions and USGS and Historical Streamflow

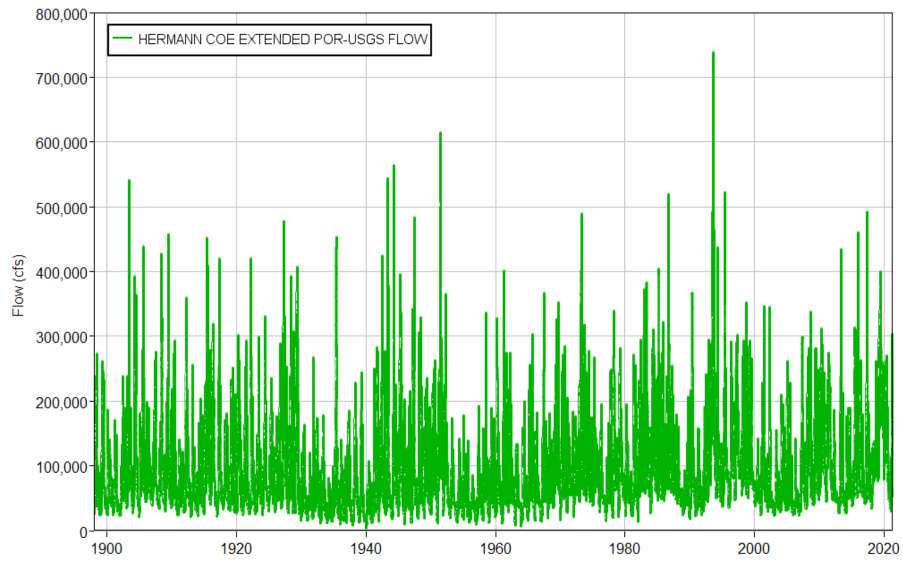


Figure 18. Missouri River at Hermann, MO USGS and Historical Streamflow

1.2 Reservoir Data

Melvern

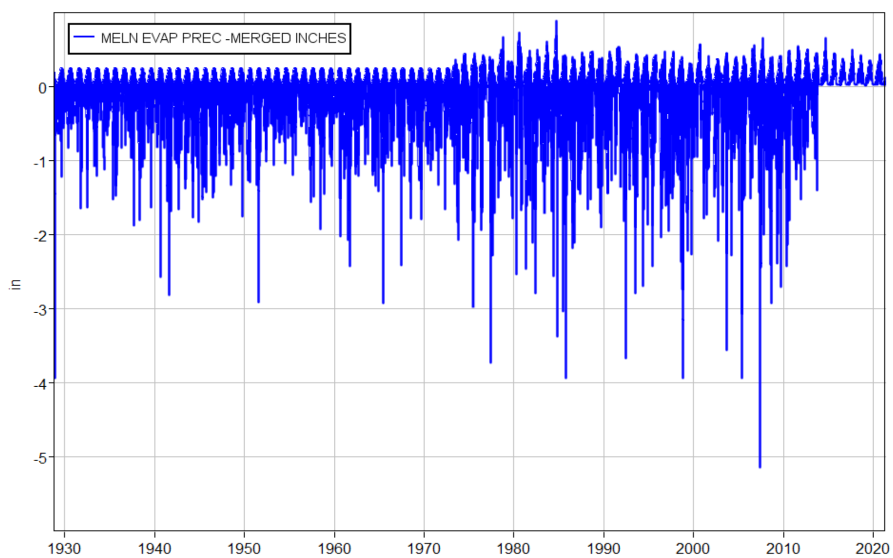


Figure 19. Melvern Combined Precipitation and Evaporation

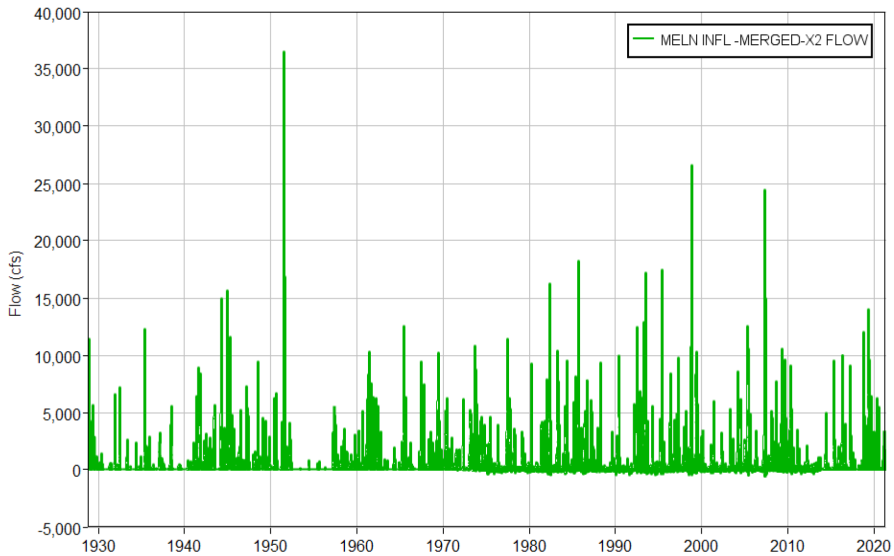


Figure 20. Melvern Reservoir Inflows

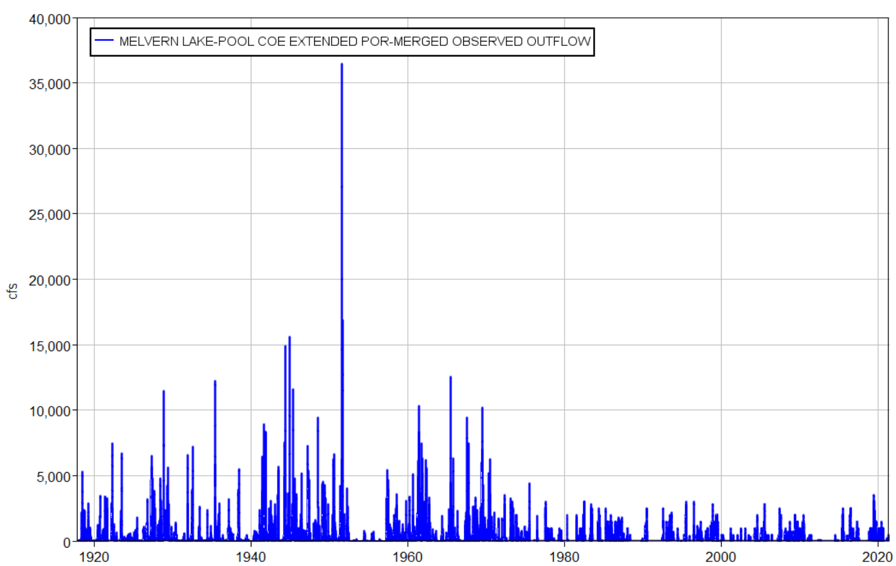


Figure 21. Melvern Reservoir Outflows

Pomona

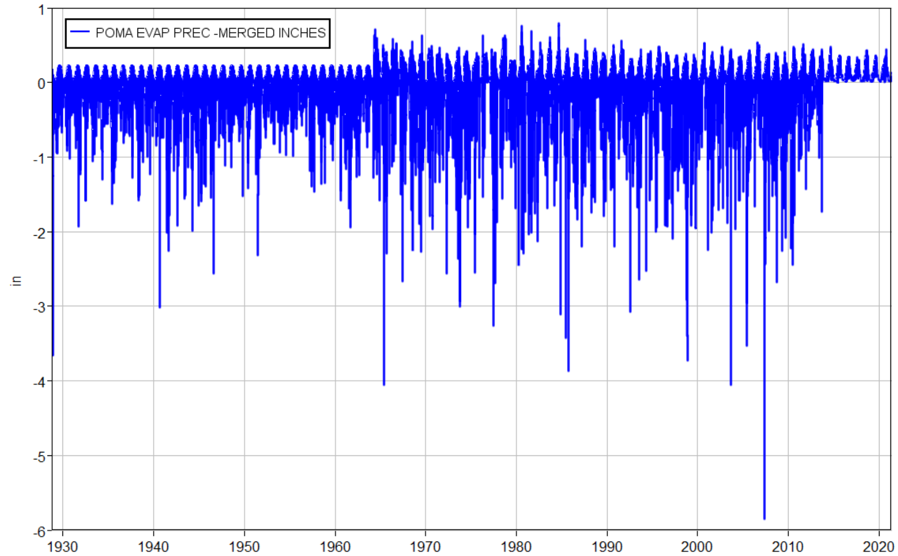


Figure 22. Pomona Combined Evaporation and Precipitation

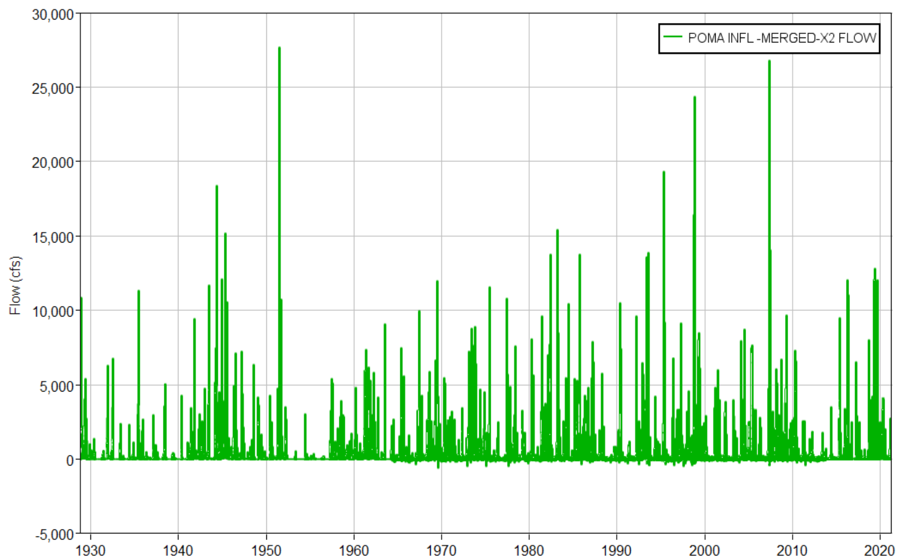


Figure 23. Pomona Reservoir Inflows

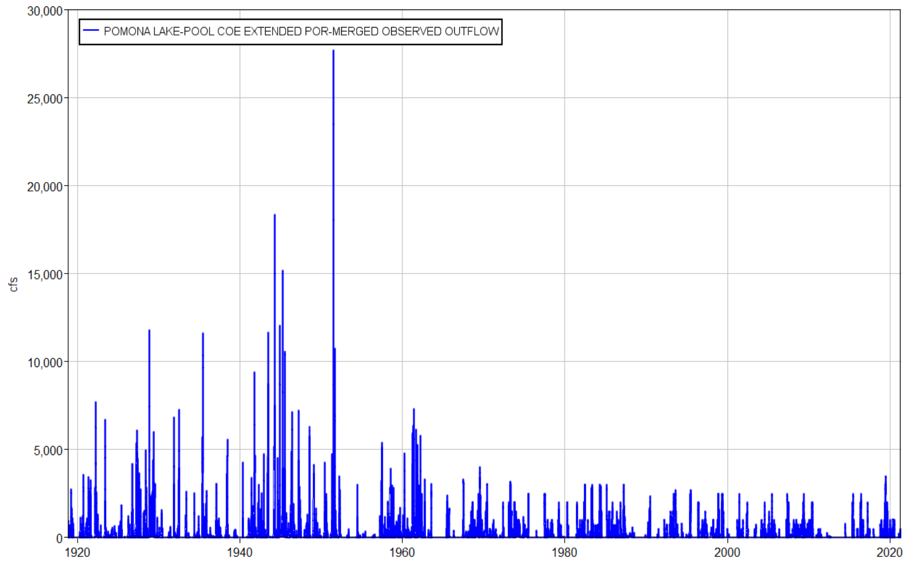


Figure 24. Pomona Reservoir Outflows

Hillsdale

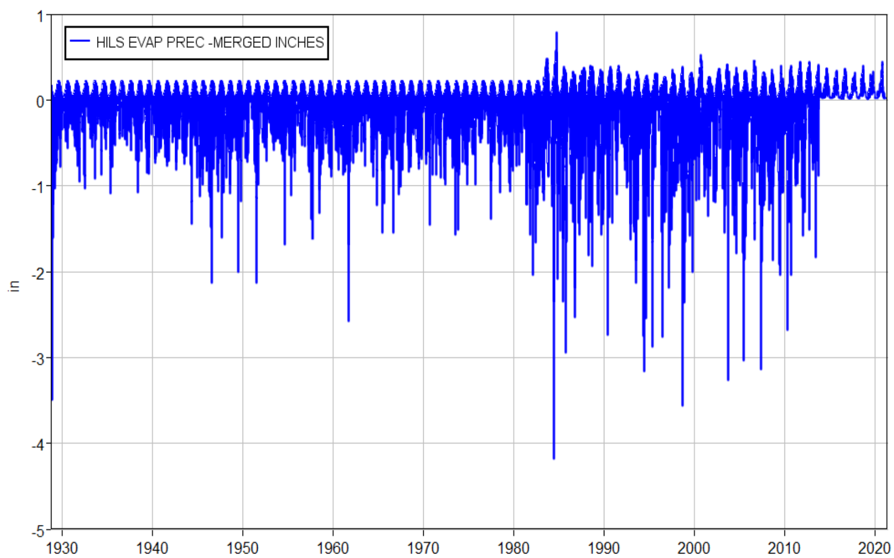


Figure 25. Hillsdale Combined Evaporation and Precipitation

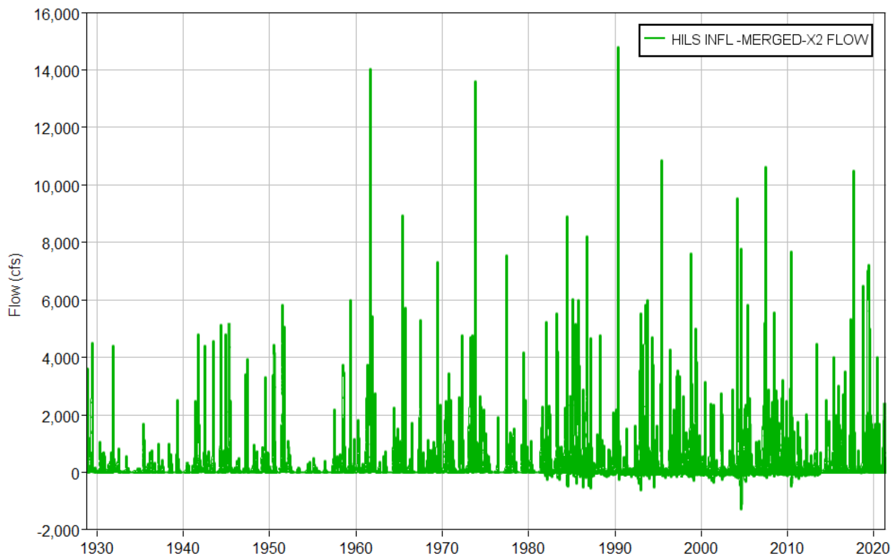


Figure 26. Hillsdale Reservoir Inflows

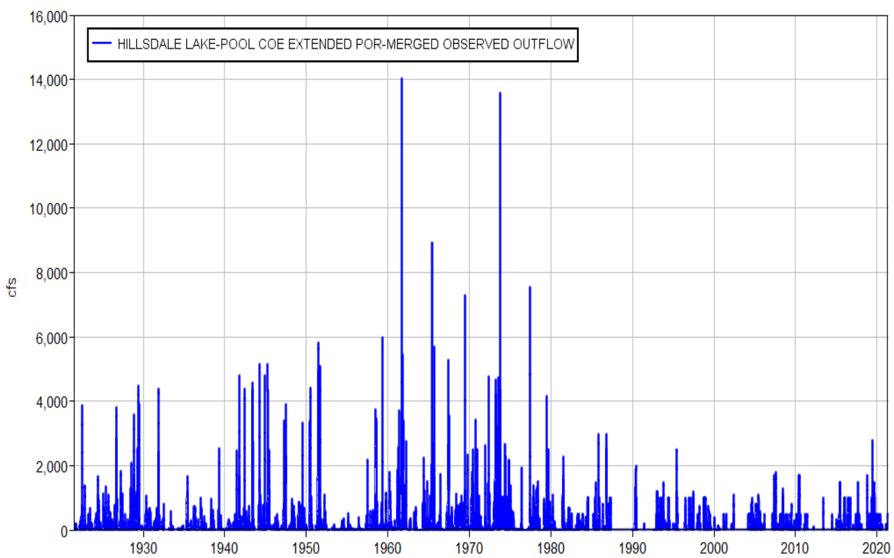


Figure 27. Hillsdale Reservoir Outflows

Stockton

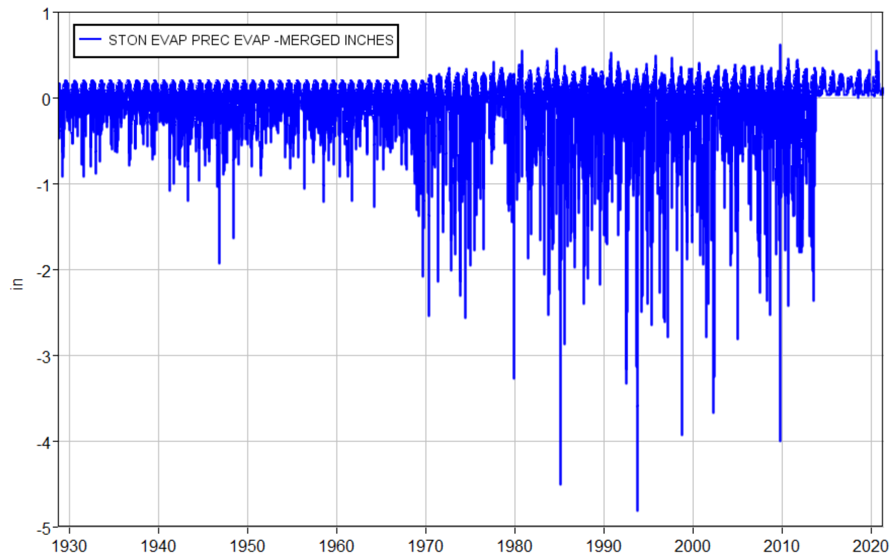


Figure 28. Stockton Combined Evaporation and Precipitation

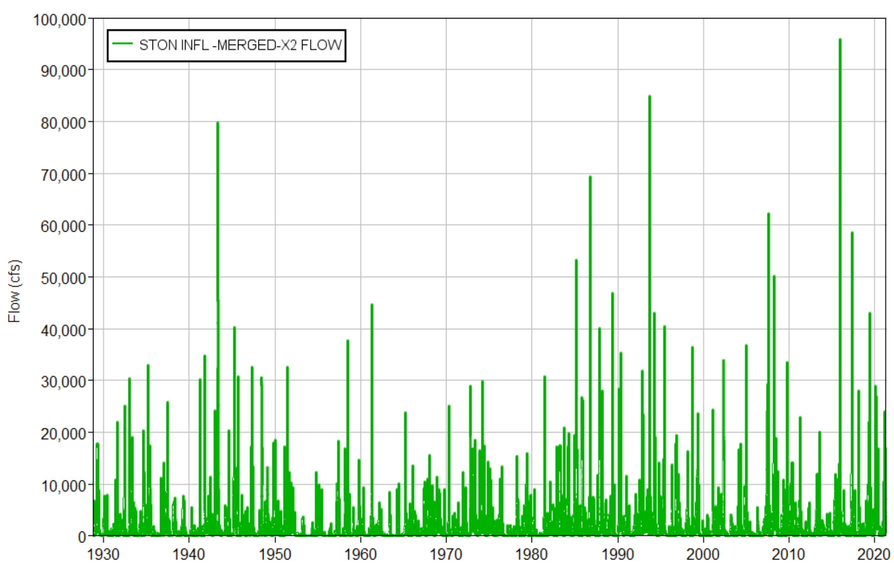


Figure 29. Stockton Reservoir Inflows

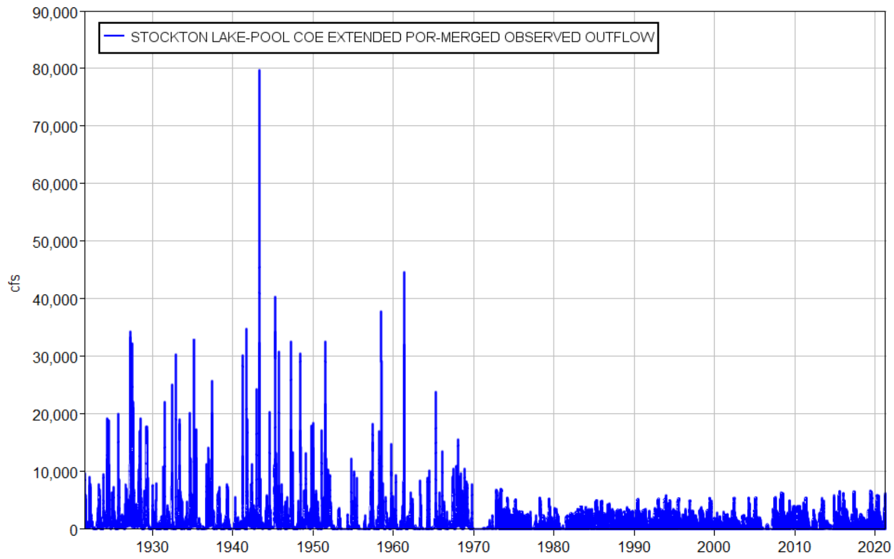


Figure 30. Stockton Reservoir Outflows

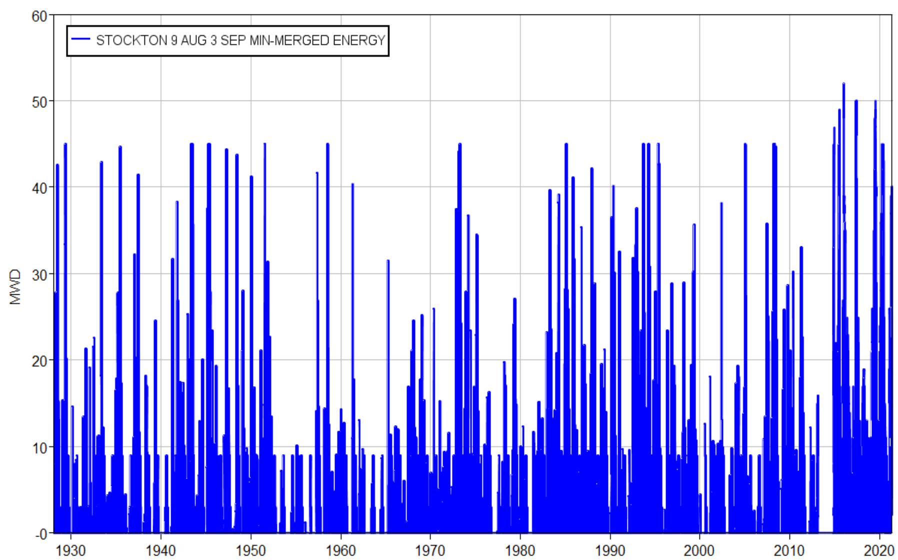


Figure 31. Stockton Energy Production in Megawatt Days

Pomme de Terre

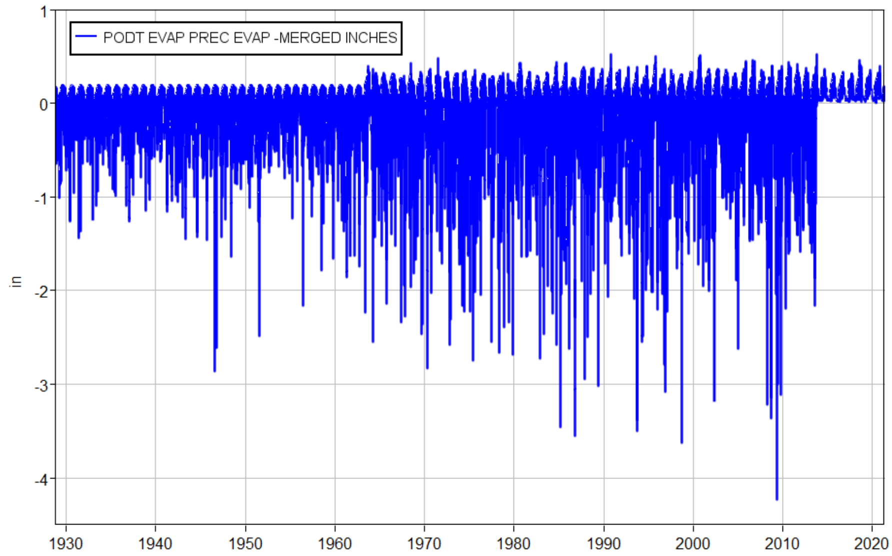


Figure 32. Pomme de Terre Combined Evaporation and Precipitation

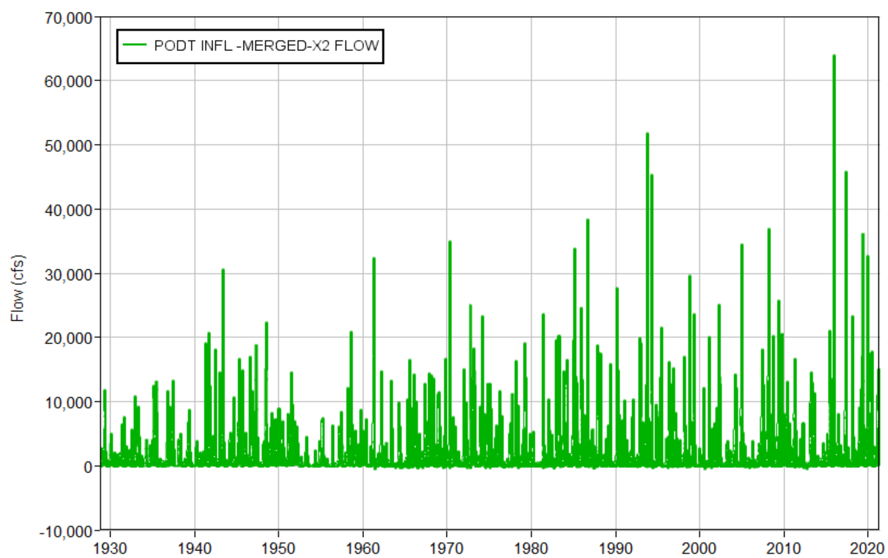


Figure 33. Pomme de Terre Reservoir Inflows

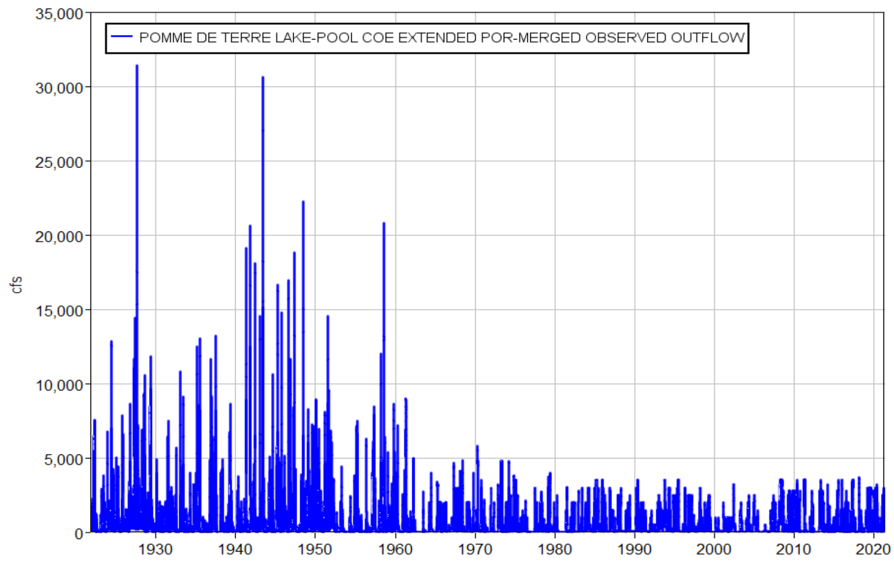
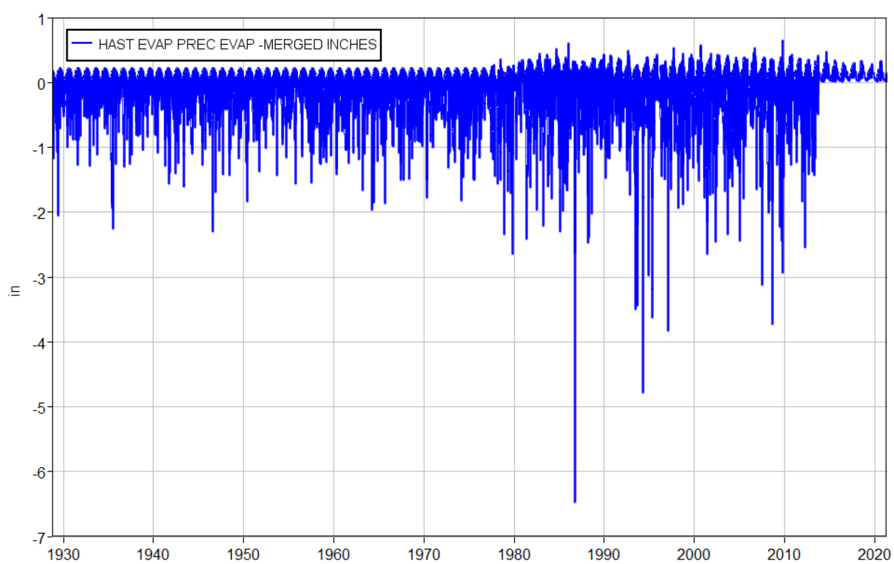


Figure 34. Pomme de Terre Reservoir Outflows

Harry S. Truman



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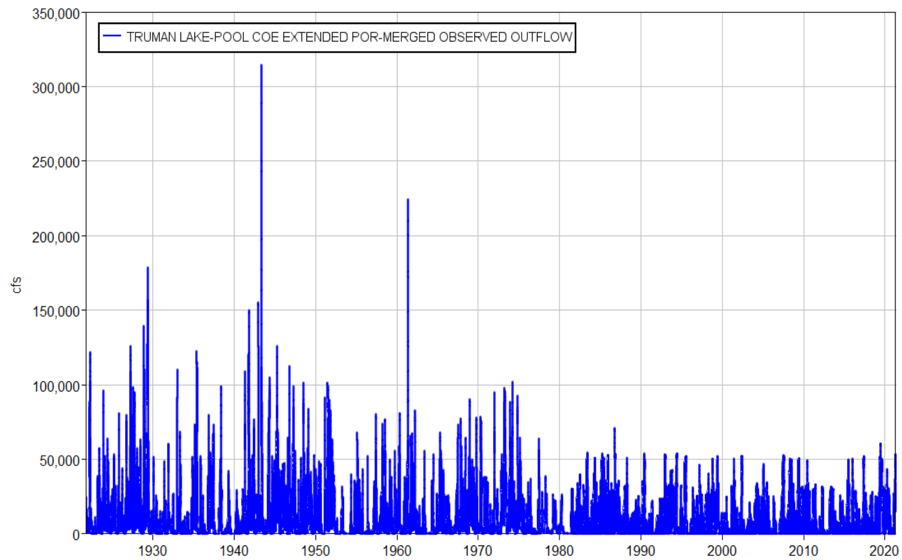


Figure 36. Harry S. Truman Reservoir Outflows

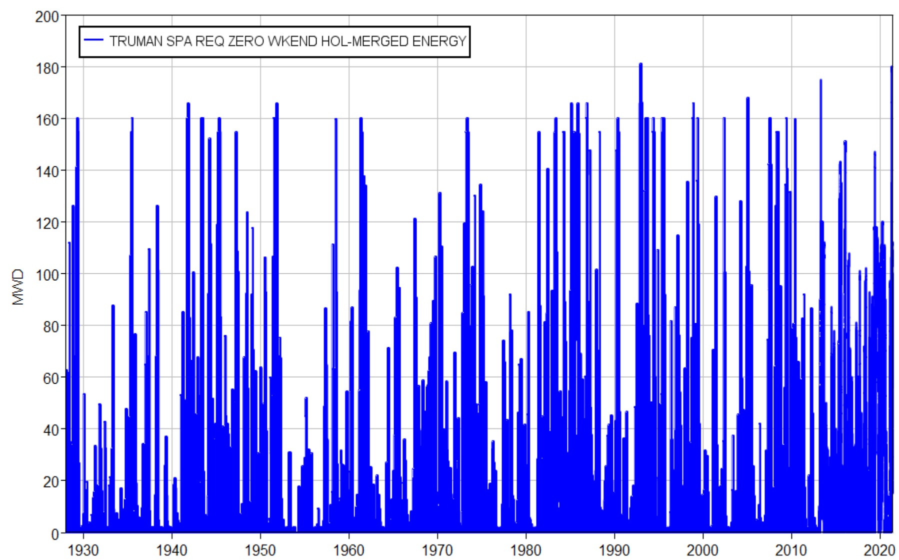


Figure 37. Harry S. Truman Energy Production in Megawatt Days

Lake of the Ozarks

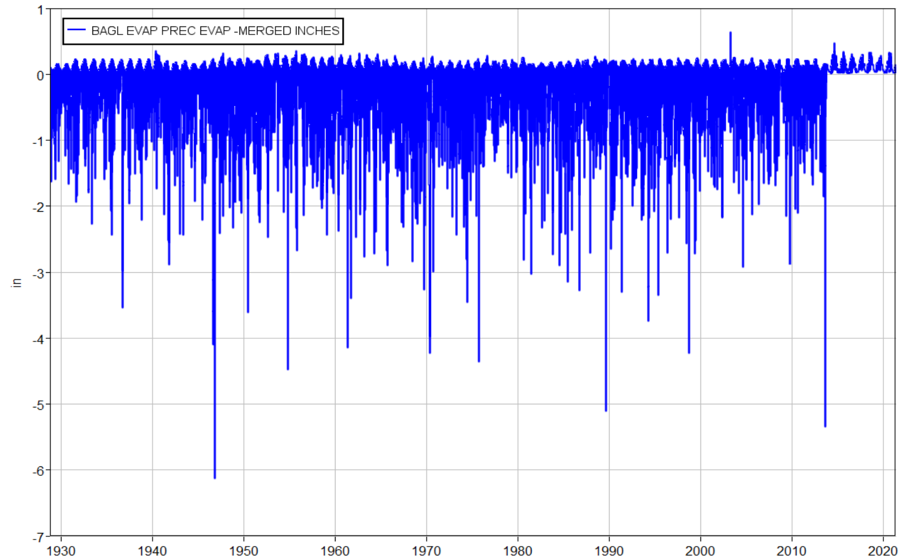


Figure 38. Lake of the Ozarks Combined Evaporation and Precipitation

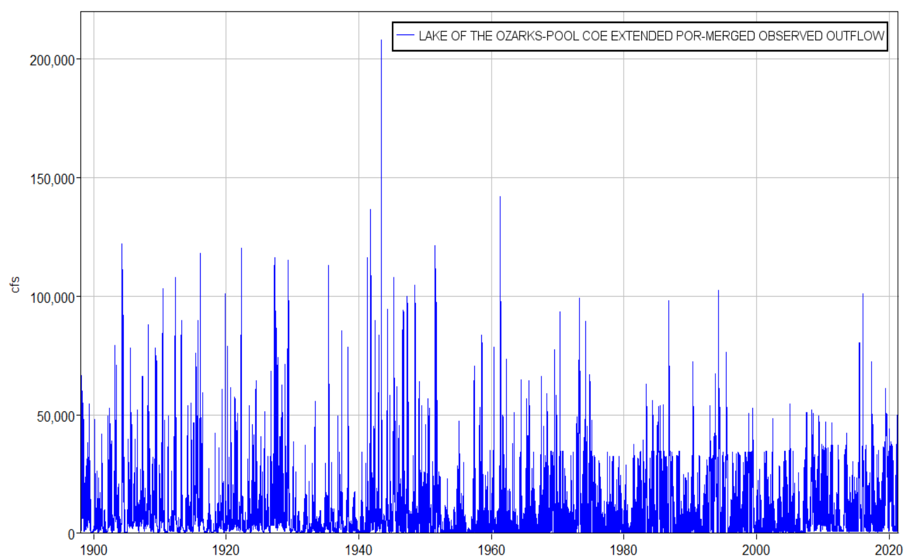


Figure 39. Lake of the Ozarks Reservoir Outflows

1.3 Local Flow Data

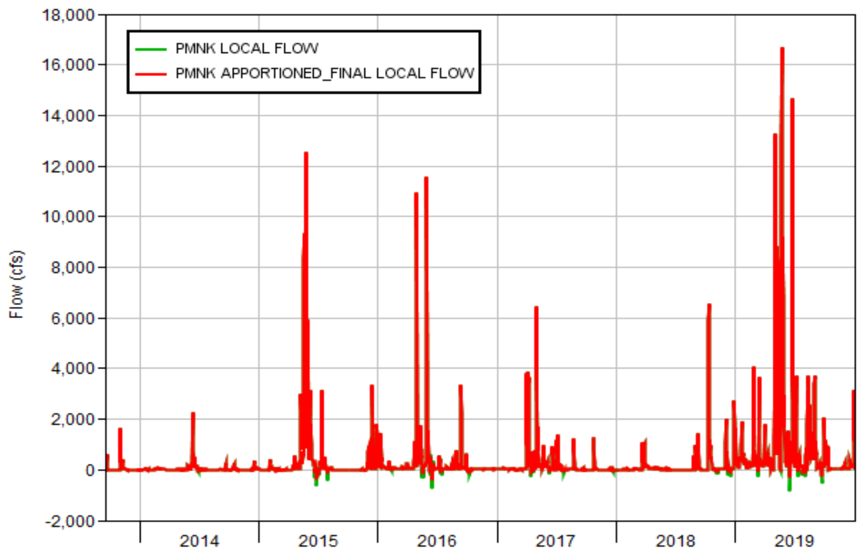


Figure 40. Raw Local Flow and Modified Local Flow at Marias De Cygnes River near Pomona, KS (PMNK)

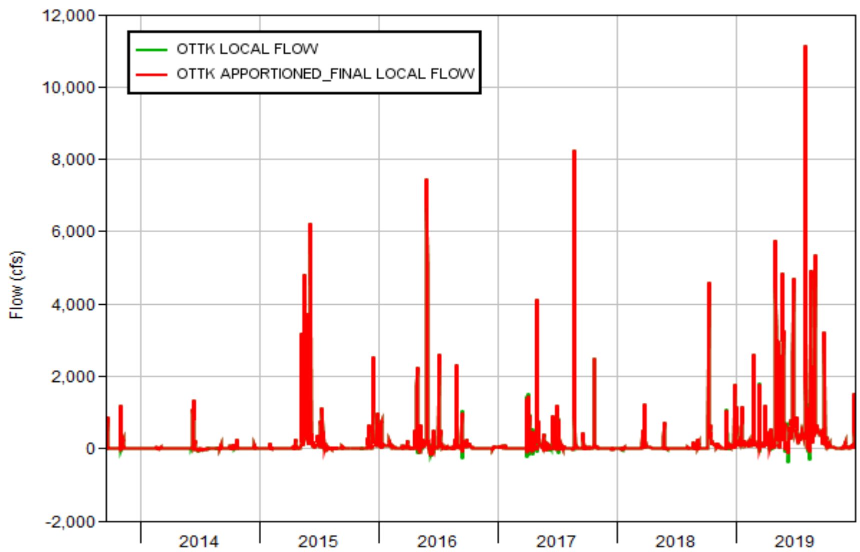
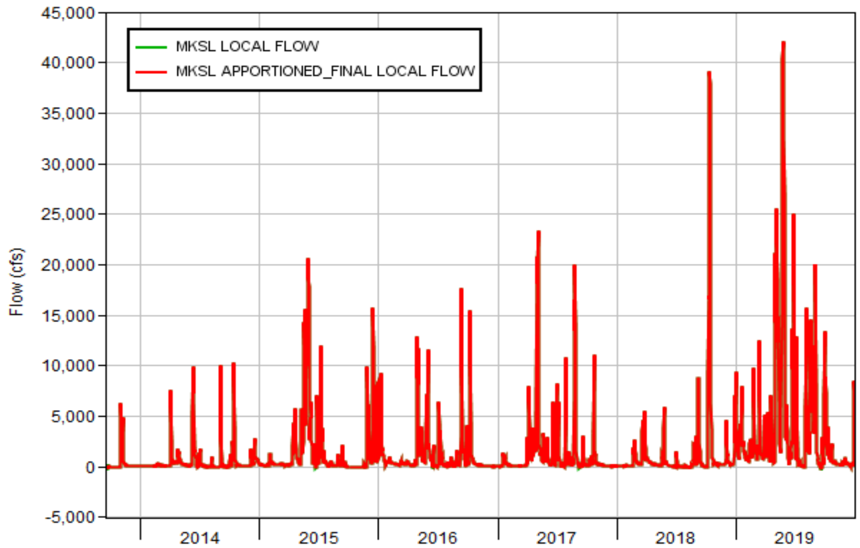


Figure 41. Raw Local Flow and Modified Local Flow at Marias De Cygnes River near Ottowa, KS (OTTK)



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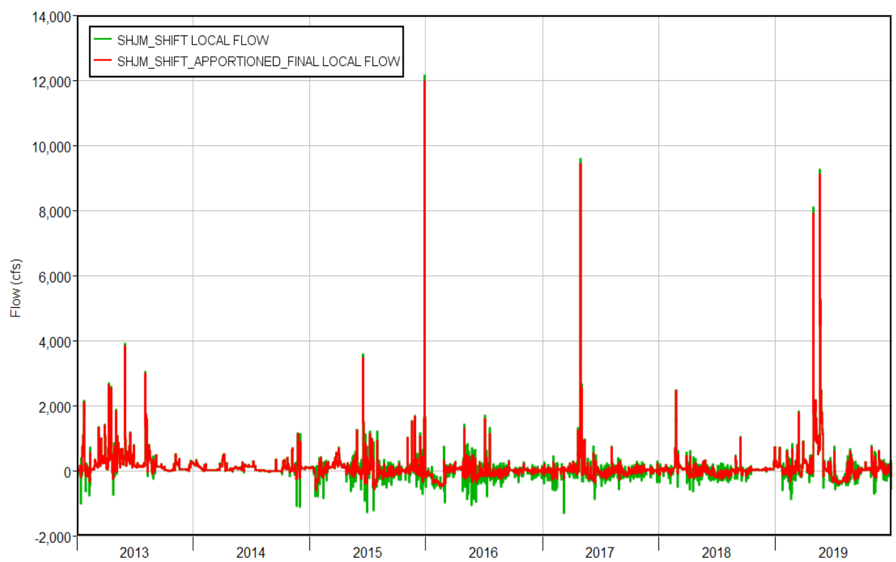

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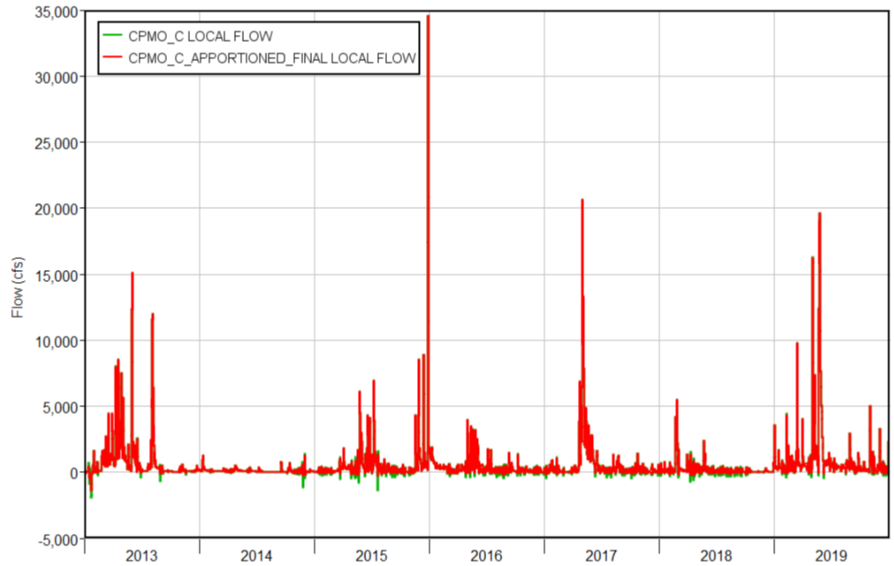

Figure 44. Raw Local Flow and Modified Local Flow at Caplinger Mills, MO (CPMO)

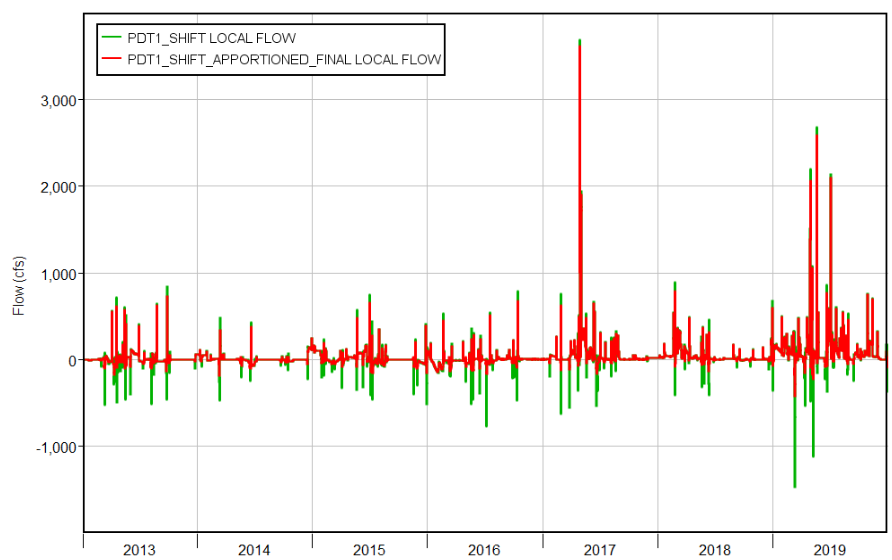

Figure 40. Raw Local Flow and Modified Local Flow at Hermitage, MO (PDT1)

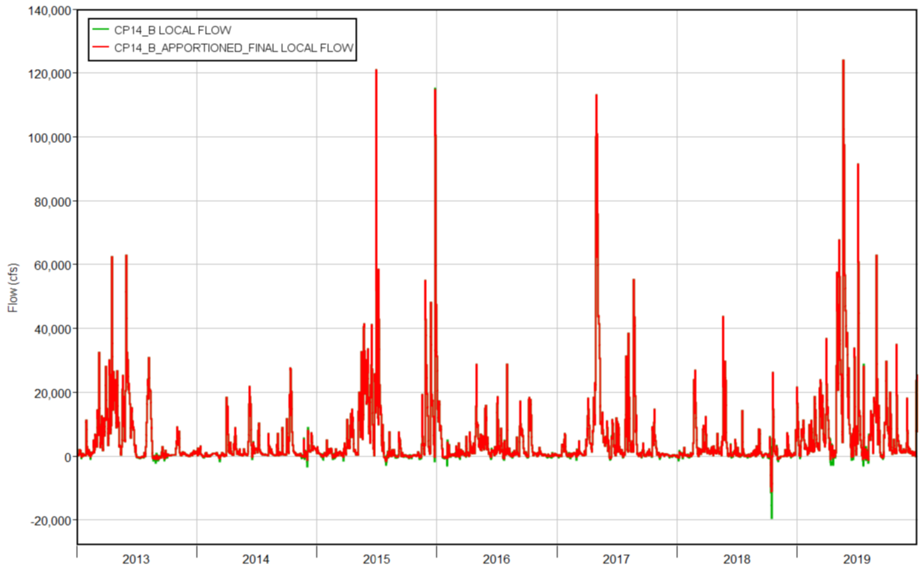

Figure 46. **Raw Local Flow and Modified Local Flow at Harry S. Truman Inflow Location (CP14)**

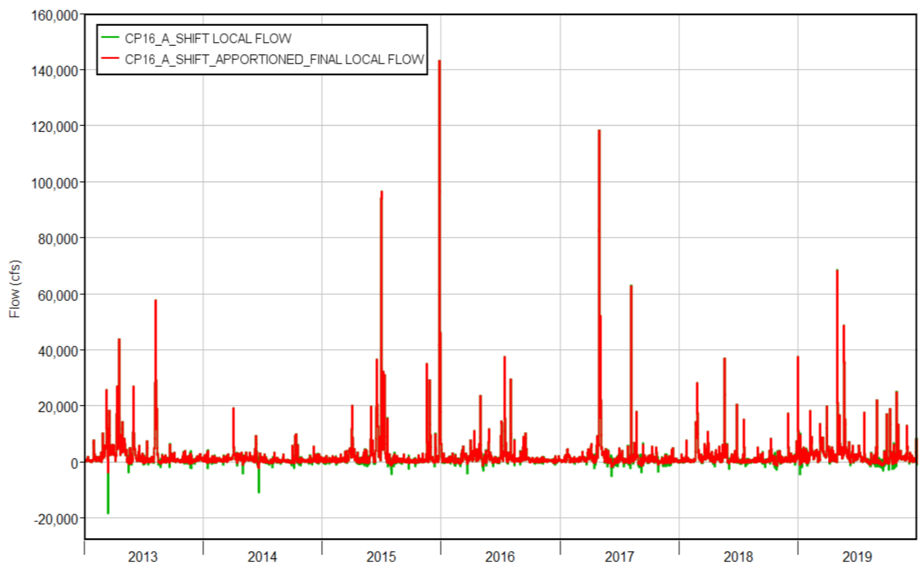

Figure 47. **Raw Local Flow and Modified Local Flow at Lake of the Ozarks Inflow Location (CP16)**

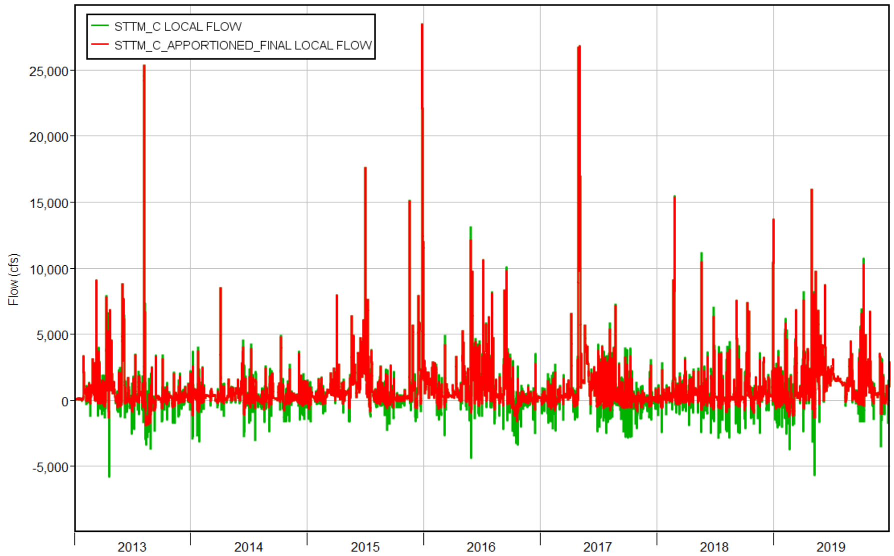

Figure 48. Raw Local Flow and Modified Local Flow St. Thomas, MO (STTM)

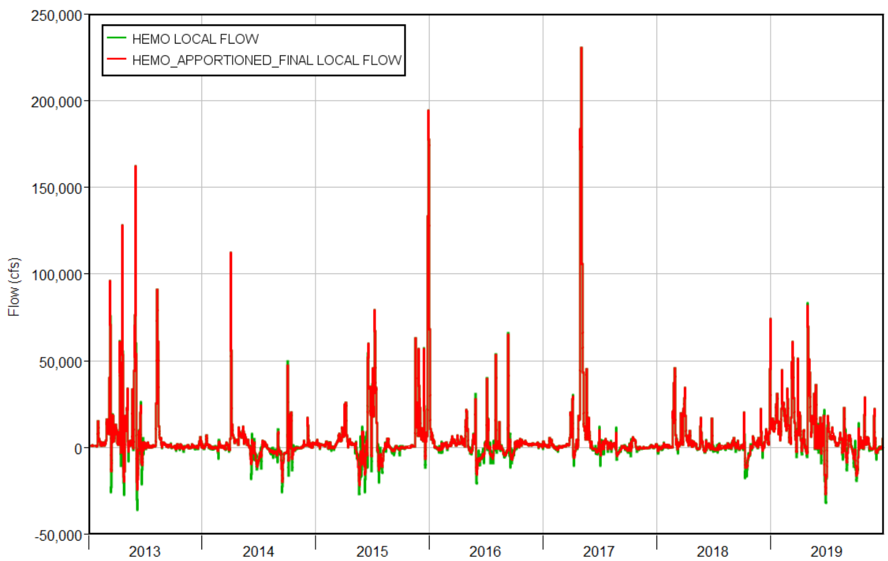

Figure 49. Raw Local Flow and Modified Local Flow at Hermann, MO (HEMO)

April 2021
USACE Kansas City District

Missouri River Flow Frequency Study – HEC-ResSim Modeling, Chariton River Basin, Tributary to the Missouri River

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Executive Summary

The following work is included as part of the Missouri River Flow Frequency Study. The overall project entails the update or development of models for the Missouri River and key tributaries.

For the Chariton River basin, an existing model was updated to reflect the current operation of the U.S. Army Corps of Engineers project on the Chariton River, Rathbun Dam. The reservoir operation set update was based on the 2016 Water Control Manual. Existing data sets were extended to cover the period of January 1, 1930 to December 31, 2019. Reservoir routing parameters were verified and changed if necessary. Updated local flows were created using the extended data set for use in the updated model simulation.

Necessary output from the model includes a complete regulated set of flows at the U.S. Geological Survey streamgage location at the Chariton River near Prairie Hill, MO, and the Rathbun Reservoir holdouts routed downstream to the USGS streamgage locations at the Chariton River near Prairie Hill, MO, and the Missouri River at Boonville, MO. Model output is available for use in the Missouri River Flow Frequency Study.

1. Introduction

The following work is included as part of the Missouri River Flow Frequency Study. The overall project entails the update or development of models for the Missouri River and key tributaries.

For the Chariton River basin, an existing model was updated to reflect the current operation of the U.S. Army Corps of Engineers (Corps) project on the Chariton River, Rathbun Dam. There are no other Corps projects in the Chariton River basin. Existing data sets were extended to cover the period of January 1, 1930 to December 31, 2019.

Necessary output from the model includes a complete regulated set of flows at the U.S. Geological Survey (USGS) streamgage location at the Chariton River near Prairie Hill, MO, and the Rathbun Reservoir holdouts routed downstream to the USGS streamgage locations at the Chariton River near Prairie Hill, MO, and the Missouri River at Boonville, MO.

2. Rathbun Lake

Rathbun Dam is owned and operated by the Corps and is located at mile 142.3 on the Chariton River. The Rathbun project was authorized by the Flood Control Act of 1954. Construction began in 1964 and dam closure occurred on September 29, 1967. Rathbun Dam and Reservoir is authorized for flood control, water supply, water quality, navigation, recreation, and fish and wildlife.

Rathbun Dam consists of two zoned rolled-earth embankments separated by high ground, both with a crest elevation of 946.0 feet. The reservoir capacity is approximately 939,000 acre-feet at an elevation of 940.0 feet, the top of the surcharge zone. Outlet works capacity at this elevation is 5,680 cfs, however maximum releases are held at 3,000 cfs to minimize the chance of the conduit becoming pressurized and protect downstream interests. The spillway capacity at the top of the surcharge zone is 45,600 cfs. Figure 1 below depicts current reservoir allocation zones and storage capacities of each zone.

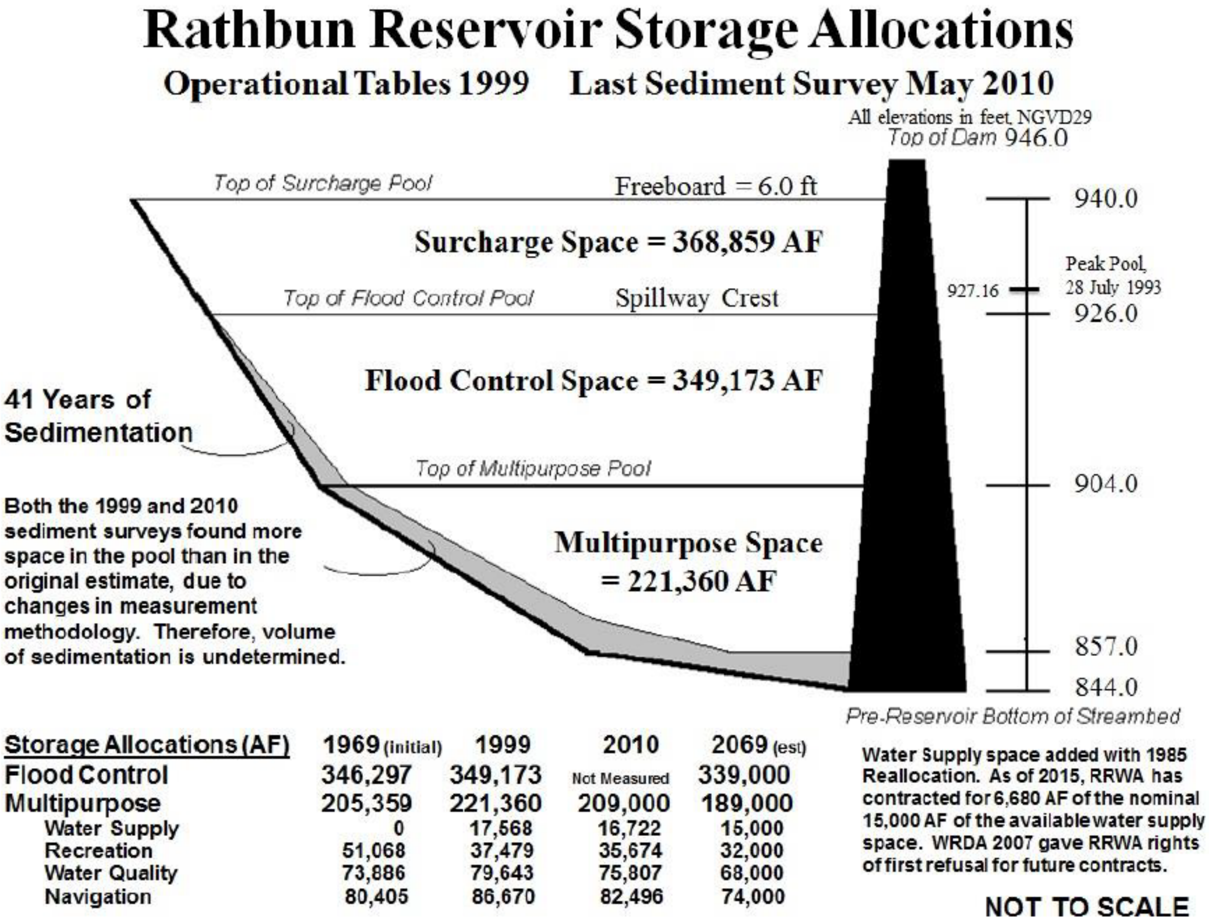

Figure 1. Reservoir Storage Allocations for Rathbun Dam and Lake (2016 WCM)

Facilities to provide release of up to 18 cubic feet per second (cfs) for the state fish hatchery as well as to provide emergency water to the Rathbun Regional Water Association (RRWA) river intake is also part of the outlet works. A separate water supply intake was completed in 2013 in Rathbun Reservoir upstream of the dam which now provides the main source of water for the RRWA treatment plant. The RRWA also has a river intake located downstream of the dam.

3. Methodology

3.1 Overview

A Corps Hydrologic Engineering Center (HEC) model, HEC-ResSim Version 3.5, was used to simulate reservoir operations and route water through the basin. HEC-ResSim is a reservoir simulation model which incorporates user-defined rules and data sets to determine reservoir outflow. The model routes those releases using hydrologic routing methods defined by the user. In the case of the Chariton River model, coefficient routing or null routing was used for all reaches. A depiction of the model junctions and reaches in the basin is shown in Figure 2 below.

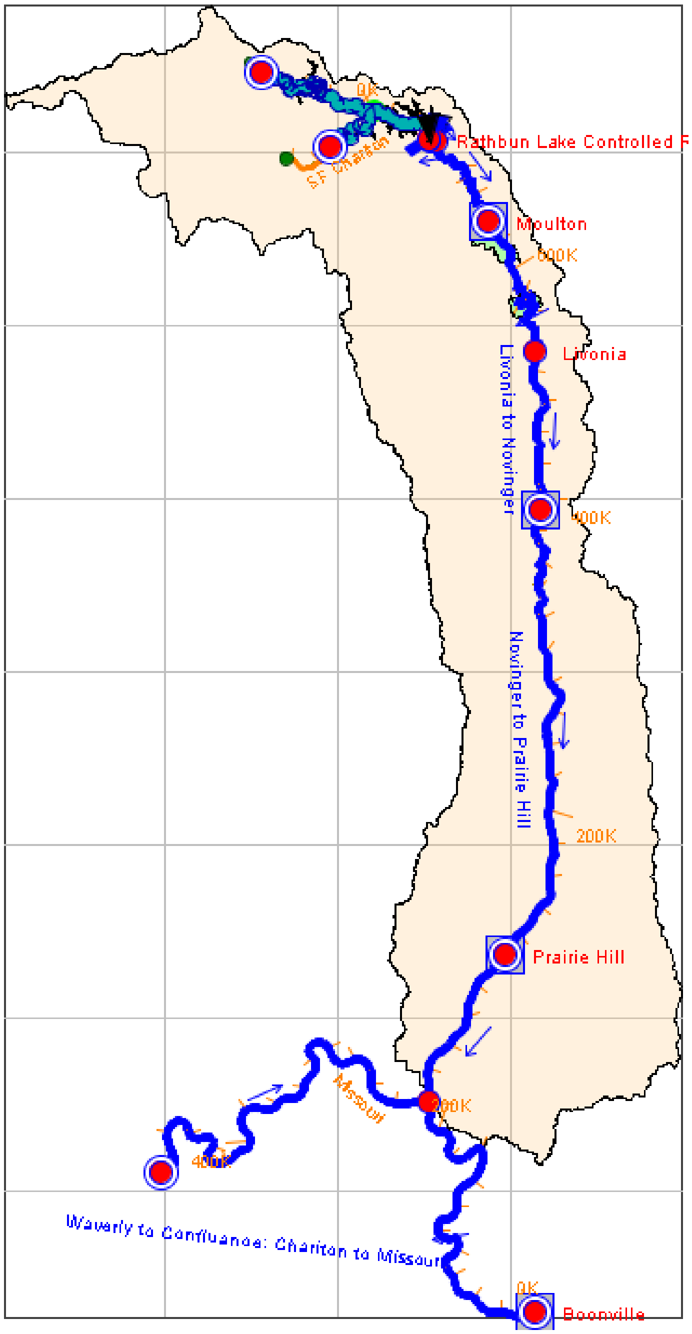

Figure 2. HEC-ResSim Model Reservoir, Reaches, and Junctions for the Chariton River Basin

In order to utilize the model, a complete data set for a number of inputs is required. Data sets were collected from observed records and extended, filling in missing and historical data with a variety of methods. Observed records were obtained from the USGS official daily streamflow records, the Corps Water Management System (CWMS) database, the RRWA, and from the existing model. The period of record for the model input data was January 1, 1930 through December 31, 2019, and the model utilizes a daily time step in simulations.

The existing reservoir network "Alt 24-11" was utilized in simulations for this project. This reservoir network was the final calibrated network utilized in simulations for a Missouri River Recovery Program modeling project in 2014. A historic data simulation was used to verify reservoir operations, hydrologic routing parameters, and model output.

In the course of this project, hydrologic routing parameters and the reservoir operation rule set were re-evaluated and updated if any changes were necessary.

4. Data Collection

Flow data are daily period-average flows in cfs. Reservoir evaporation and precipitation data are daily period-cumulative values in inches. Reservoir elevation data are daily instantaneous values in feet. Four-letter IDs for streamgage locations are used throughout this report and are from the CWMS database. Table 1 defines each ID, the gage owner, description and the period of record of the gage. All data manipulation and the final data results are all located in the DSS file "1930-2019_InputData.dss".

Table 1. Streamgages in the Chariton River Basin HEC-ResSim Model

CWMS ID	Owner	Streamgage Description	Data Availability
RATN	Corps	Rathbun Dam and Reservoir[1]	Sep 28, 1967 – Current
MLTI	USGS	06904010 Chariton River near Moulton, IA	Aug 2, 1979 – Current
LIVM	USGS	06904050 Chariton River at Livonia, MO	May 1, 1974 – Aug 1, 2017
NOVM	USGS	06904500 Chariton River at Novinger, MO	Oct 1, 1930 – Current[2]
PRIM	USGS	06905500 Chariton River near Prairie Hill, MO	Apr 9, 1929 – Current
WVMO	USGS	06895500 Missouri River at Waverly, MO	Oct 1, 1928 – Current[3]
BNMO	USGS	06909000 Missouri River at Boonville, MO	Oct 1, 1925 – Current

[1] The Rathbun Gage has been operated by the USGS since Oct 1, 2000 (gage number 06903880). However, all official data comes from the Corps.

[2]Streamgage was not in operation from Sep 30, 1952 – Oct 1, 1954

[3]Streamgage was not in operation from Apr 1, 1977 – Apr 1, 1978

4.1 Rathbun Lake Inflow, Outflow, & Elevation

4.1.1 Inflow

Inflow from January 1, 1930 to September 28, 1967 (prior to dam construction and closure) was taken from previous computations in the Kansas City District Water Management office utilizing the "rathbunc.xls" spreadsheet from an Upper Mississippi River System Flow Frequency Study. Methodologies for computing inflow follow. Drainage areas for relevant incremental basins are listed below in Table 2. A plot of the extended inflow record can be found in Attachment A. When looking at the plot, the max annual flow seems to have a marked increase starting in 1980, therefore some trend analysis was conducted to help determine the change points. Initially there was concern the data extension method may not have been sufficient, however, downstream gages that do not require extension showed the same trend. These changes are likely due to land use changes, such as drain tile installation, climate cycle patterns to include the 1930's drought, and climate change factors. Efforts to homogenize the data were not identified for this study.

Table 2. Relevant Drainage Areas in the Chariton River Basin

Location	Drainage Area (mi^2)
RATN	549
NOVM	1,370
PRIM	1,870

- January 1, 1930 through September 28, 1930 24:00 UTC: Estimated Rathbun Lake inflow was computed by regressing approved USGS daily flows at Prairie Hill by three days and proportioning the flow based on a relative drainage area ratio. The below equation describes the methodology, where "Q" is flow, "DA" is drainage area, and "t" is in days.

$$Q_{RATN\ IN(t)} = Q_{PRIM(t-3)} * \frac{DA_{RATN}}{DA_{PRIM}}$$

- September 29, 1930 through September 27, 1967 24:00 UTC: Estimated Rathbun Lake inflow was computed by regressing approved USGS daily flows at Novinger by two days and proportioning the flow based on a relative drainage area ratio. For the time period between September 30, 1952 and October 1, 1954, the USGS gage at Novinger was not in operation, so Prairie Hill flows were used by the same method described above. Methodology for regressing and proportioning Novinger flows is described in the equation below.

$$Q_{RATN\ IN(t)} = Q_{NOVM(t-2)} * \frac{DA_{RATN}}{DA_{NOVM}}$$

- September 28, 1967 through December 31, 2019 24:00 UTC: Computed daily average inflows from the CWMS database were available after dam closure. The time series utilized was "RATN.Flow-In.Ave.1Day.1Day.Best-NWK", which populates daily flows at 12:00 UTC each day. A modeling assumption was made that a 12-hour shift in the data would not significantly affect model results, and a simple shift of values was used to adjust the data to 24:00 UTC of that day. For example, the value for September 28, 1967 at 12:00 UTC was shifted forward to September 28, 1967 at 24:00 UTC to match the USGS data.

4.1.2 Outflow

Computed outflow from September 28, 1967 through December 31, 2019 12:00 UTC was available from the CWMS database. The time series utilized was "RATN.Flow-Out.Ave.1Day.1Day.Best-NWK". Values were again shifted forward by 12 hours to match the USGS data and populate the values at 24:00 UTC. Before dam closure, no releases were made, so the time series was extended back to January 1, 1930 by a repeat fill of 0 cfs. A plot of the extended outflow record can be found in Attachment A.

4.1.3 Elevation

Observed elevation from September 28, 1967 through December 31, 2019 12:00 UTC was available from the CWMS database. The time series utilized was "RATN.Elev.Inst.1Day.0.Best-NWK". Values were shifted from 12:00 UTC to 24:00 UTC by a simple shift. The time series was extended back to January 1, 1930 using a repeat fill of 857.0 ft, the bottom of the multi-purpose zone and streambed elevation. Pre-dam streambed elevation is 944.0 ft, but a value of 857.0 feet was used to assume the reservoir was in place but empty. Elevation values in the model are used only to compare to model output, not as an actual model input, so the value does not affect model results. The model uses a lookback elevation of 904.0 feet (the top of the multi-purpose zone) to initialize elevation output. A plot of the extended elevation record can be found in Attachment A.

4.2 Rathbun Lake Evaporation & Precipitation

The current version of HEC-ResSim does not have a reservoir precipitation function, so evaporation and precipitation were summed and entered as reservoir evaporation. Evaporation values in inches are required and are utilized as a net outflow from the reservoir. Since they are an outflow component, evaporation values are shown as positive numbers. In order to accurately account for precipitation as an inflow component, precipitation values were subtracted from the evaporation values. The net result time series was utilized as the Rathbun Evaporation in the model. The below equation describes the summation of evaporation and precipitation data.

$$Model\ Evaporation = Evap_{RATN} - Precip_{RATN}$$

Observed cumulative daily evaporation and precipitation data were available from September 28, 1967 through December 31, 2019 in the CWMS database. The time series utilized were "RATN.Evap.Inst.1Day.0.Best-NWK" and "RATN.Precip.Total.1Day.1Day.Best-

NWK". As with the other lake data, a simple shift was completed on this data to populate values at 24:00 UTC and match the USGS data.

While monthly average evaporation numbers were available for use to extend the time series record back to January 1, 1930, no precipitation data was available in the CWMS database. Daily values provided with the existing HEC-ResSim model from the previous study were utilized to extend the net evaporation record back through 1930. These data were available in the DSS file "WCM Revision - Lake Data - 1920s to 2013.dss". A plot of the extended net evaporation record can be found in Attachment A.

4.3 Rathbun Lake Water Supply, Fish and Wildlife, & Navigation

4.3.1 Water Supply

Water supply data was obtained from the RRWA for their period of record, which began on January 1, 1978. While the previous model utilized monthly average data, RRWA was able to provide daily data for this analysis. The change does not significantly affect model results but does improve model accuracy. Data from January 1, 1978 through December 31, 2019 was pulled from the spreadsheet "RRWA Chariton River Withdrawal 1975-2021.xlsx".

Water usage has increased over time, so to extend the time series back to January 1, 1930, monthly averages from the first year of usage were created and used to estimate water supply usage. The monthly averages (in cfs) from 1978 are shown in Table 3 below. A plot of the extended water supply record can be found in Attachment A.

Table 3. RRWA Water Supply Usage, Monthly Averages for 1978

Month	Average Flow (cfs)
January	1.393
February	1.590
March	1.612
April	1.336
May	1.104
June	1.202
July	1.265
August	1.574
September	1.616
October	1.386
November	1.287
December	1.449

4.3.2 Fish and Wildilfe

A maximum release of 18 cfs is available for use by the Iowa Department of Natural Resources (IDNR) for the fish hatchery. Releases for fish are available in the CWMS database from September 29, 1967 through December 31, 2019. The time series utilized was "RATN-Diversion.Flow.Ave.1Day.1Day.Best-NWK". Releases have remained fairly constant over time, so a period of record monthly average was computed and used to extend the time series back to January 1, 1930. The period of record used to calculate the monthly averages was October 1, 1967 through December 31, 2019. Average monthly values in cfs can be found in Table 4 below. A plot of the extended fish and wildlife record can be found in Attachment A.

Table 4. IDNR Fish Hatchery, Period of Record Monthly Average Flows

Month	Average Flow* (cfs)
January	8.46
February	8.39
March	8.07
April	7.66
May	7.65
June	7.79
July	8.29
August	9.19
September	9.79
October	9.16
November	7.90
December	8.12

*Average flows were calculated using the period of record of October 1, 1967 through December 31, 2019

4.3.3 Navigation

No navigation releases have been made from Rathbun Dam to date. A NULL time series with a repeat fill value of 0 cfs was utilized for this input.

4.4 Streamgage Data

The streamgages in the basin are all owned and operated by the USGS. For the period of record of each gage, the approved daily discharge data set was pulled from the USGS website. The period of record of each gage can be found in Table 1. For those gages whose period of record did not extend back to January 1, 1930 or that had gaps in their record, the data set was filled and extended using daily values provided with the existing HEC-ResSim model from the previous study. These data were available in the DSS file "WCM Revision - Historic - 1920s to 2013.dss".

The Chariton River at Livonia, MO streamgage location was discontinued in 2017, and is not a downstream control point for Rathbun Dam. The streamgage location is not utilized in any of the rules in the reservoir operation set. For these reasons, local flows were not computed at this location. Rather, the local flows at the downstream location of Novinger incorporates the incremental flow in the Moulton to Livonia reach as well as the Livonia to Novinger reach.

The extended official record data sets were used to compute local flows in the model, except at the Missouri River at Waverly, MO location. In order to tie this model in with the other HEC-ResSim models in the study, flow output at Waverly from outside model sources was used to compute local flows at Boonville. This flow was obtained from the Missouri River Basin Water Management Division's Mainstem HEC-ResSim model with input from the Kansas City District Kansas River HEC-ResSim model (for the Kansas River Flood and Sediment Study), including spreadsheet routing for Smithville Dam. The Waverly model output time series name is "/MISSOURI RIVER/WAVERLY, MO/FLOW/30DEC1929 – 01JAN2020/1DAY/REGULATED-NWK-DRAFT". The data set provided went from February 3, 1930 through October 31, 2019. USGS approved flows were used to extend the record back to January 1, 1930 and through December 31, 2019. Plots of the extended streamgage records can be found in Attachment A. The Waverly location additionally depicts the modeled flows used when computing local flows.

5. Local Flow Computations

5.1 Raw Local Flow Calculations

Raw local flows were computed using model output and the extended official streamflow records at each gage location. An example of the raw computed local flows at Novinger is shown in the equation below.

$$NOVM_{local} = NOVM_{obs} - NOVM_{model}$$

At each location, all model input parameters were held to 0 cfs except for the gage immediately upstream. The official extended streamflow record at the upstream gage was routed downstream to do the local flow computation. For example, at Novinger, the extended data set at Moulton was used as the local flow at that location. All other model parameters were held to 0 cfs. The observed record was routed down to Novinger, and then the above equation could be used to compute a raw local flow time series.

At Moulton, the streamgage downstream of Rathbun Dam, local flows were computed using a combination of historical inflows and observed releases at Rathbun. This combined data set used the historical inflow time series from January 1, 1930 through September 27, 1967, and the observed Rathbun Dam releases from September 28, 1967 through December 31, 2019. The time series name in the input DSS file is "/RATN/FLOW/28DEC1929 – 02JAN2020/1DAY/PREDAM-IN_POSTDAM-OUT". This time series was used as the Rathbun Dam release, with all other flow parameters set to 0 cfs. That flow was routed downstream to Moulton, and the above equation applied to calculate raw local flow.

At Boonville, the modeled Waverly flows from the "MODELED-NWK-DRAFT" time series were used as the local flows at the Waverly location from the Missouri River. Observed extended flows at Prairie Hill were used as the local flows at the Prairie Hill location from the Chariton River. All other flow parameters were held to 0 cfs. Both these inputs were routed down to Boonville, and the raw local flow data was calculated using the equation above.

5.2 Local Flow Manipulation

Once raw local flows had been computed, flows were blended and distributed using a spreadsheet method developed by the Kansas City District Water Management staff. The spreadsheet (called "LocalFlow.xlsx") required the raw local flow and the modeled flow after the initial routing at each location (i.e., $NOVM_{local}$ and $NOVM_{model}$ from the raw local flow equation).

5.2.1 Blending

Raw local flow was split into positive and negative values, then the negative values were blended using a running average of between 3 and 7 days. The length of the running average depended on the number and magnitudes of the negative values. Those blended negative values were then summed with the positive values to obtain a blended local flow.

5.2.2 Apportioning

After calculating a blended local flow, that flow could be added to the modeled flow to obtain a blended total flow at each location. A small percentage of flow from positive values could be skimmed from the time series and distributed into the negative values to reduce any remaining negatives further. This percentage was very small, with the largest percentage of 1.11% occurring at Moulton. This can be explained by the period of record of the Moulton gage. Since it did not come into operation until 1979, a large portion of the data set was estimated, creating an additional source of error in the model. For those gages that were in operation for the model period of record, less than 1% of the positive flow was necessary to account for negative flows.

The apportioned and blended flows were added together to create a final local flow time series. Negatives still existed in the time series but were reduced to the point where the modeled river flow and the final local flow summation did not result in negative total flows in the model. The raw local flow and final local flow time series are plotted together at Moulton, Novinger, Prairie Hill, and Boonville in Attachment A.

6. Hydrologic Routing Parameters

The reaches in the Chariton River HEC-ResSim model all utilize the coefficient routing method or null routing. These routing parameters were analyzed as part of this project and adjusted if necessary. This was only necessary at one location.

At Prairie Hill, model results plotted against observed data showed a clear trend of the model routing the flow too slowly. Peak routed flows occurred one day later than observed peaks in many cases. The original coefficient routing between Novinger and Prairie Hill had 50% of the flow routing on Day 2 and 50% of the flow routing on Day 3. Shifting this routing back a day to 50% of the flow routing on Day 1 and 50% of the flow routing on Day 2 provided more reasonable results. Figure 3 below shows the original and modified routings against the observed flow for a selected time window in 2010. The blue line is observed flow, the red line is the original routing parameter flow result, and the green line is the new routing parameter flow result.

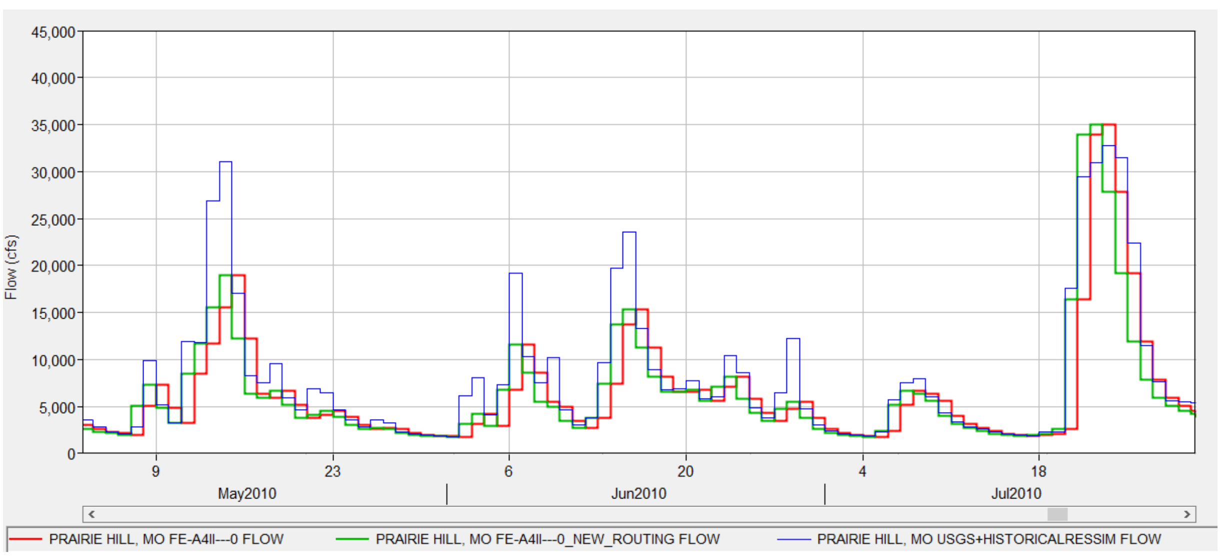

Figure 3. Prairie Hill Routing Parameters

For consistency across HEC-ResSim models in this study, where model overlap occurs routing parameters are used. There are two reaches in the Chariton River Basin model that overlap with the Missouri River Mainstem model: Waverly to the Chariton River confluence, and the Chariton River confluence to Boonville. In the Missouri River model, the river reach between Waverly and Boonville is one reach accounting for all incremental flows between the two locations. For consistency, the reach from Waverly to the Chariton River confluence contains the routing parameters for the larger reach in the Missouri River Mainstem model. The reach on the Chariton River from Prairie Hill to the confluence with the Missouri contains the routing parameters for the entire reach from Prairie Hill to Boonville. The reach from the Chariton River confluence to Boonville utilizes the null routing method, since incremental flows are all accounted for between Waverly and the confluence on the Missouri River and between Prairie Hill and the confluence on the Chariton River.

Table 5 shows the reach routing parameters utilized in the Chariton River Basin model. All reaches used coefficient routing or null routing.

Table 5. Reach Routing Parameters for the Chariton River Basin Model

Reach					
Start	**End**	**Routing Method**	**Day 1**	**Day 2**	**Day 3**
Rathbun Dam	Below Gage	Null Routing	-	-	-
Below Gage	RRWA Diversion	Null Routing	-	-	-
RRWA Diversion	Fish Hatchery Return	Null Routing	-	-	-
Fish Hatchery Return	Moulton	Coefficient Routing	0.250	0.750	0.000
Moulton	Livonia	Coefficient Routing	0.170	0.830	0.000
Livonia	Novinger	Coefficient Routing	0.560	0.440	0.000
Novinger	Prairie Hill	Coefficient Routing	0.500	0.500	0.000
Prairie Hill	Confluence	Coefficient Routing	0.000	1.000	0.000
Waverly	Confluence	Coefficient Routing	0.354	0.618	0.028
Confluence	Boonville	Null Routing	-	-	-

7. HEC-ResSim Input Parameters

This project utilized the same model parameters that were developed in the Missouri River Recovery Program model, with some changes to the rule set and alternatives, and slight changes to the coefficients for some routing reaches. The physical properties of Rathbun Dam and its outlet works were the same.

7.1 HEC-ResSim Rules

The rule set used in developing the regulated flows was a copy of the rule set developed in the existing HEC-ResSim model, called “Alt 24 II – FE-Copy”. A water management evaluation of the rule set and the 2016 Rathbun Dam and Reservoir Water Control Manual (WCM) found four discrepancies between the operation set and the WCM.

1. In the Surcharge Zone, maximum outlet works releases are supposed to be gradually closed as spillway releases increase to keep a maximum total flow of 3,000 cfs from the dam. As stated in the WCM,

   "Should the Reservoir elevation rise above 929.8 feet (the elevation at which spillway flow will be approximately 3,000 cfs) the outlet gates should be gradually reopend to restore full release capability of the project during the event of a spillway flood."

   In the original rule set, the elevation at which the spillway flows are approximately 3,000 cfs is set as 929.5 feet instead of 929.8 feet

   In the period of this simulation (January 1, 1930 through December 31, 2019), the modeled reservoir elevation never reaches far enough into the Surcharge Zone for this rule to make a difference in releases. For that reason, the rule was not modified for this project.

2. In the 2016 WCM, the rate of release change restrictions were updated. The original rule set still used the release rate restrictions listed in the 1980 WCM. These rules are utilized by the model during simulations, as shown in the Release Decision Report in the model. The Release Rate: Increase and the Release Rate: Decrease rules were both updated to match the new WCM.

3. In the Lower Water Quality Zone, there is a Low Pool Water Quality rule that specifies a maximum release of 0 cfs if the pool drops into that zone. This rule came from the 1980 WCM, and in the updated 2016 WCM both the zone and the rule were removed from the manual.

   In the period of this simulation, the modeled reservoir elevation never gets this low for the rule to be utilized. For that reason, the rule was not modified for this project.

4. In the original rule set, elevations for Phase I and Phase II in the Flood Control Zone were defined to a precision of a hundredth of a foot. In the 2016 WCM, Phase elevations were listed with a precision of a tenth of a foot. It is likely that since this model was utilized in the development of a new Water Control Plan for Rathbun Dam and Reservoir for the 2016 WCM, more precise elevations were utilized during the development and then rounded to the nearest tenth of a foot for the official WCM update.

   Though changing these elevations does not make a significant difference in model output, for consistency the zone elevations were modified to match the 2016 WCM.

Also during the water management evaluation, model output downstream resulted in some large negative values, especially at the Moulton gage just downstream from the dam. These large negative values are a result of using a regulated Rathbun Dam release scenario for the entirety of the simulation, when the local flows were developed using historical inflows and observed reservoir releases. In addition, at Moulton the official gage record begins in 1979, so a large portion of the flows are estimated, which introduces another source of error to the model. The release decision report during the time periods of negative flows indicated that one rule was prevalent in many cases, the minimum reservoir release rule of 11 cfs. During dry periods, this minimum release wasn't enough to push flows downstream above 0 cfs after incorporating the local flows into the model.

In order to minimize the negative flows in the main stem of the Chariton River, an analysis was conducted on changing one of the rules in the operation set. Rather than using a minimum reservoir release of 11 cfs for water quality, the rule was changed to set a minimum release target at Moulton of 11 cfs. This rule modification was also used in the Missouri River Mainstem model to aid in reducing or eliminating negative flows in the river. The results of the rule change were significant at the Moulton gage, and visible downstream at Novinger and Prairie Hill as well. The below figures 4-6 illustrate the change, with the green line depicting the minimum target flow at Moulton rather than a minimum release rule.

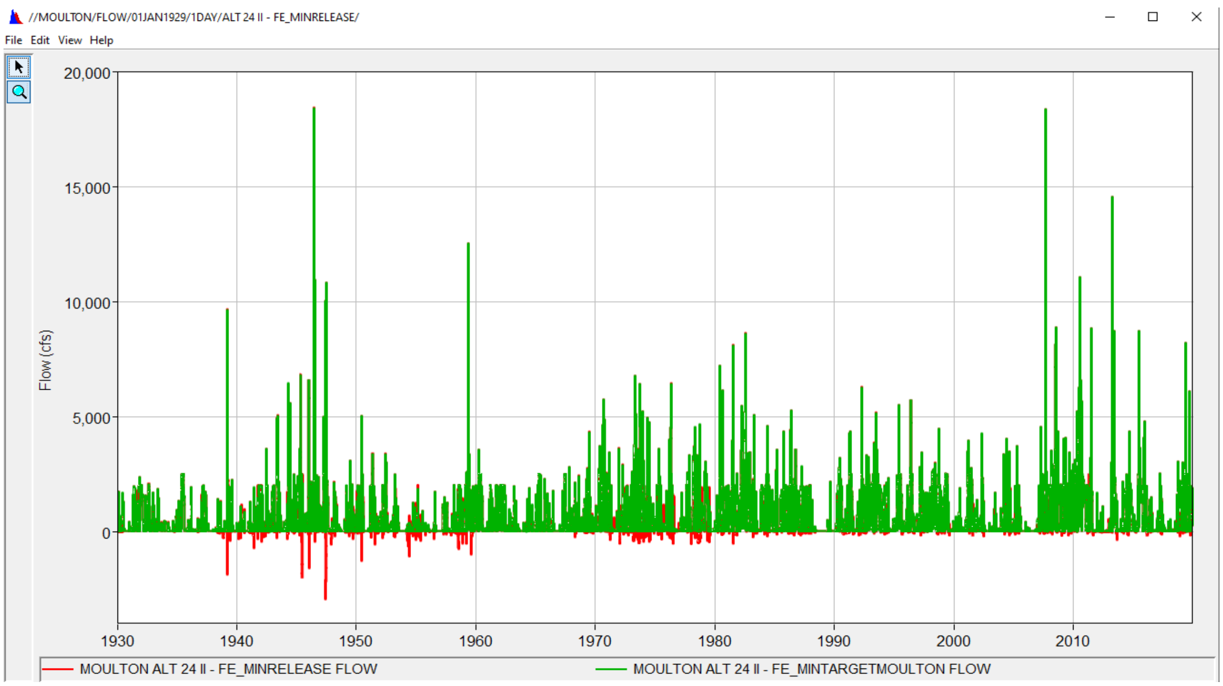

Figure 4. **Comparison of a Minimum Release Rule and a Minimum Target Flow Rule at Moulton, IA**

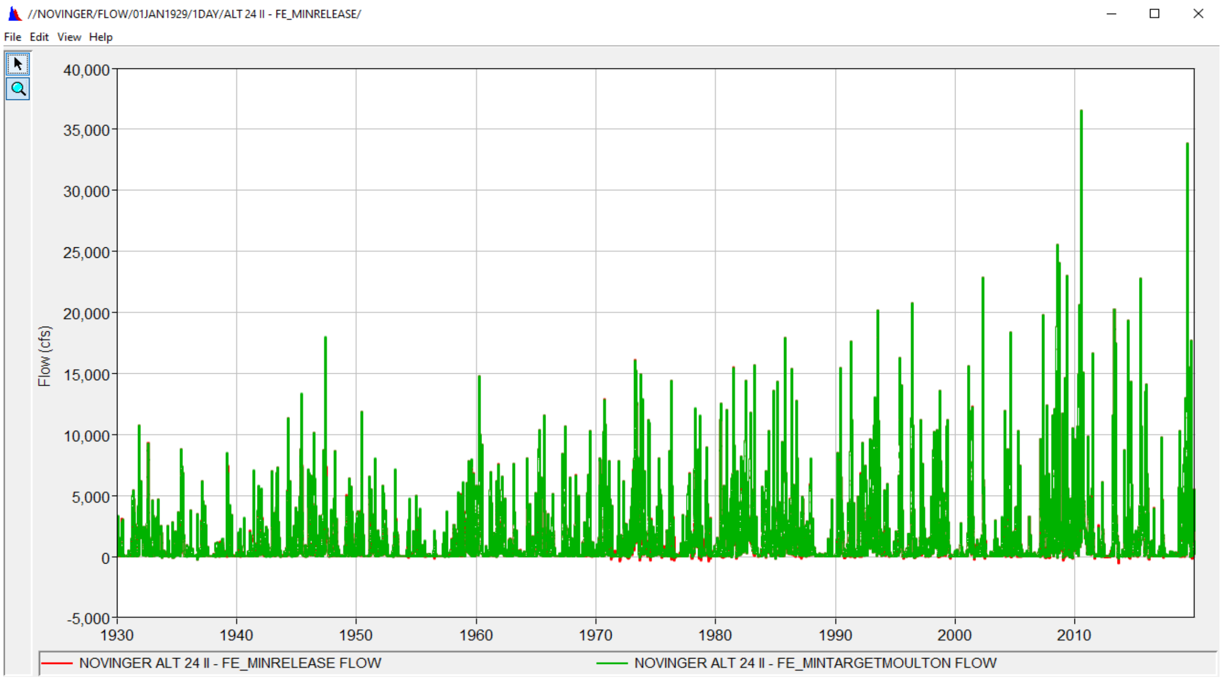

Figure 5. Comparison of a Minimum Release Rule and a Minimum Target Flow Rule at Novinger, MO

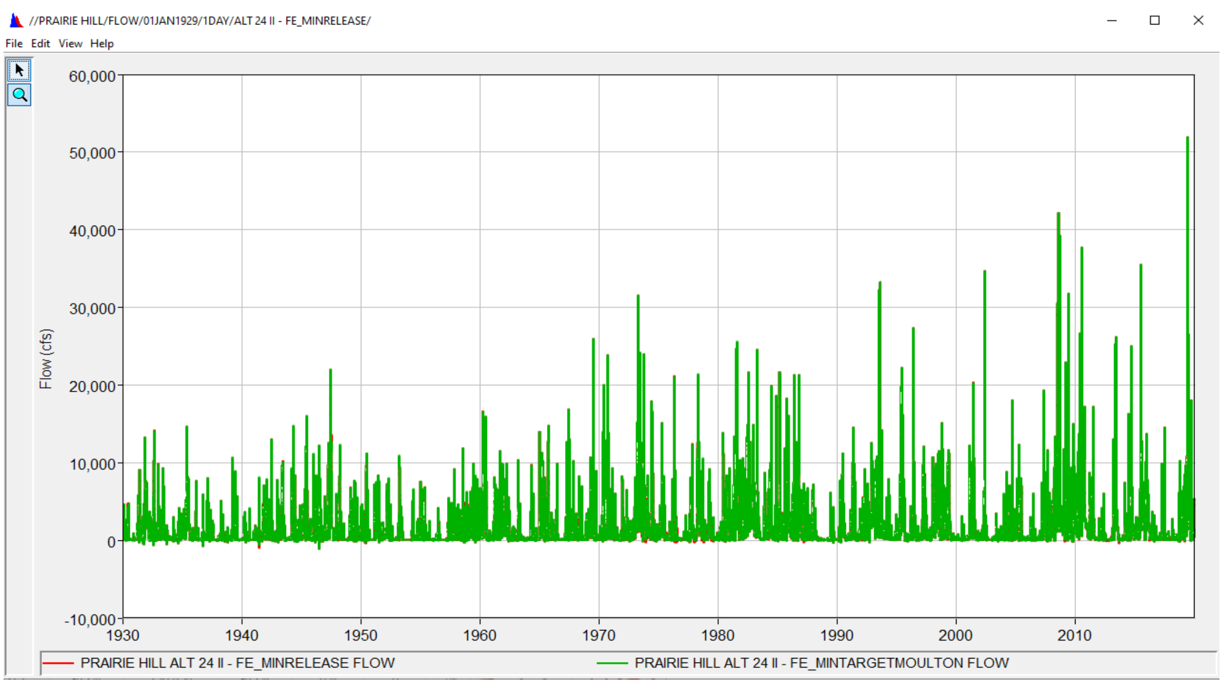

Figure 6. Comparison of a Minimum Release Rule and a Minimum Target Flow Rule at Prairie Hill, MO

At Rathbun Dam, this rule change did not make a significant difference overall in the reservoir releases. A comparison of annual outflow volume between the rule sets shows that in most cases, the percent difference is less than 1% in annual outflow volume. In general, releases are slightly higher in order to meet the release target rule, which is an expected result. Figure 8 shows a comparison of Rathbun Lake elevations when the minimum target rule is implemented rather than the minimum release rule. Lake elevations are very similar, with slight decreases in peak and minimum elevations in some years.

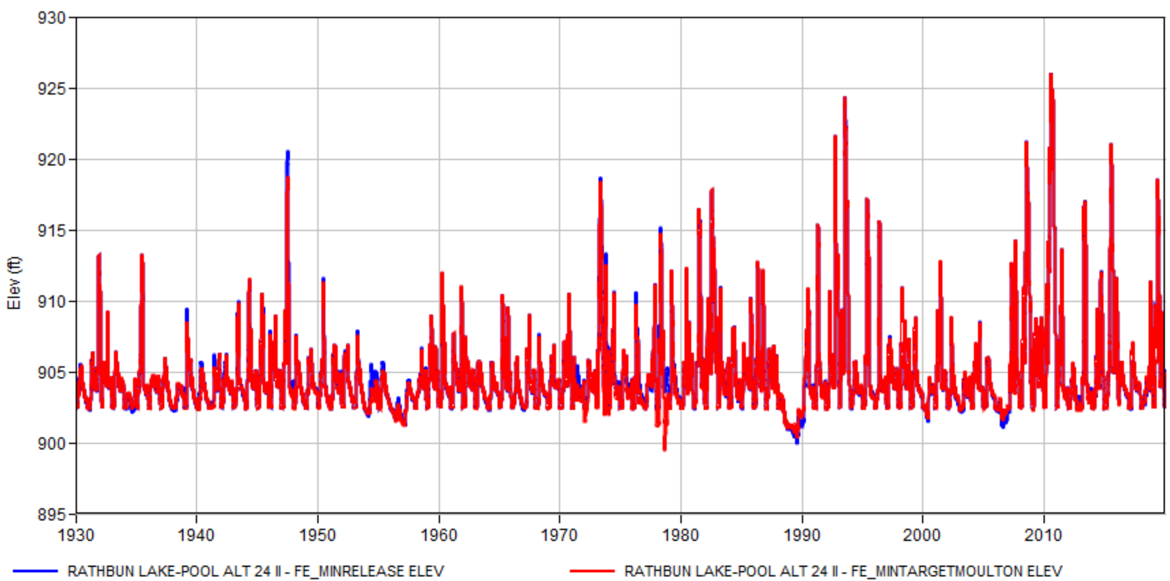

Figure 7. Comparison of a Minimum Release Rule and a Minimum Target Flow Rule at Rathbun Lake

This project is part of a larger flow frequency study, which places a higher priority on the accuracy of modeled annual peak flows. For this reason, the percent difference in annual peak flows at Moulton, Novinger, and Prairie Hill were compared. Figures 8-10 below show the percent difference between the rule sets.

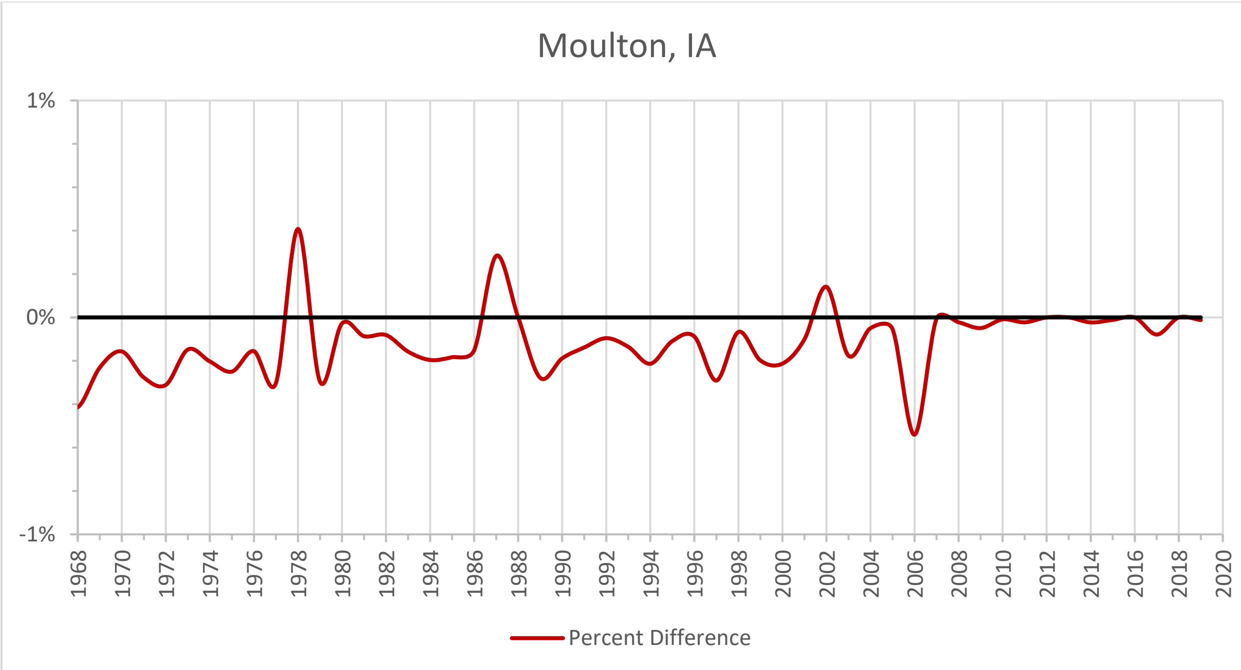

Figure 8. Percent Difference in Annual Peak Flows at Moulton, IA

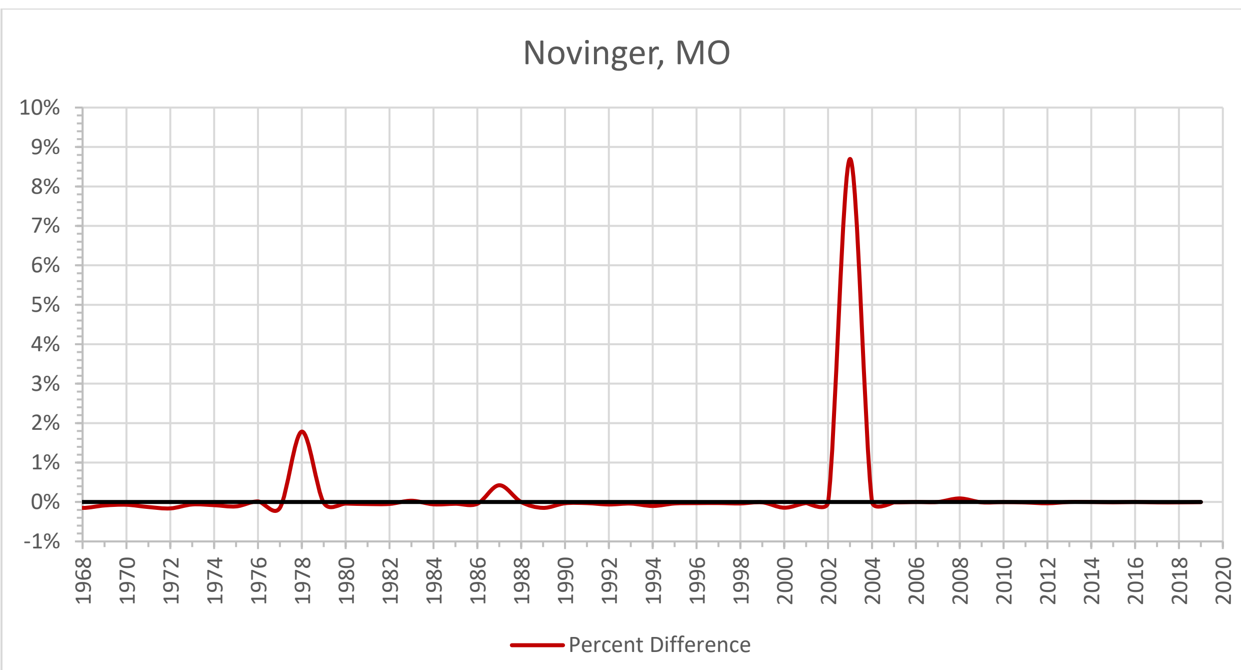

Figure 9. Percent Difference in Annual Peak Flows at Novinger, MO

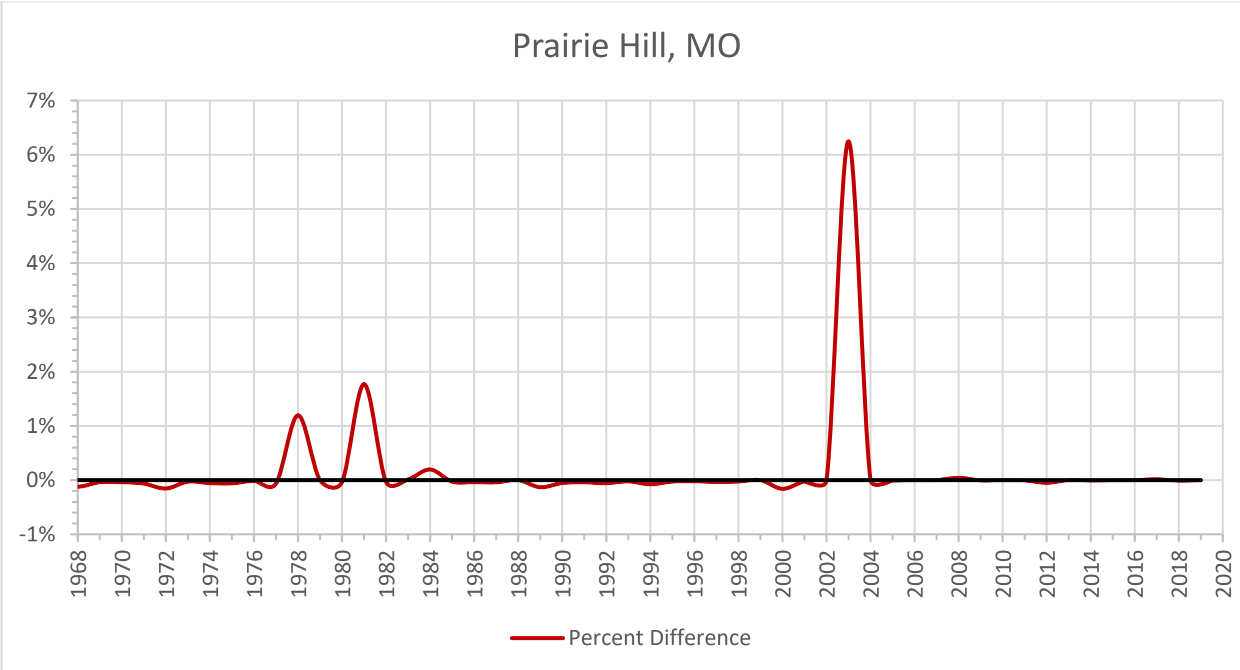

Figure 10. Percent Difference in Annual Peak Flows at Prairie Hill, MO

Overall, annual peak flows differ by less than 1% in each location. At Novinger and Prairie Hill, a larger discrepancy in peak flows occurs in 2003. This discrepancy does not occur at Moulton because the annual peak flow at that gage occurs at a different time of year than it does downstream.

The peak flows increase at Novinger and Prairie Hill in 2003 because guide curve operations result in reservoir releases increasing a few days sooner under the minimum target rule rather than the minimum reservoir release rule. These release increases combined with high local flows to increase the annual peak by the amount of the attenuated releases. Since the change in rule set results in an increase in peak flows in 2003, however, and overall, the change in annual peak flows are minimal, the rule change was put in place in the final operation rule set. A table of the rule set and the guide curve utilized in this project can be found in Attachment B.

8. Conclusion

An existing HEC-ResSim model for the Chariton River basin from the Kansas City District was used to perform this analysis. Data sets were extended to run from January 1, 1930 through December 31, 2019, and local flows were re-calculated with updated data. After a water management evaluation of the model, reservoir routing parameters were updated on one reach (Novinger to Prairie Hill) and changed to match other models for consistency on the Missouri River. The Rathbun Reservoir Operation Set was modified to match the current Water Control Manual updated in 2016. One additional rule change was necessary to minimize negative total flows in the main stem Chariton River. Rather than a minimum release rule from Rathbun Dam, a downstream control function was used to set a minimum release target at the nearest streamgage downstream from the dam (at Moulton, IA).

After these updates, HEC-ResSim output for Rathbun Reservoir holdouts routed to Prairie Hill and Boonville and a regulated flow time series at Prairie Hill were supplied for use in the Missouri River Flow Frequency Study. A plot of each of these outputs can be found in Attachment A. Holdouts were calculated within HEC-ResSim by applying the "Compute Holdouts" option to the FE-A4II alternative. After reviewing the holdouts and their impact on the Boonville peaks, the results showed that the reservoir has negligible impact on the Missouri River. Therefore, observed flows at downstream gages can be used for input to the Missouri River without adjustment.

Attachment A

1.1 Rathbun Dam & Reservoir Data

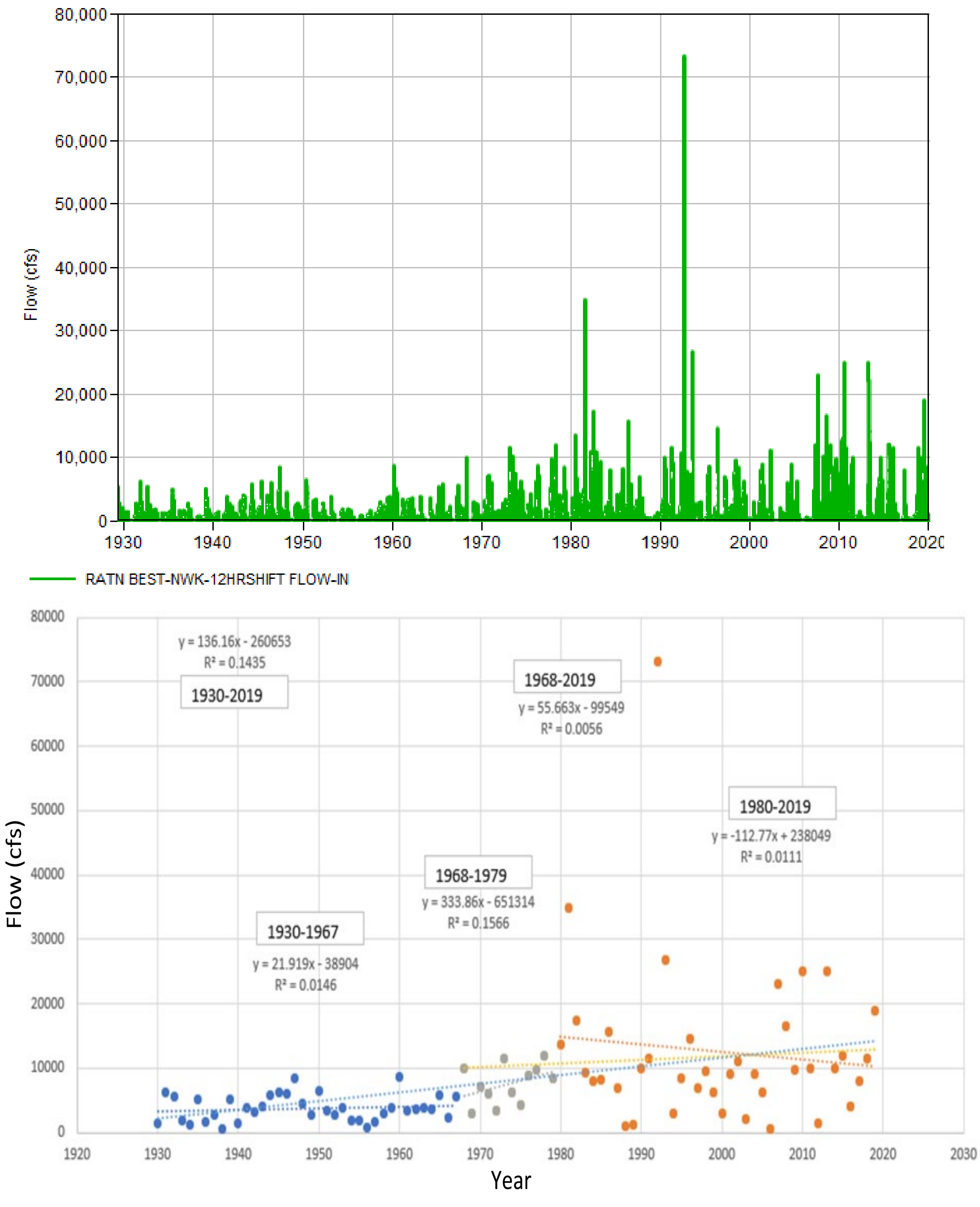

Figure A- 1. Rathbun Reservoir Inflow, and Annual Peak Trend Data

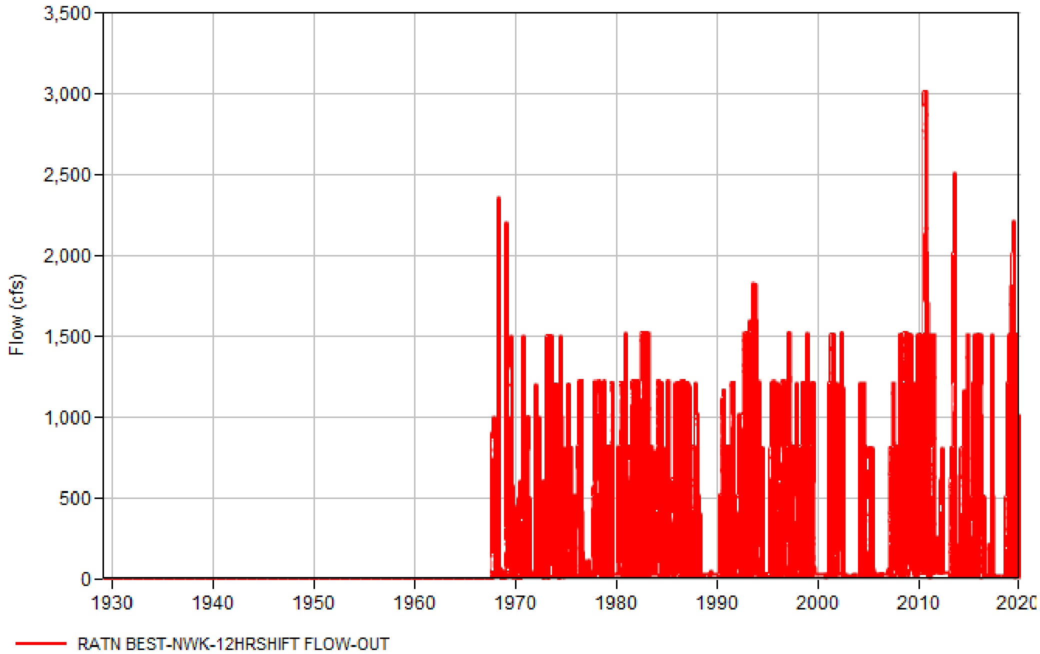

Figure A- 2. Rathbun Dam Releases

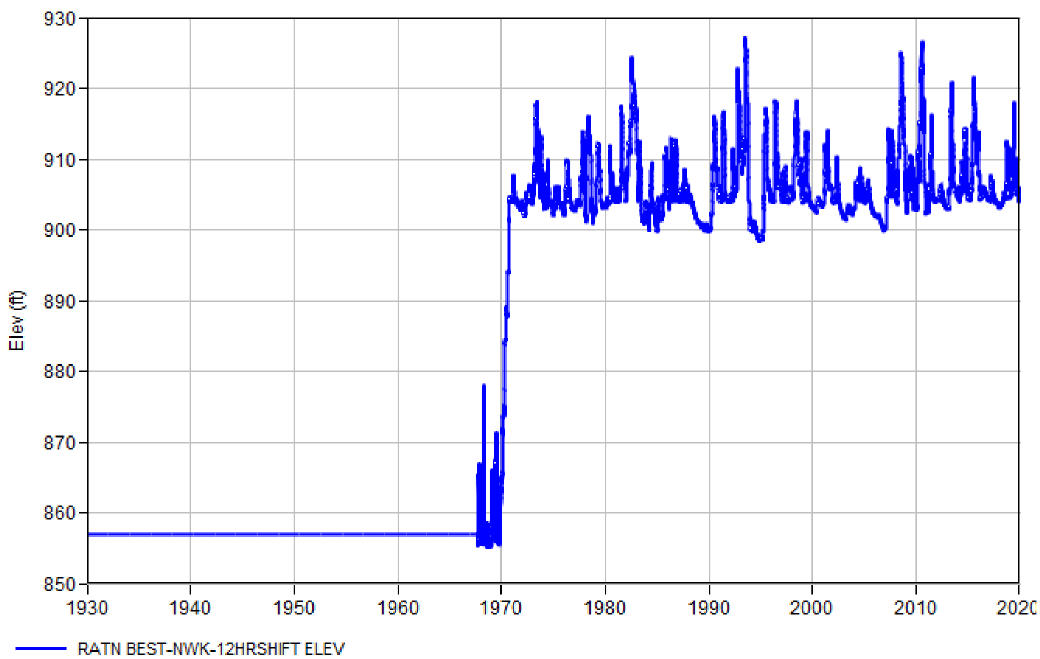

Figure A- 3. Rathbun Reservoir Elevation

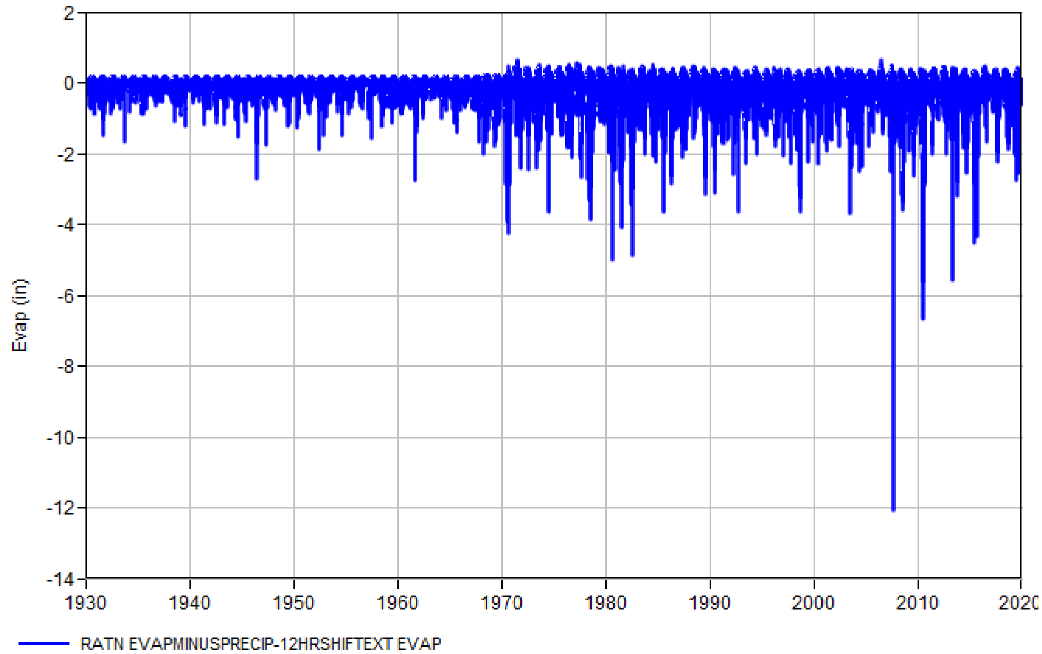

Figure A- 4. Rathbun Reservoir Net Evaporation

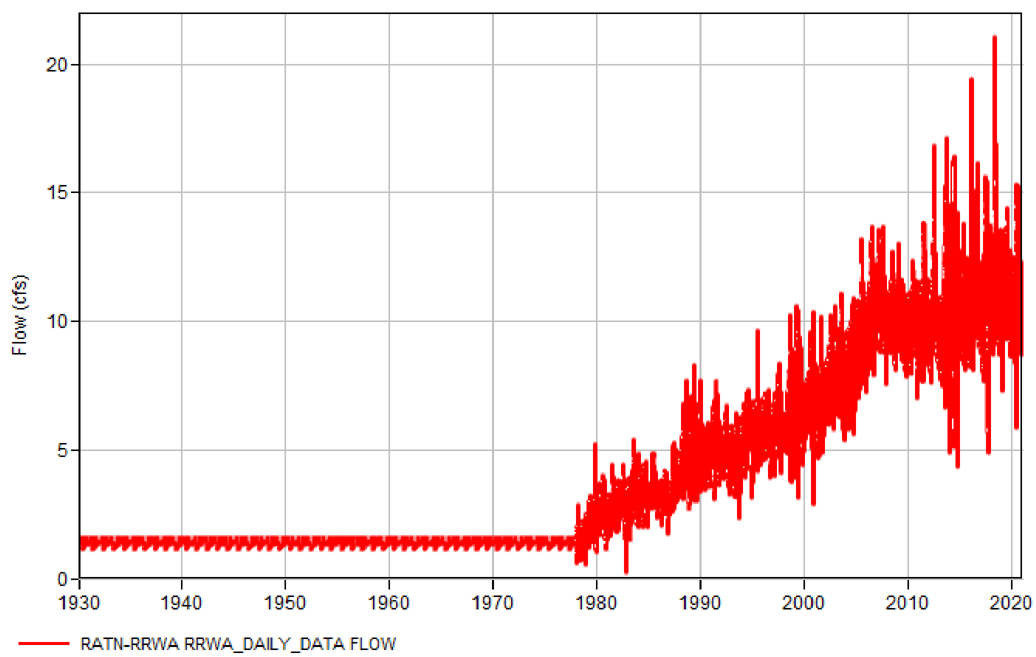

Figure A- 5. Rathbun Regional Water Association, Total Water Usage

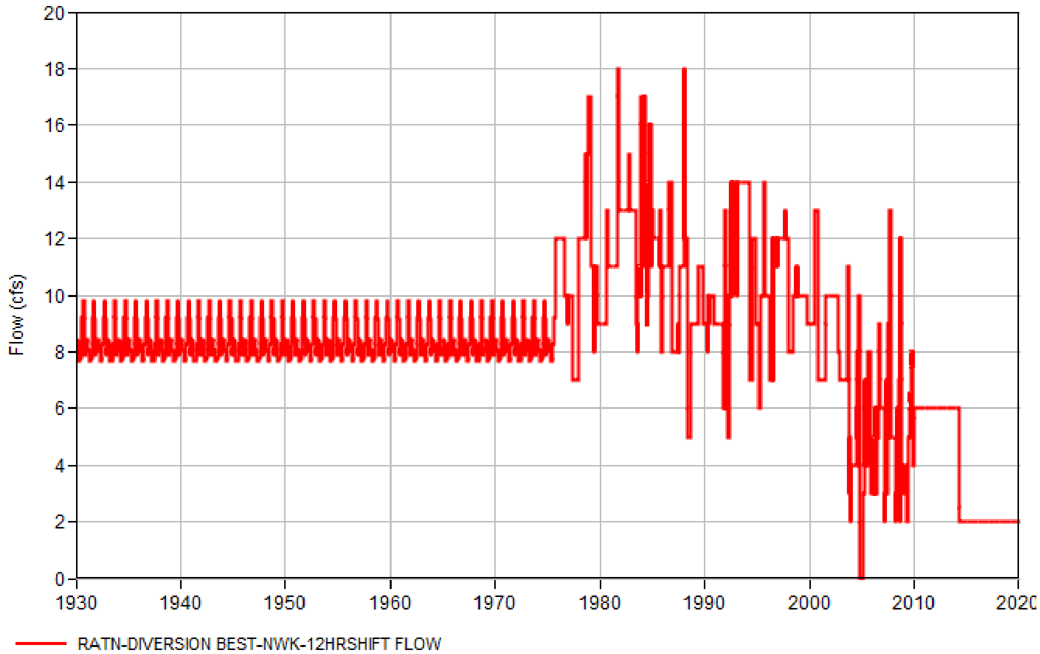

Figure A- 6. Iowa Department of Natural Resources, Fish Hatchery Water Usage

1.2 Streamflow Data

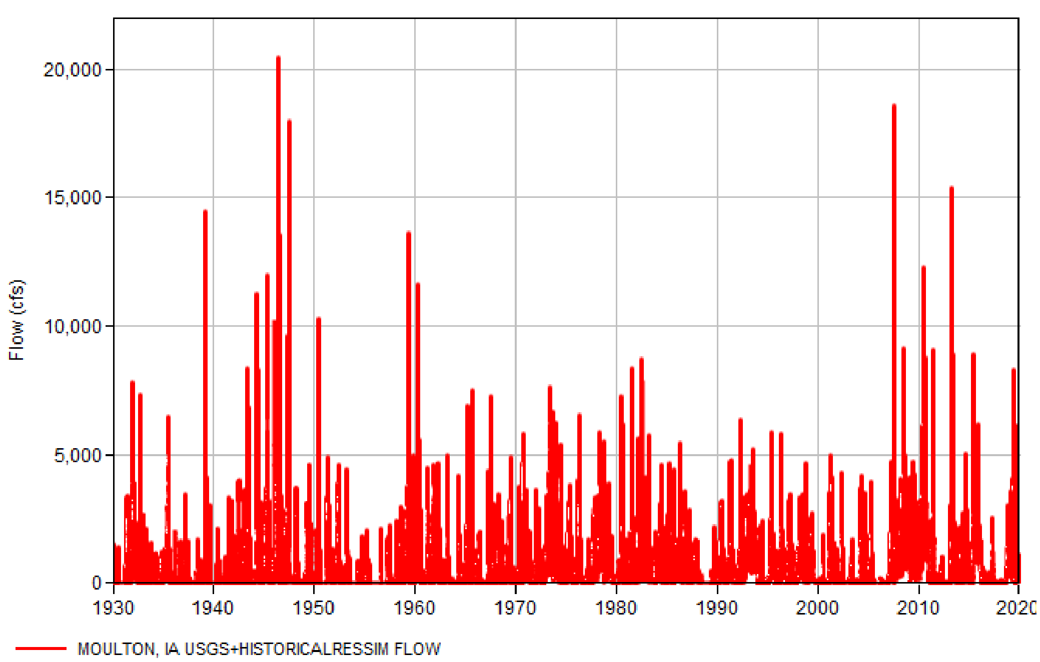

Figure A- 7. Chariton River at Moulton, IA Streamflow

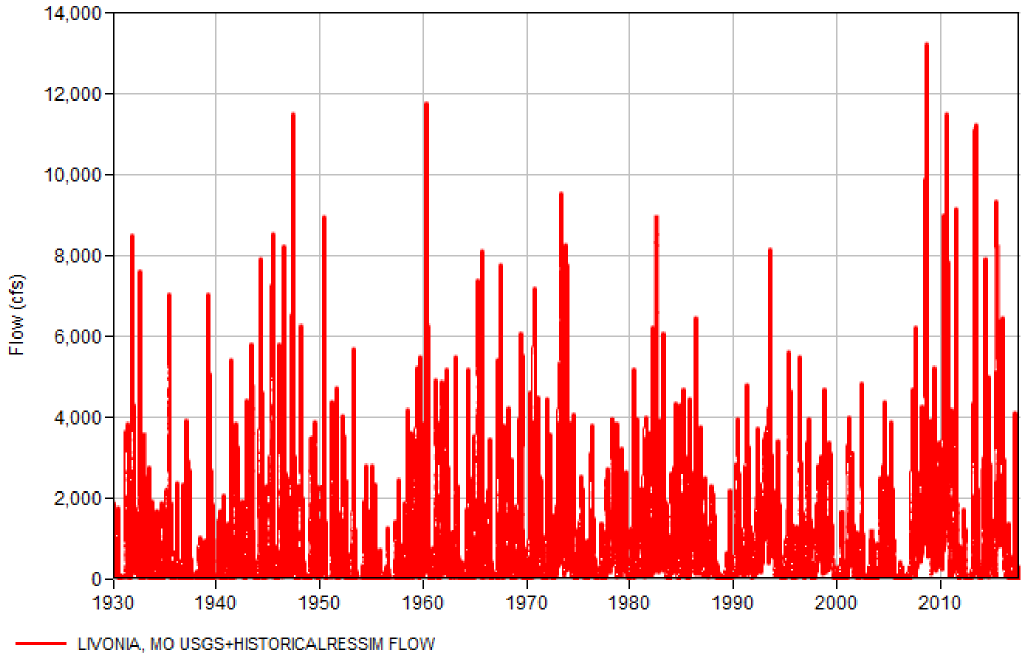

Figure A- 8. Chariton River at Livonia, MO Streamflow

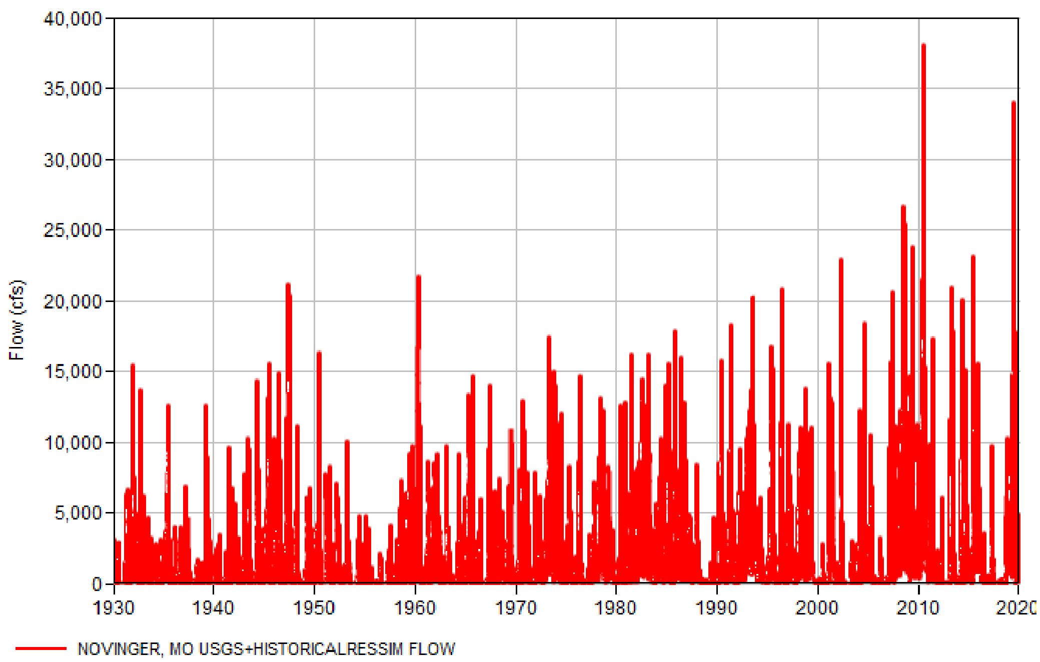

Figure A- 9. Chariton River at Novinger, MO Streamflow

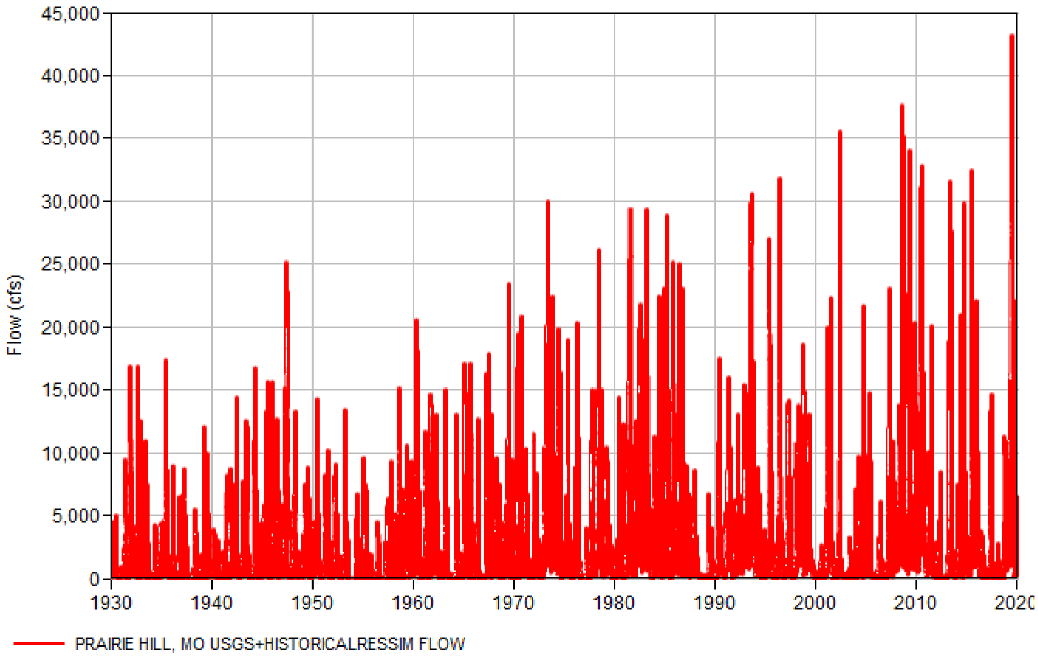

Figure A- 10. Chariton River at Prairie Hill, MO Streamflow

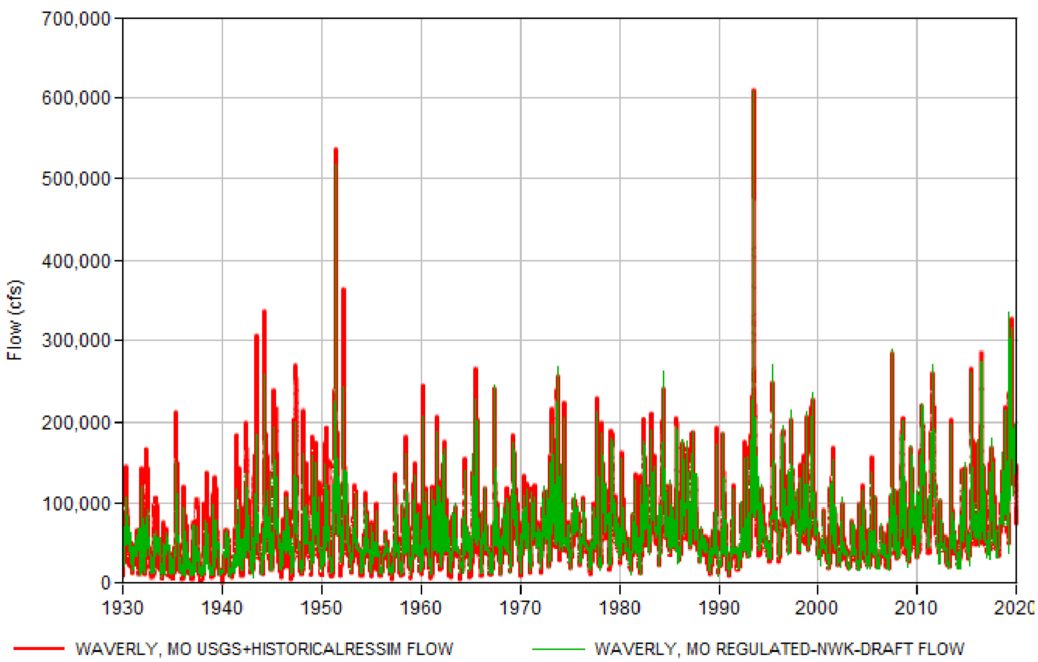

Figure A- 11. Missouri River at Waverly, MO Modeled Flow and Observed Flow

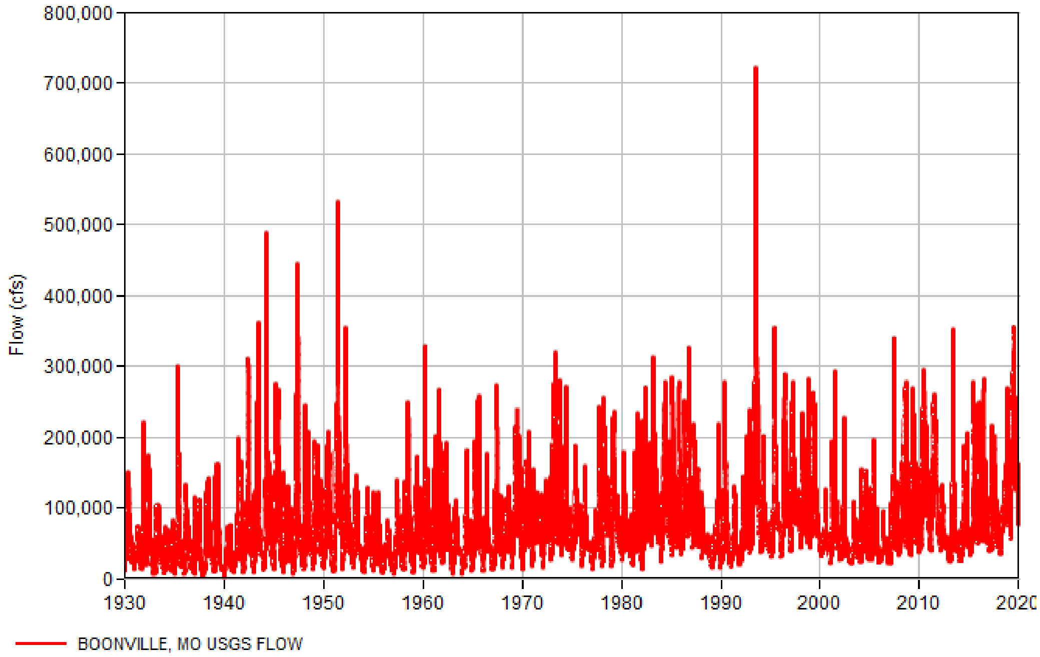

Figure A- 12. Missouri River at Boonville, MO Streamflow

1.3 Local Flow Data

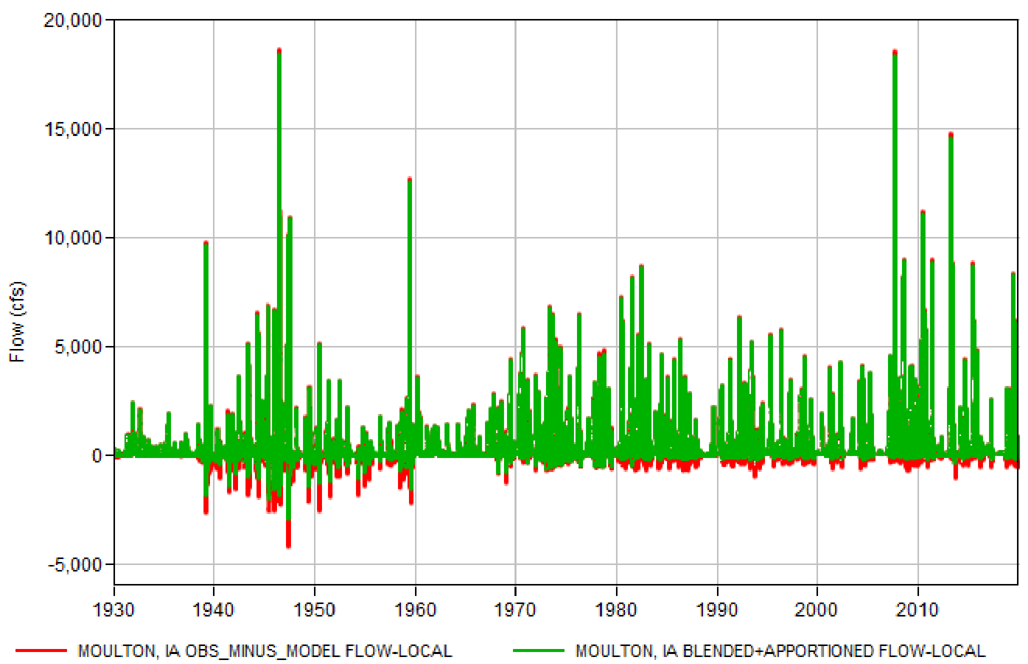

Figure A- 13. Raw Local Flow and Modified Local Flow at Moulton, IA

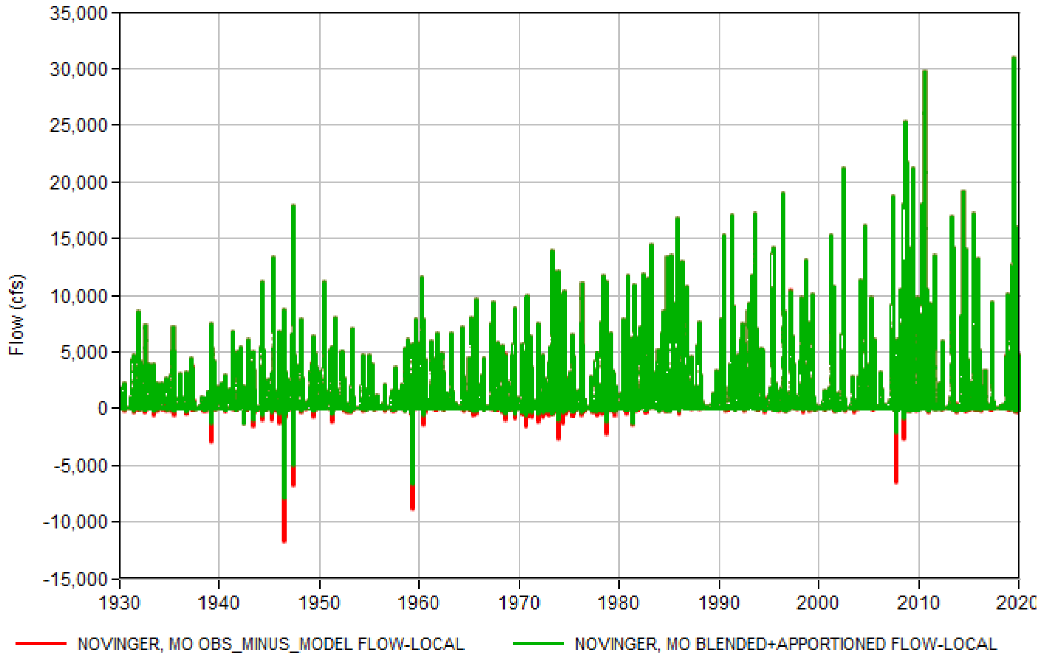

Figure A- 14. Raw Local Flow and Modified Local Flow at Novinger, MO

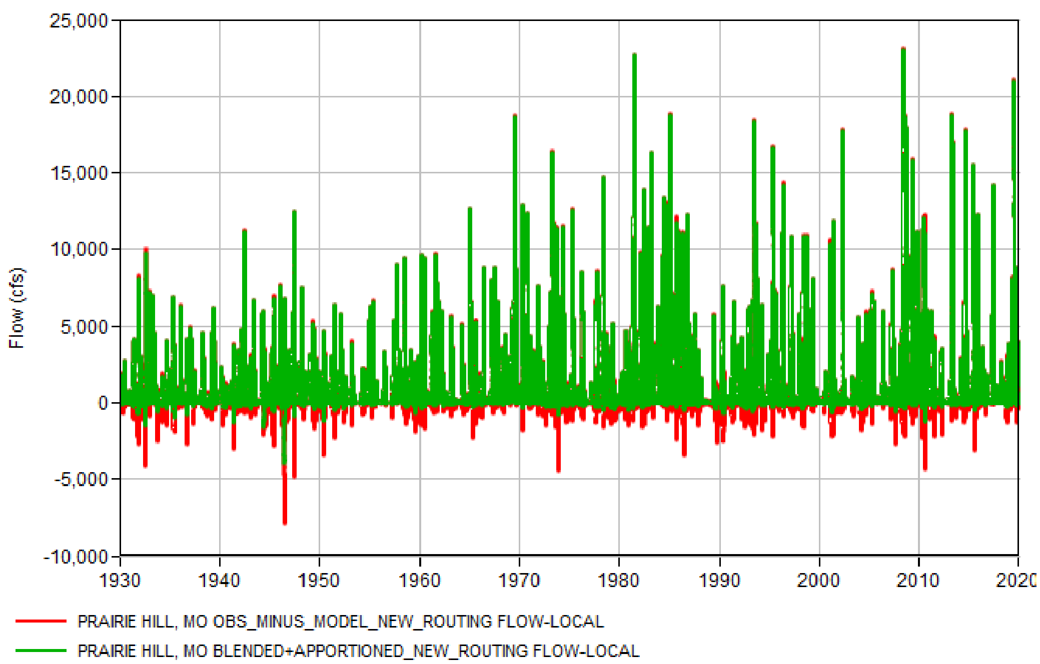

Figure A- 15. Raw Local Flow and Modified Local Flow at Prairie Hill, MO

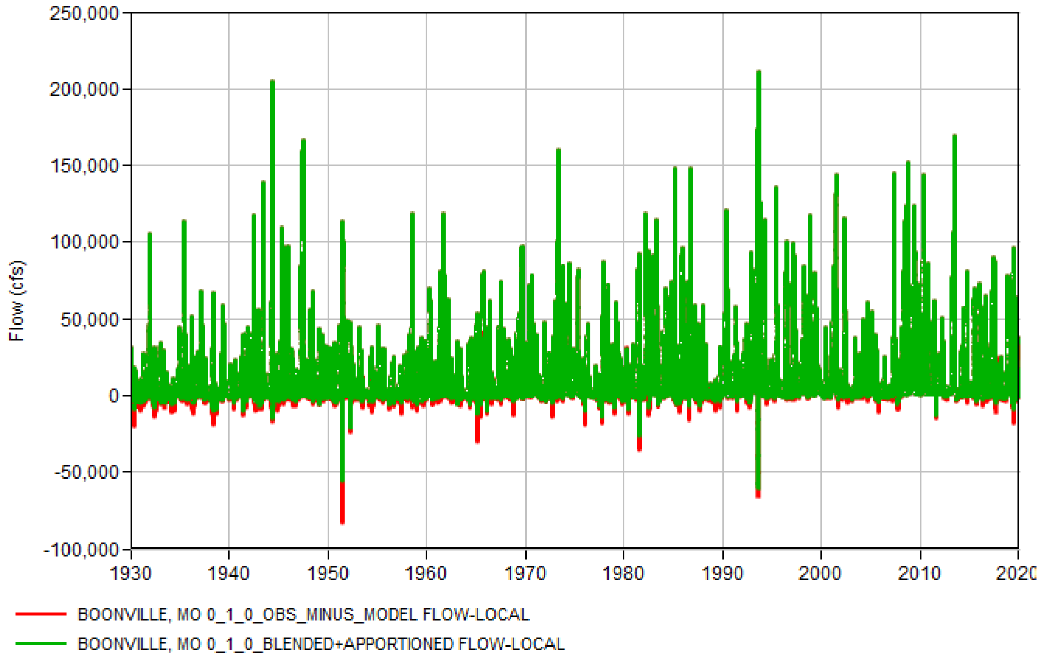

Figure A- 16. Raw Local Flow and Modified Local Flow at Boonville, MO

1.4 HEC-ResSim Results

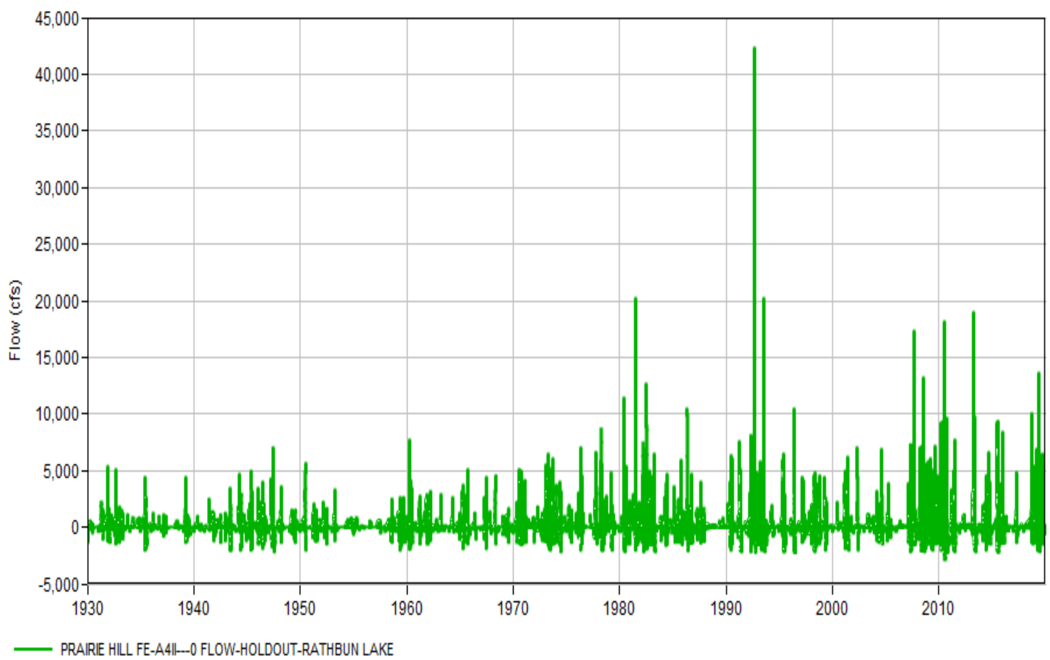

Figure A- 17. Rathbun Reservoir Holdouts Routed to Prairie Hill, MO

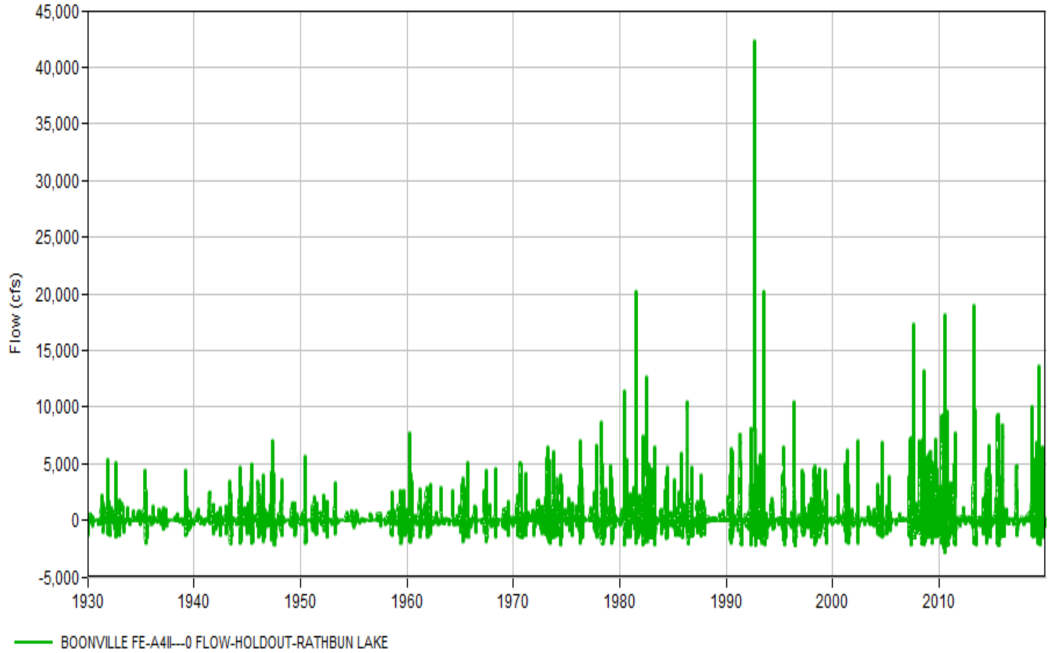

Figure A- 18. Rathbun Reservoir Holdouts Routed to Boonville, MO

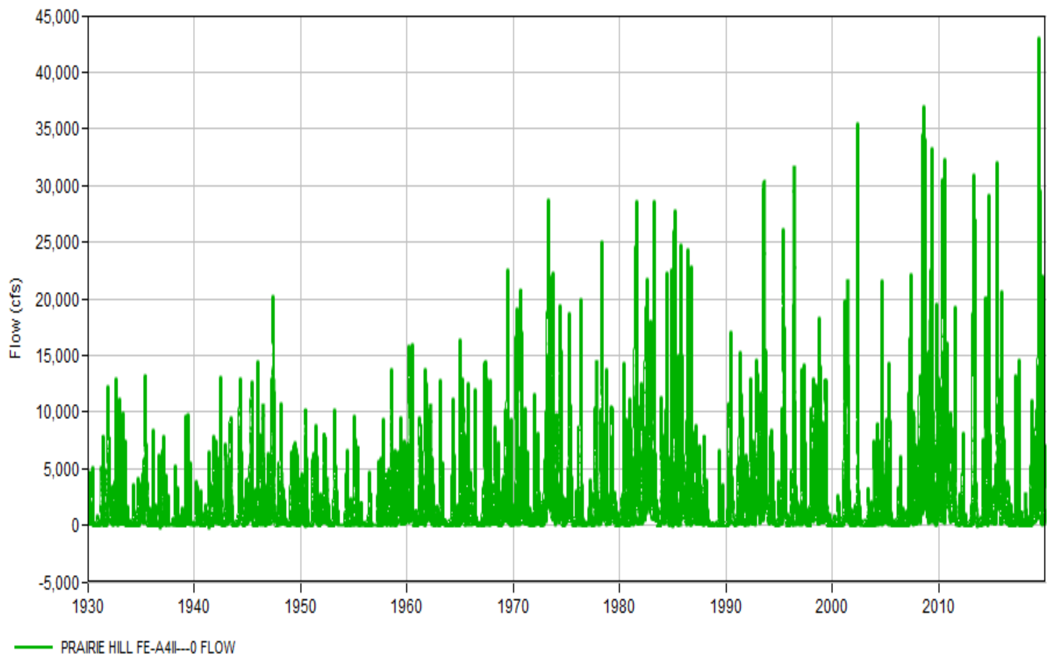

Figure A- 19. Simulated Regulated Flow at Prairie Hill, MO

Attachment B

1.1 Rathbun Dam and Reservoir Operation Rule Set

Table B- 1. Rule stack used in HEC-ResSim for Rathbun Dam and Lake (Operation Set "Alt 24 II – FE-Copy)

Zone	Rule Name	Operates Release from	Rule Type	Limit Type	Flow Limit (cfs)	Function of	Down-stream Location
Surcharge (Top Elevation 940.0 ft)							
	Fish	Rathbun Lake-Fish Hatchery	Release Function	Specified	0-20	Historical Flows	-
	Navigation Support	Rathbun Lake	Downstream Control Function	Minimum	0-175,000	Navigation Support Requirement	Boonville
	Max Controlled Release	Rathbun Lake-Controlled Outlet	Release Function	Specified	0-3,000	Pool Elevation	-
Flood Control – Phase III (Top Elevation 926.0 ft)							
	Fish	Rathbun Lake-Fish Hatchery	Release Function	Specified	0-20	Historical Flows	-
	Water Quality – Min Rel Target	Rathbun Lake	Downstream Control Function	Minimum	11	Date	Moulton
	Release Rate: Increase	Rathbun Lake	Release Rate of Change Limit	Increasing	100-500 cfs/hr	Release	-
	Release Rate: Decrease	Rathbun Lake	Release Rate of Change Limit	Decreasing	50-500 cfs/hr	Release	-
	Downstream – Moulton III	Rathbun Lake	Downstream Control Function	Maximum	4,000	Date	Moulton
	Downstream – Novinger III	Rathbun Lake	Downstream Control Function	Maximum	21,000	Date	Novinger
	Downstream – Prairie Hill III	Rathbun Lake	Downstream Control Function	Maximum	23,000	Date	Prairie Hill
	Max Release – Phase III	Rathbun Lake-Controlled Outlet	Release Function	Maximum	3,000	Date	-
	Navigation Support	Rathbun Lake	Downstream Control Function	Minimum	0-175,000	Navigation Support Requirement	Boonville

Zone	Rule Name	Operates Release from	Rule Type	Limit Type	Flow Limit (cfs)	Function of	Down-stream Location
Flood Control – Phase II (Top Elevation 918.8 – 924.4 ft, Function of Date)							
	Fish	Rathbun Lake-Fish Hatchery	Release Function	Specified	0-20	Historical Flows	-
	Water Quality – Min Rel Target	Rathbun Lake	Downstream Control Function	Minimum	11	Date	Moulton
	Release Rate: Increase	Rathbun Lake	Release Rate of Change Limit	Increasing	100-500 cfs/hr	Release	-
	Release Rate: Decrease	Rathbun Lake	Release Rate of Change Limit	Decreasing	50-500 cfs/hr	Release	-
	Downstream – Moulton II	Rathbun Lake	Downstream Control Function	Maximum	2,500	Date	Moulton
	Downstream – Novinger II	Rathbun Lake	Downstream Control Function	Maximum	13,000	Date	Novinger
	Downstream – Prairie Hill II	Rathbun Lake	Downstream Control Function	Maximum	13,000	Date	Prairie Hill
	Max Release – Phase II	Rathbun Lake-Controlled Outlet	Release Function	Maximum	2,200	Date	-
	Navigation Support	Rathbun Lake	Downstream Control Function	Minimum	0-175,000	Navigation Support Requirement	Boonville
Flood Control – Phase I (Top Elevation 907.1 – 916.8 ft, Function of Date)							
	Fish	Rathbun Lake-Fish Hatchery	Release Function	Specified	0-20	Historical Flows	-
	Water Quality – Min Rel Target	Rathbun Lake	Downstream Control Function	Minimum	11	Date	Moulton
	Release Rate: Increase	Rathbun Lake	Release Rate of Change Limit	Increasing	100-500 cfs/hr	Release	-
	Release Rate: Decrease	Rathbun Lake	Release Rate of Change Limit	Decreasing	50-500 cfs/hr	Release	-
	Downstream – Moulton I	Rathbun Lake	Downstream Control Function	Maximum	2,000	Date	Moulton
	Downstream – Novinger I	Rathbun Lake	Downstream Control Function	Maximum	8,000	Date	Novinger

Zone	Rule Name	Operates Release from	Rule Type	Limit Type	Flow Limit (cfs)	Function of	Down-stream Location
	Downstream – Prairie Hill I	Rathbun Lake	Downstream Control Function	Maximum	8,000	Date	Prairie Hill
	Max Release – Phase I	Rathbun Lake-Controlled Outlet	Release Function	Maximum	1,500	Date	-
	Navigation Support	Rathbun Lake	Downstream Control Function	Minimum	0-175,000	Navigation Support Requirement	Boonville
Conservation (Top Elevation 902.5 – 905.6 ft, Function of Date)							
	Fish	Rathbun Lake-Fish Hatchery	Release Function	Specified	0-20	Historical Flows	-
	Water Quality – Min Rel Target	Rathbun Lake	Downstream Control Function	Minimum	11	Date	Moulton
	IF Block Rule	**IF Condition**			**Value 2**		
	Navigation Support	Navigation	(				
			Pool Elevation	>=	896.0 ft		
		AND	Pool Elevation	<=	904.0 ft		
		AND	Current Time Step	>=	01Jan		
		AND	Current Time Step	<	15May		
			)				
		OR	(				
			Pool Elevation	>=	900.0 ft		
		AND	Pool Elevation	<=	904.0 ft		
		AND	Current Time Step	>=	15May		
		AND	Current Time Step	<=	01Oct		
			)				
		OR	(				
			Pool Elevation	>=	896.0 ft		
		AND	Pool Elevation	<=	904.0 ft		
		AND	Current Time Step	>	01Oct		
		AND	Current Time Step	<=	31Dec		

Zone	Rule Name	Operates Release from	Rule Type	Limit Type	Flow Limit (cfs)	Function of	Down-stream Location
			)				
		AND	Navigation Support Requirement	>	0 cfs		
		Rules Applied:					
		Max Release – Phase I					
		Navigation Support					
	Below MPP – Max Lake Release	Rathbun Lake-Controlled Outlet	Release Function	Maximum	25	Date	-
	Release Rate: Increase	Rathbun Lake	Release Rate of Change Limit	Increasing	100-500 cfs/hr	Release	-
	Release Rate: Decrease	Rathbun Lake	Release Rate of Change Limit	Decreasing	50-500 cfs/hr	Release	-
Lower Water Quality (Top Elevation 885.0 ft)							
	Fish	Rathbun Lake-Fish Hatchery	Release Function	Specified	0-20	Historical Flows	-
	Low Pool Water Quality	Rathbun Lake-Controlled Outlet	Release Function	Maximum	0	Date	-
	Release Rate: Increase	Rathbun Lake	Release Rate of Change Limit	Increasing	100-500 cfs/hr	Release	-
	Release Rate: Decrease	Rathbun Lake	Release Rate of Change Limit	Decreasing	50-500 cfs/hr	Release	-
Inactive (Top Elevation 857.0 ft)							

1.2 Rathbun Dam and Reservoir Guide Curve

Table B- 2. Guide Curve in HEC-ResSim for Rathbun Dam and Lake

Date	Elevation (ft)*
01Jan	902.5
01Mar	902.5
01Apr	905.6
01Jun	905.6
01Aug	904.0
30Sep	904.0
01Oct	905.0
01Dec	905.0
31Dec	902.5

*Elevations between dates are linearly interpolated