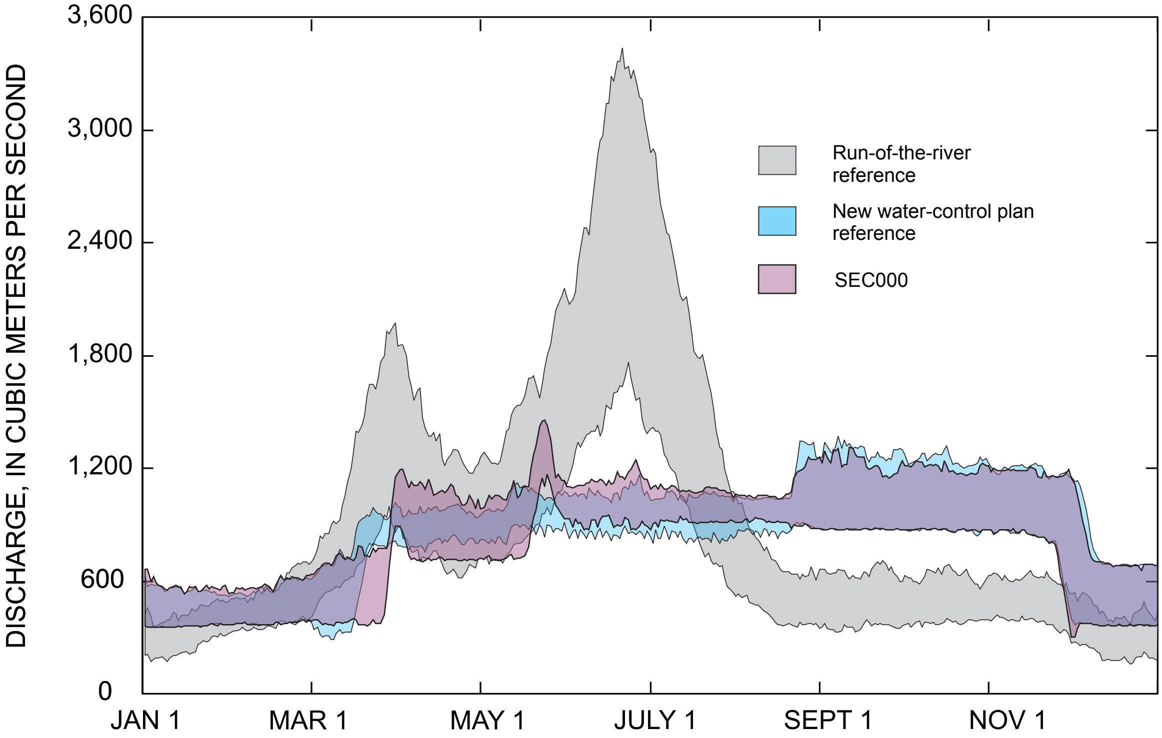
Analysis of Pulsed Flow Modification Alternatives, Lower Missouri River, 2005



Open-File Report 2008–1113

U.S. Department of the Interior
U.S. Geological Survey

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By Robert B. Jacobson

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic kilometer (km^3)	810713.2	acre-foot (ac-ft)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second per day ($m^3/s/d$)	35.31	cubic foot per second per day ($ft^3/s/d$)

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By Robert B. Jacobson

Abstract

The graphical, tabular, and statistical data presented in this report resulted from analysis of alternative flow regime designs considered by a group of Missouri River managers, stakeholders, and scientists during the summer of 2005. This plenary group was charged with designing a flow regime with increased spring flow pulses to support reproduction and survival of the endangered pallid sturgeon. Environmental flow components extracted from the reference natural flow regime were used to design and assess performance of alternative flow regimes. The analysis is based on modeled flow releases from Gavins Point Dam (near Yankton, South Dakota) for nine design alternatives and two reference scenarios; the reference scenarios are the run-of-the-river and the water-control plan implemented in 2004. The alternative designs were developed by the plenary group with the goal of providing pulsed spring flows, while retaining traditional social and economic uses of the river.

Introduction

A group of managers, stakeholders, and scientists (Missouri River Plenary Group, hereafter referred to as the plenary group) met during the summer of 2005 to design a more naturalized flow regime for the Lower Missouri River. The plenary group consisted of representatives of many interests on the Missouri River, including Federal and State Government agencies, Native American Tribes, and groups representing agriculture, navigation, public water supply, hydroelectric power, and environmental interests. The primary objective for a new flow regime was to support reproduction and survival of the endangered pallid sturgeon, *Scaphirhynchus albus*, while minimizing negative effects to social and commercial benefits of present river management. Specific flow-regime requirements for pallid sturgeon reproduction are unknown; therefore, much of the design process was based on features of the natural flow regime. The U.S. Geological Survey (USGS) facilitated the design process by developing tools to visualize, extract, and analyze Environmental Flow Components (EFCs) from simulation model outputs. Analyses were completed for two reference flow regimes and for nine design scenarios developed by the plenary group.

Purpose and Scope

The purpose of this report is to act as a repository for graphical and tabular results of the analysis of alternative flow regimes. The materials are intended to provide support for extended interpretations and analyses published elsewhere.

This analysis focuses on modeled flow releases from Gavins Point Dam (fig. 1) for two reference scenarios and nine alternative designs (table 1). The reference scenarios are the run of the river (ROR) and the new water-control plan (NWCP) implemented in 2004 (U.S. Army Corps of Engineers, 2006a). The alternative scenarios were developed by the plenary group with the objective of providing pulsed spring flows while retaining traditional social and economic uses of the river. Flow regime time series were developed by the U.S. Army Corps of Engineers using the Missouri River daily routing model (DRM) (U.S. Army Corps of Engineers, 1998). This report is limited to visualization and analysis of outputs of the DRM model for the reference and alternative flow regimes.

Acknowledgments

Daily routing model output files were provided by Roy McAllister and Michael Swenson, U.S. Army Corps of Engineers, Northwestern Division, Omaha, Nebraska.

Methods

The input to this analysis consisted of output of the DRM for modeled flow-regime scenarios. The DRM synthesizes Lower Missouri River (LMOR) discharge based on historical data for tributary inflows, calculations of streamflow depletions from evapotranspiration and consumptive use, and modifications of reservoir outflows according to water-control rules. The model simulates how reservoirs would be managed with a set of water-control rules, given the actual range of

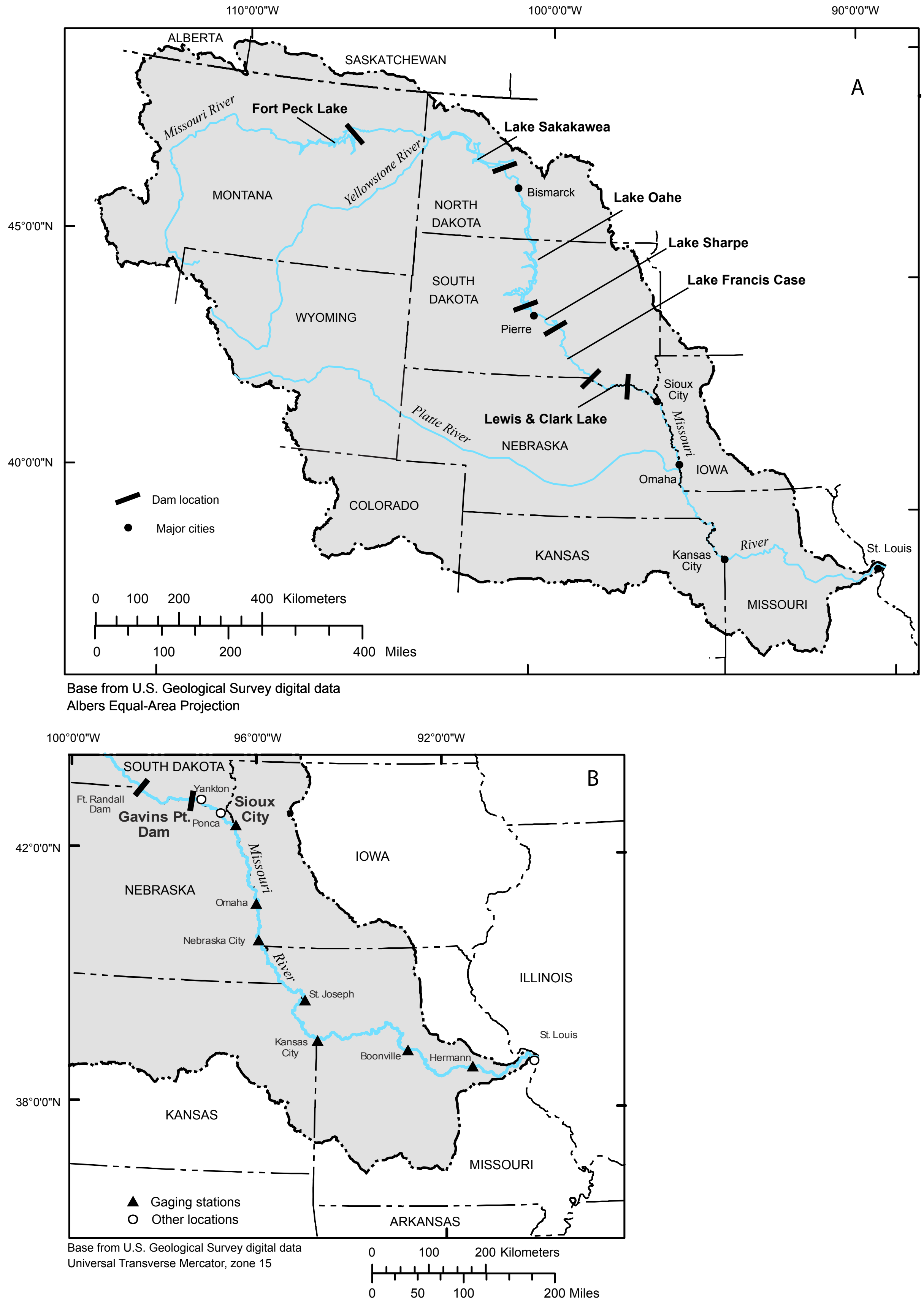


Figure 1. Map showing Missouri River Basin, Lower Missouri River (LMOR), and locations discussed in the text.

variability of historical inflow data. Historical data are available, or have been estimated, for the period 1898–1997. The DRM uses these data and water-control rules to generate 100 years of daily flows for 14 locations on the mainstem Missouri River. The 14 locations consist of nine streamflow-gaging stations on the Lower Missouri River and five streamflow-gaging stations in inter-reservoir river segments. This analysis focuses on evaluation of alternative flow regimes at Sioux City, Iowa, 125 kilometers (km) downstream from Gavins Point Dam and at additional sites downstream at Nebraska City, Nebraska, and St. Joseph, Missouri. The Sioux City, Iowa, streamflow-gaging station provides a view of the flow regime for discharges that are representative of the upstream 300 km of the LMOR. Flooding assessments were performed at Nebraska City, Nebraska, and St. Joseph, Missouri, because these were areas identified by stakeholders as sensitive to flooding.

Alternative flow-regime scenarios for this analysis were developed through collaborative discussion within the plenary group. Conceptual hydrographs developed through discussions were coded into reservoir release rules for the DRM (U.S. Army Corps of Engineers, 2005). Different sub-groups within the plenary group developed conceptual hydrographs that varied according to ecological and social values held by the group (table 1). In addition to the general shape of the conceptual hydrograph, rules are required to address varying hydroclimatic conditions from year to year. Variable hydroclimatic conditions are addressed with storage precludes and flood-control constraints. Storage precludes account for low storage in the reservoirs during drought by limiting spring-pulse releases from Gavins Point Dam. Precludes stipulate an amount of storage that is necessary before a pulse can be released, and may stipulate a prorationing of flow for the pulse based on storage on certain dates (U.S. Army Corps of Engineers, 2006b). The rules also account for high-flow years by using flood-control constraints. Flood-control constraints limit releases of pulses during wet climatic conditions by setting maximum target flows downstream in the mainstem. Flood-control constraints are the flows that turn off upstream releases, so they must be relaxed (increased or lifted) in many years to allow pulses to occur. Flow-regime scenarios, storage precludes, and flood-control constraints are listed in table 2.

Visualization of Model Results

DRM output data for reference and alternative flow regimes were analyzed to provide a graphical understanding of similarities and differences among scenarios. The method involved calculating duration hydrographs to show annual and inter-annual variability of discharge on a single graph (Jacobson and Heuser, 2001). Inter-annual variability is shown as the band of daily discharges from 25 percent exceedance to 75 percent exceedance as modeled by the DRM. To provide a graphical comparison with reference flow regimes, duration hydrographs of alternatives were superimposed graphically on the ROR and NWCP duration hydrographs (figs. 2–9).

Extracting Flow Pulses

The main analysis consisted of extracting flow pulses from the DRM output to compare relative performance among design alternatives and to compare to the reference flow regimes. The approach used is similar to the Index of Hydrologic Alteration (IHA) method (Richter and others, 1996; The Nature Conservancy, 2005) in which environmental flow components (EFCs) are defined as ecologically meaningful parameters of the flow regime. The concept of EFCs is used in this analysis, although the complexity of the Missouri River hydrograph and the design task required customized computer code to extract information on flow pulses.

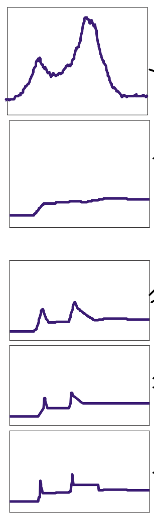
The process employs a two-step approach in which the statistical properties of the population of all possible pulses in the flow regime were subsequently used to parameterize extraction of a subset of pulses thought to be ecologically significant. This method serves to scale the size of extracted pulses by inherent scale of pulses in the flow regime. The procedure was automated by Perl scripts (Practical Extraction and Report Language, ActiveState Corporation, Vancouver, British Columbia). The basic steps are given in the following list:

1. Develop an unfiltered pulse dataset (UPD) from the ROR flow regime at Sioux City, Iowa, by identifying each rising, falling, flat, and peak component of the hydrograph time series to isolate all pulses regardless of duration.
    - Beginnings and endings of all pulses were identified as changes in slope from decreasing to increasing.
    - Peaks were identified as points or parts of the time series in which increasing discharge was followed by decreasing discharge.
    - Because hydrographs of regulated rivers are prone to plateau periods of no measured change, a criterion was needed to assign a plateau to peaks or flats. Seven days was used as a maximum plateau to be identified as a peak.
    - Each pulse in the UPD was attributed with start date, start discharge, peak date, peak discharge, end date, and end discharge.
2. Calculate simple EFCs for each of the UPD pulses (table 2.).
3. Tabulate quantiles of the UPD pulses.
4. Iteratively test various quantiles for their utility as parameters for extracting subsets of pulses of the UPD, and for combining small pulses into dominant, larger pulses. This is a subjective calibration step in which pulses are eliminated, combined, and extracted depending on their EFC's relative to quantiles of the UPD EFCs.

Table 1. Selected flow-regime alternative design parameters, indicators of ecological benefits, and indicators of social-economic costs.

[m^3/s, cubic meters per second; km^3, cubic kilometers; FCC, flood-control constraint; >, greater than]

Shape



Scenario	Alternative	Alternative parameters: Pulse magnitude, Gavins Point Dam release, m^3/s — Early	Late	Preclude for pulse, system storage, km^3 — All Pulse	Relaxation of flood-control constraints, additional m^3/s — Early	Late
ROR	Run of the river					
NWCP	Current water-control plan	0	0			
RF2500	25th Percentile natural flow regime—full lift FCC	510	680	38	510	680
RF250F3	25th Percentile natural flow regime—partial lift FCC	510	680	38	280	450
HMU000	Multiple use, full lift FCC	480	570	38	480	570
HMU0F3	Multiple use, partial lift FCC	480	570	38	260	340
HMU0F0	Multiple use, no lift FCC	480	570	38	0	0
HMU000[1]	Multiple use, partiallLift FCC	480	570	38	260	340
HMU403	Multiple use, partial lift FCC	480	570	49.3	260	340
HMU493	Multiple use, partial lift FCC	480	570	60.4	260	340
SEC000	Socio-economic	480	570	38	260	450

Scenario	Indicators of ecological benefits: Realized pulse rising peak at Sioux City, Iowa, median, m^3/s — Early	Late	Realized pulse duration at Sioux City, Iowa, median, days — Early	Late	Annual number of pulses > 10% of reference, realized at Sioux City, Iowa — Early	Late	Indicators of social-econcomic costs: Design volume of spring pulse, km^3 — Early	Late	Total	Minimum system storage during 1930's, km^3	Median days exceeding flood levels for agricultural land, March–April and May–June, Nebrasksa City, Nebraska — Early	Late	75th percentile, days > flood stage, April–June, St. Joseph, Missouri — All Pulses
ROR	1310	1360	50	50	1.23	1.53				NA	33	78	44.5
NWCP	290	240	20	21.5	0.6	0.34	0.18	0.33	0.51	32.8	7.1	14.2	6.0
RF2500	450	580	20	31	0.94	1.02	0.28	0.91	1.19	31.6	13.7	29.5	9.0
RF250F3	450	530	20	31	0.95	0.99	0.28	0.91	1.19	31.6	13.8	29.2	9.0
HMU000	410	480	15	28	0.71	0.92	0.18	0.33	0.51	32.5	13.9	30.1	9.0
HMU0F3	450	530	20	31	0.67	0.75	0.18	0.33	0.51	32.7	13.8	29.8	9.0
HMU0F0	300	330	18	30	0.53	0.56	0.18	0.33	0.51	33.3	13.4	26.7	9.0
HMU000[1]	450	530	20	31	0.67	0.75	0.18	0.33	0.51	32.7	13.8	29.8	9.0
HMU403	350	430	12	28	0.67	0.75	0.18	0.33	0.51	32.9	13.9	29.8	9.0
HMU493	360	360	16	28	0.66	0.75	0.18	0.33	0.51	33.2	13.9	29.6	9.0
SEC000	420	510	16	27	0.78	0.95	0.16	0.33	0.49	32.8	14.0	28.4	9.0

[1]HMU000 is repeated to show sequence of rising preludes with full lift of flood-control constraints.

Table 2. Simple environmental flow components used in flow-regime analysis

[m^3/s, cubic meters per second; $m^3/s/d$, cubic meters per second per day]

Environmental flow component	Calculation	Units
Duration	(End date) - (Start date)	Days
Relative Rising Peak	(Peak discharge) - (Start discharge)	m^3/s
Rate of Rise	(Relative Rising Peak)/((Peak date) - (End date))	$m^3/s/d$
Relative Falling Peak	(Peak discharge) - (Start discharge)	m^3/s
Rate of Fall	(Relative Rising Peak)/((Peak date) - (End date))	$m^3/s/d$
Relative Peak	Greater of Relative Rising Peak and Relative Falling Peak	m^3/s

5. Once calibrated from the ROR flow regime, similar parameter values were used on all flow scenarios. Extraction of filtered pulses was based on:
   - A primary criterion required candidate pulse peaks to equal or exceed the median discharge.
   - EFCs were calculated for pulses that met this first criterion, and tested against a second criterion:
     a. The duration must equal or exceed the median duration of the UPD and,
     b. Either the relative rise or the relative fall must exceed the 75th percentile of those variables from the UPD.
   - If the pulse failed to meet the second criterion, it was combined with the next pulse, and retested against the second criterion.
   - The next pulse in the time series was combined with any pulse meeting the second criterion if the relative rise to the next pulse peak was less than or equal to the 75th percentile of relative rise in the UPD.
6. New EFCs were calculated from redefined starts, peaks, and ends of the filtered pulses, and tabulated.
7. All discharge values in the time series were then reclassified as pulses or non pulses.

The design process on LMOR also needed to address the bimodal nature of the natural flow regime (for example, fig. 2). Discrete date windows for the early and late spring pulses were defined based on the long-term record of the ROR flow regime. The early pulse was defined as having the peak date between March 1 and April 30. The later pulse was similarly defined as having the peak date between May 1 and July 31. The pulses may start or end beyond these dates, but the pulses are identified from the record as those with peaks that occur within these date windows.

Graphical and Statistical Analysis of Pulsed Flow Modification Alternatives

Statistical parameters of pulse peak dates, peak discharges, relative rising peak discharges, durations, and rates of rise and fall were extracted from all 11 flow-regime scenarios (table 2). The early and late peaks were analyzed separately.

Non-parametric, Kolmogorov-Smirnov goodness-of-fit statistics(Systat Software, 2006) were used to test differences between cumulative distribution functions of EFC's of alternative flow regime scenarios to EFC's of the reference flow regime and to each other (tables 3–9). These comparisons indicate how distributions of ecological indicators vary by flow design and within the context of 100 years of hydroclimatic variability. Flow regimes that are determined to be significantly different by this test are not necessarily ecologically different because the Kolmogorov-Smirnov test assesses only differences in the distributions, not the functions of specific parts of the distributions.

Results

Results of the graphical comparisons of the interquartile ranges of alternative flow regimes to the ROR and NWCP flow regimes (figs. 2–9) indicate subtle differences among the alternatives. Visually, minimal difference is evident between R25000 and R250F3, although flood-control constraints were completely relaxed for R25000, and only partially relaxed for R250F3 (figs. 2, 3). Similarly, minimal difference is evident visually between HMU000 and HMU0F3 (figs. 4, 5). A substantial difference is evident, however, in HMU0F0, an alternative for which there was no relaxing of flood-control constraints for flow pulses (fig. 6).

The series HMU000, HMU403, and HMU493 indicate the effect of increasing system storage precludes on when flow pulses can be released (table 3, figs. 4, 7, 8). Visually, there is minimal difference among these alternatives. The SEC000 alternative has a more prominent early pulse than the HMU series (fig. 9). The late pulse of SEC000 appears similar to that of the RF series.

The Kolmogorov-Smirnov tests (tables 3–10) assess whether or not two samples come from the same distribution by comparing their cumulative distribution functions (Systat Software, 2006). Low p-values indicate low probability that two samples came from the same distribution.

Distributions of early-pulse relative rising peak magnitudes vary little among alternative design flow regimes, but all designs are significantly different from the ROR (table 3). The NWCP does not differ significantly from the HMU series.

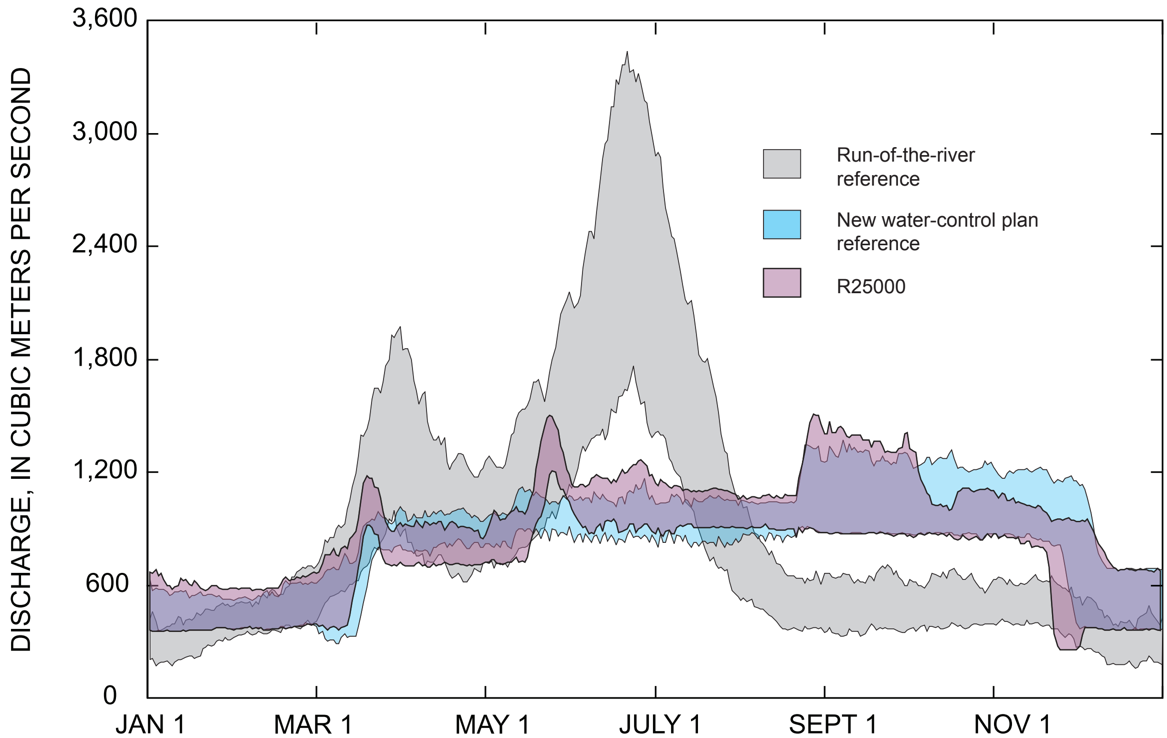


Figure 2. Duration hydrographs, Missouri River at Sioux City, Iowa, showing interquartile range of daily discharge exceedances for the run-of-the-river reference, new water-control plan reference, and the R25000 alternative, modeled for historical conditions 1898–1997.

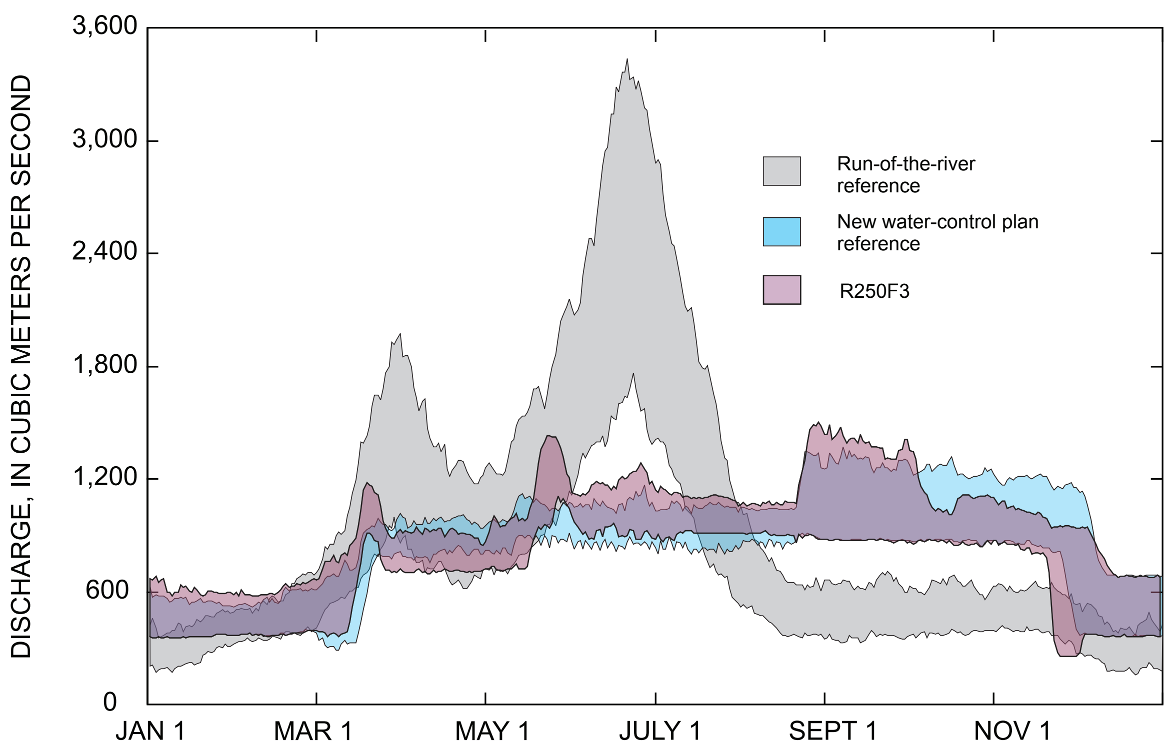


Figure 3. Duration hydrographs, Missouri River at Sioux City, Iowa, showing interquartile range of daily discharge exceedances for the run-of-the-river reference, new water-control plan reference, and the R250F3 alternative, modeled for historical conditions 1898–1997.

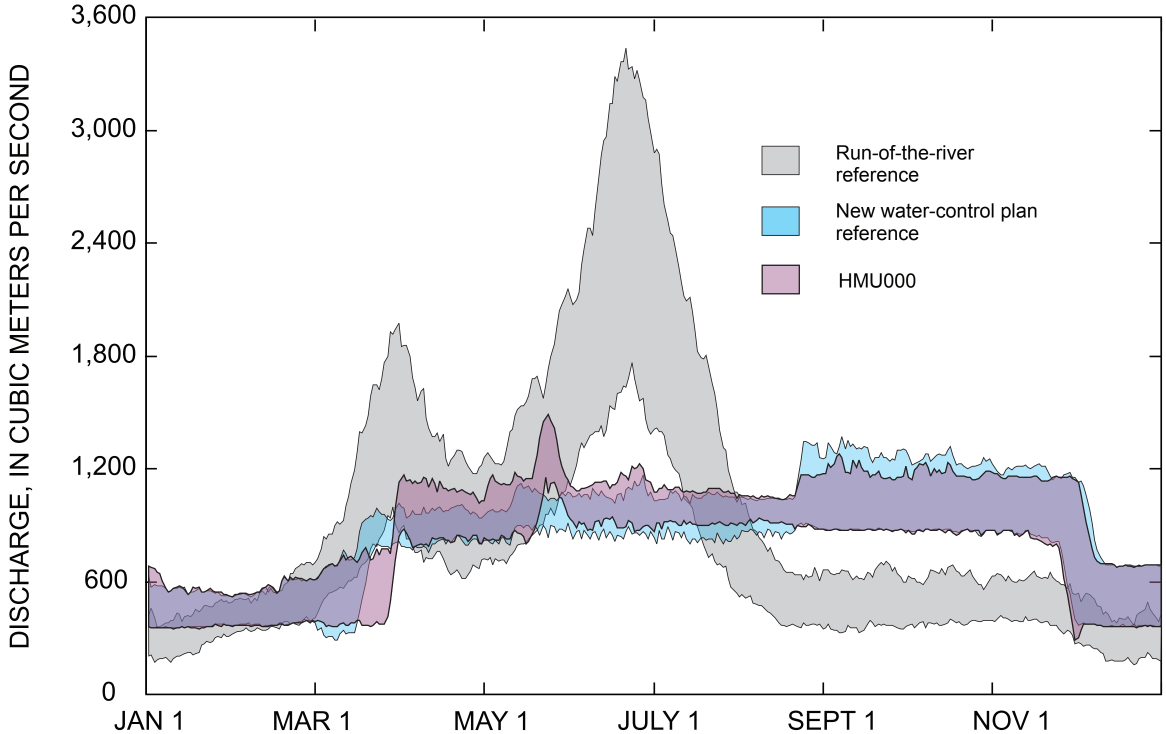


Figure 4. Duration hydrographs, Missouri River at Sioux City, Iowa, showing interquartile range of daily discharge exceedances for the run-of-the-river reference, new water-control plan reference, and the HMU000 alternative, modeled for historical conditions 1898–1997.

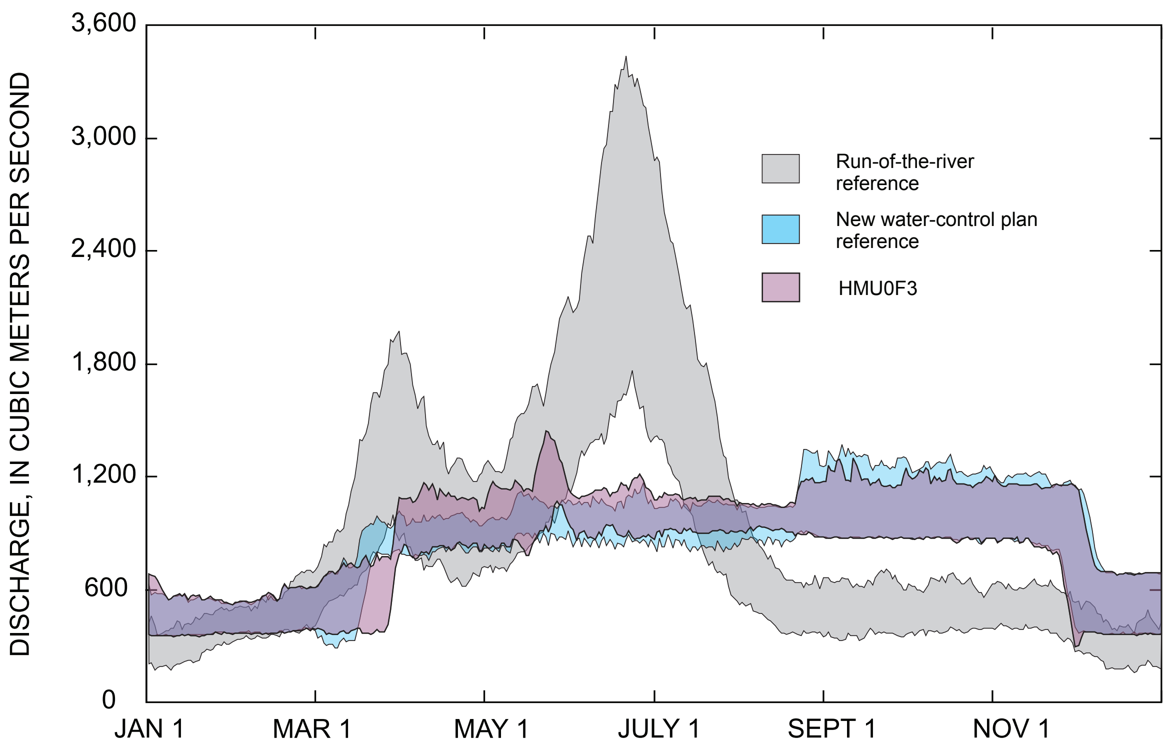


Figure 5. Duration hydrographs, Missouri River at Sioux City, Iowa, showing interquartile range of daily discharge exceedances for the run-of-the-river reference, new water-control plan reference, and the HMU0F3 alternative, modeled for historical conditions 1898–1997.

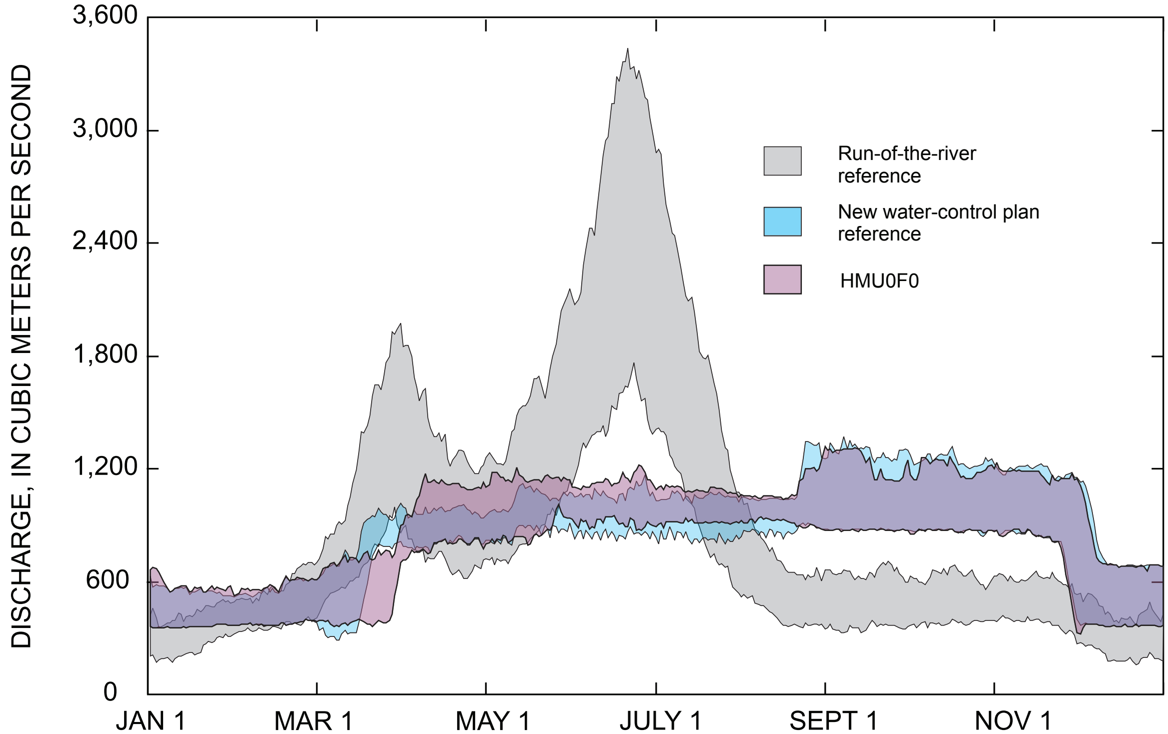


Figure 6. Duration hydrographs, Missouri River at Sioux City, Iowa, showing interquartile range of daily discharge exceedances for the run-of-the-river reference, new water-control plan reference, and the HMU0F0 alternative, modeled for historical conditions 1898–1997.

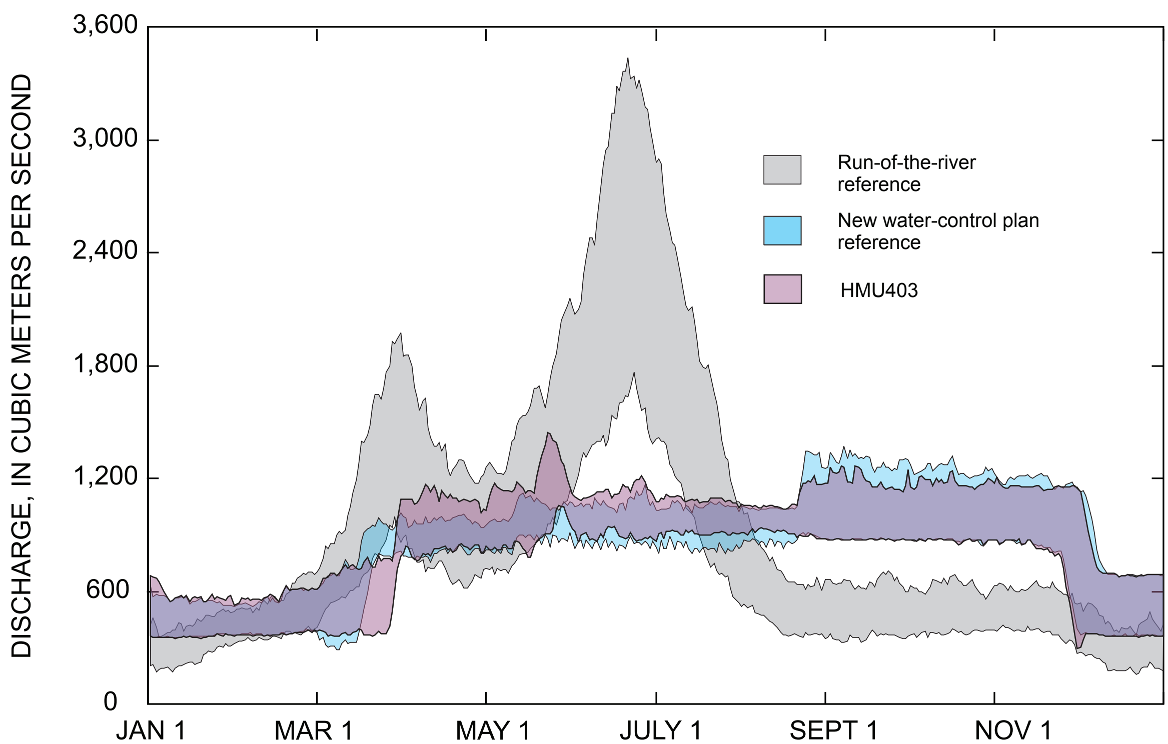


Figure 7. Duration hydrographs, Missouri River at Sioux City, Iowa, showing interquartile range of daily discharge exceedances for the run-of-the-river reference, new water-control plan reference, and the HMU403 alternative, modeled for historical conditions 1898–1997.

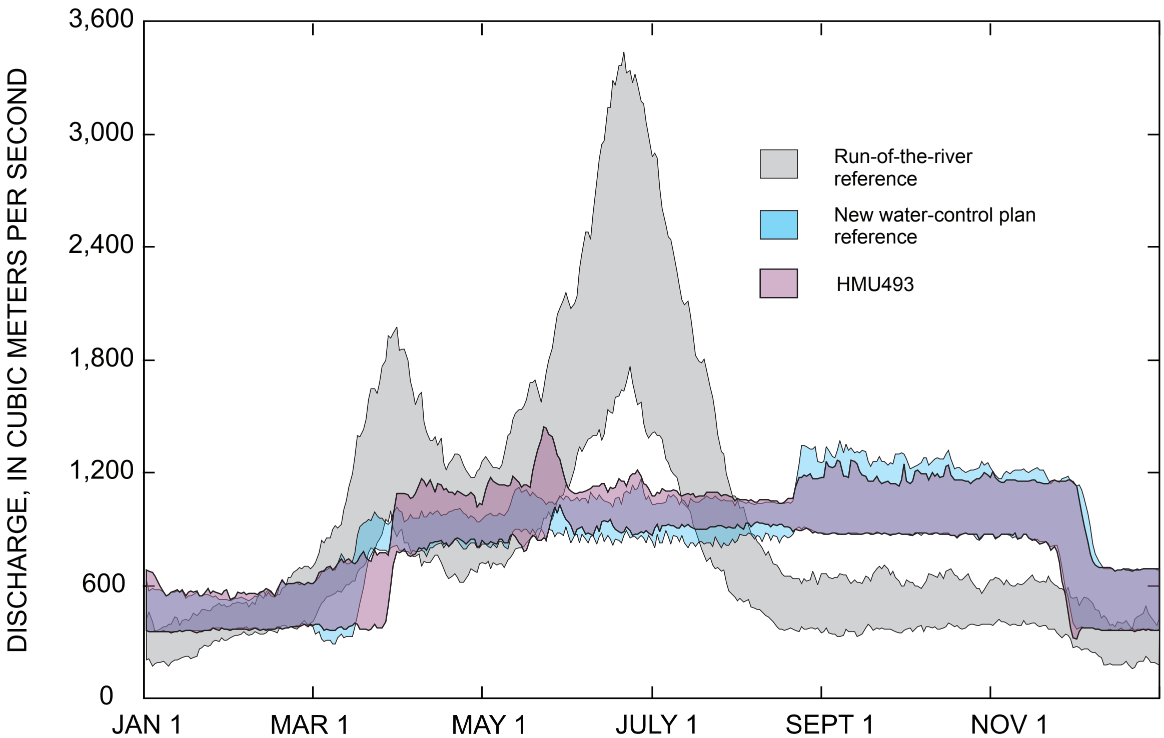


Figure 8. Duration hydrographs, Missouri River at Sioux City, Iowa, showing interquartile range of daily discharge exceedances for the run-of-the-river reference, new water-control plan reference, and the HMU493 alternative, modeled for historical conditions 1898–1997.

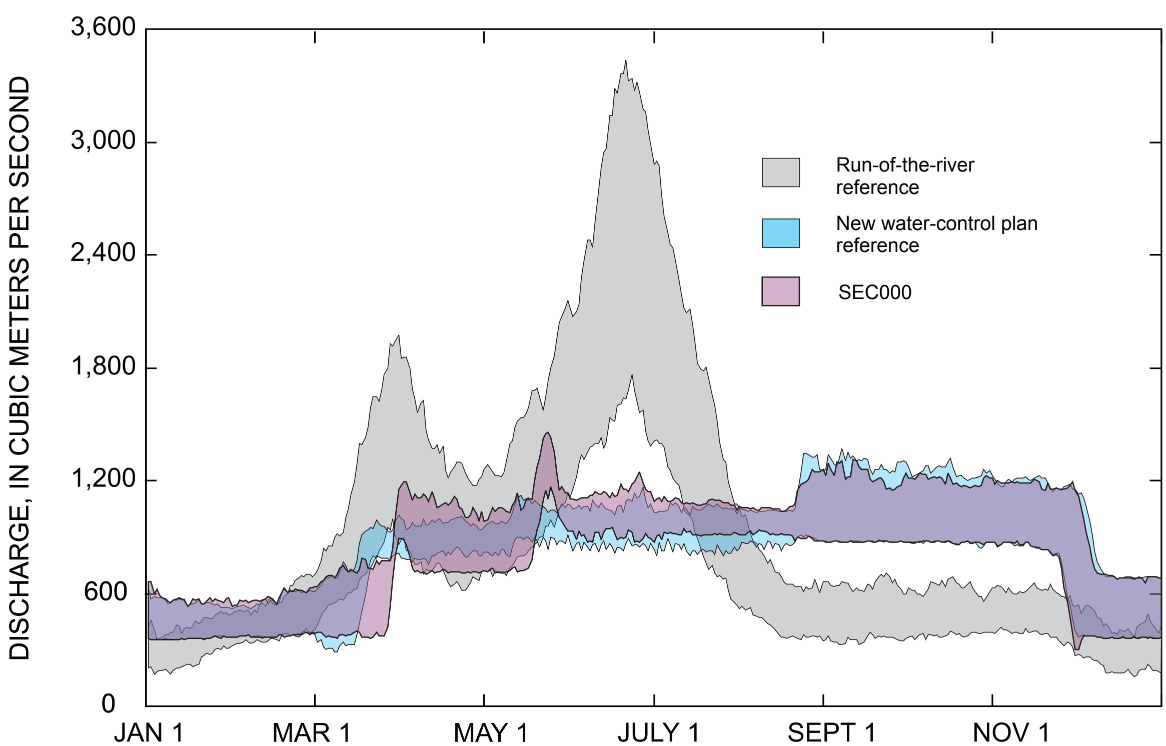


Figure 9. Duration hydrographs, Missouri River at Sioux City, Iowa, showing interquartile range of daily discharge exceedances for the run-of-the-river reference, new water-control plan reference, and the SEC000 alternative, modeled for historical conditions 1898–1997.

Table 3. Comparisons of early pulse magnitude distributions.

[Two sided probabilities that distributions are equal, Kolmogorov-Smirnov non-parametric test. Paired comparisons significant at the 0.05 level are shown in bold. Scenarios: ROR, run-of-the-river reference; NWCP, new water-control plan reference; R2500, 25th percentile of natural reference; R250F3, 25th percentile of natural reference with partial lift of flood-control constraints; HMU000, multiple use with full lift of flood-control constraints; HMU0F3, multiple use with partial lift of flood-control-constraints; HMU0F0, multiple use with no lift of flood-control constraints; HMU403, multiple use with partial lift of flood-control constraints plus 49.3 cubic kilometers storage preclude; HMU493, multiple use with partial lift of flood-control constraints and 60.4 cubic kilometers storage preclude; SEC000, social-economic scenario no lift of flood-control constraints.

	Reference regime	Current water-control plan	25th percentile of reference regime		Multiple use, increasing flood-control constraints			Multiple use, increasing storage precludes		Social-economic
	ROR	NWCP	R25000	R250F3	HMU000	HMU0F3	HMU0F0	HMU403	HMU493	SEC000
ROR	*1.00*									
NWCP	**0.00**	*1.00*								
R25000	**0.00**	**0.00**	*1.00*							
R250F3	**0.00**	**0.00**	1.00	*1.00*						
HMU000	**0.00**	0.08	0.12	0.11	*1.00*					
HMU0F3	**0.00**	0.64	0.02	**0.02**	0.40	*1.00*				
HMU0F0	**0.00**	0.47	**0.00**	**0.00**	0.07	0.46	*1.00*			
HMU403	**0.00**	0.70	**0.02**	**0.02**	0.30	1.00	0.51	*1.00*		
HMU493	**0.00**	0.47	**0.02**	**0.01**	0.38	1.00	0.53	1.00	1.00	
SEC000	**0.00**	**0.05**	0.19	0.18	1.00	0.32	0.04	0.29	0.36	*1.00*

Table 4. Comparisons of late pulse magnitude distributions.

[Two sided probabilities that distributions are equal, Kolmogorov-Smirnov non-parametric test. Paired comparisons significant at the 0.05 level are shown in bold. Scenarios: ROR, run-of-the-river reference; NWCP, new water-control plan reference; R2500, 25th percentile of natural reference; R250F3, 25th percentile of natural reference with partial lift of flood-control constraints; HMU000, multiple use with full lift of flood-control constraints; HMU0F3, multiple use with partial lift of flood-control-constraints; HMU0F0, multiple use with no lift of flood-control constraints; HMU403, multiple use with partial lift of flood-control constraints plus 49.3 cubic kilometers storage preclude; HMU493, multiple use with partial lift of flood-control constraints and 60.4 cubic kilometers storage preclude; SEC000, social-economic scenario no lift of flood-control constraints.

	Reference regime	Current water-control plan	25th percentile of reference regime		Multiple use, increasing flood-control constraints			Multiple use, increasing storage precludes		Social-economic
	ROR	NWCP	R25000	R250F3	HMU000	HMU0F3	HMU0F0	HMU403	HMU493	SEC000
ROR	*1.00*									
NWCP	**0.00**	*1.00*								
R25000	**0.00**	**0.00**	*1.00*							
R250F3	**0.00**	**0.00**	0.07	*1.00*						
HMU000	**0.00**	**0.00**	**0.00**	0.24	*1.00*					
HMU0F3	**0.00**	**0.00**	**0.00**	**0.01**	0.44	*1.00*				
HMU0F0	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.02**	*1.00*			
HMU403	**0.00**	**0.00**	**0.00**	**0.01**	0.48	1.00	**0.03**	*1.00*		
HMU493	**0.00**	**0.00**	**0.00**	**0.02**	0.63	0.89	**0.04**	1.00	*1.00*	
SEC000	**0.00**	**0.00**	0.07	0.94	0.74	**0.05**	**0.00**	0.07	0.17	*1.00*

Table 5. Comparisons of early pulse duration distributions.

[Two sided probabilities that distributions are equal, Kolmogorov-Smirnov non-parametric test. Paired comparisons significant at the 0.05 level are shown in bold. Scenarios: ROR, run-of-the-river reference; NWCP, new water-control plan reference; R2500, 25th percentile of natural reference; R250F3, 25th percentile of natural reference with partial lift of flood-control constraints; HMU000, multiple use with full lift of flood-control constraints; HMU0F3, multiple use with partial lift of flood-control-constraints; HMU0F0, multiple use with no lift of flood-control constraints; HMU403, multiple use with partial lift of flood-control constraints plus 49.3 cubic kilometers storage preclude; HMU493, multiple use with partial lift of flood-control constraints and 60.4 cubic kilometers storage preclude; SEC000, social-economic scenario no lift of flood-control constraints.

	Reference regime	Current water-control plan	25th percentile of reference regime		Multiple use, increasing flood-control constraints			Multiple use, increasing storage precludes		Social-economic
	ROR	**NWCP**	**R25000**	**R250F3**	**HMU000**	**HMU0F3**	**HMU0F0**	**HMU403**	**HMU493**	**SEC000**
ROR	*1.00*									
NWCP	**0.00**	*1.00*								
R25000	**0.00**	0.18	*1.00*							
R250F3	**0.00**	0.29	1.00	*1.00*						
HMU000	**0.00**	**0.03**	**0.03**	**0.02**	*1.00*					
HMU0F3	**0.00**	**0.01**	**0.01**	**0.01**	1.00	*1.00*				
HMU0F0	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.00	*1.00*			
HMU403	**0.00**	**0.02**	**0.02**	**0.01**	1.00	1.00	**0.00**	*1.00*		
HMU493	**0.00**	0.10	0.11	0.07	0.95	0.96	**0.00**	1.00	*1.00*	
SEC000	**0.00**	0.18	0.12	0.06	0.99	0.59	**0.00**	0.75	1.00	*1.00*

Table 6. Comparisons of late pulse duration distributions.

[Two sided probabilities that distributions are equal, Kolmogorov-Smirnov non-parametric test. Paired comparisons significant at the 0.05 level are shown in bold. Scenarios: ROR, run-of-the-river reference; NWCP, new water-control plan reference; R2500, 25th percentile of natural reference; R250F3, 25th percentile of natural reference with partial lift of flood-control constraints; HMU000, multiple use with full lift of flood-control constraints; HMU0F3, multiple use with partial lift of flood-control-constraints; HMU0F0, multiple use with no lift of flood-control constraints; HMU403, multiple use with partial lift of flood-control constraints plus 49.3 cubic kilometers storage preclude; HMU493, multiple use with partial lift of flood-control constraints and 60.4 cubic kilometers storage preclude; SEC000, social-economic scenario no lift of flood-control constraints.

	Reference regime	Current water-control plan	25th percentile of reference regime		Multiple use, increasing flood-control constraints			Multiple use, increasing storage precludes		Social-economic
	ROR	**NWCP**	**R25000**	**R250F3**	**HMU000**	**HMU0F3**	**HMU0F0**	**HMU403**	**HMU493**	**SEC000**
ROR	*1.00*									
NWCP	**0.00**	*1.00*								
R25000	**0.00**	**0.00**	*1.00*							
R250F3	**0.00**	**0.00**	0.98	*1.00*						
HMU000	**0.00**	**0.00**	0.53	0.59	*1.00*					
HMU0F3	**0.00**	**0.00**	0.74	0.84	1.00	*1.00*				
HMU0F0	**0.00**	**0.00**	0.55	0.60	0.47	0.55	*1.00*			
HMU403	**0.00**	**0.00**	0.77	0.90	1.00	1.00	0.58	*1.00*		
HMU493	**0.00**	**0.00**	0.72	0.87	0.95	1.00	0.56	1.00	*1.00*	
SEC000	**0.00**	**0.00**	0.13	0.18	0.46	0.74	0.32	0.60	0.73	*1.00*

Table 7. Comparisons of days per year low-lying agricultural lands are affected by flows, early pulse, Nebraska City, Nebraska.

[Two sided probabilities that distributions are equal, Kolmogorov-Smirnov non-parametric test. Paired comparisons significant at the 0.05 level are shown in bold. Scenarios: ROR, run-of-the-river reference; NWCP, new water-control plan reference; R2500, 25th percentile of natural reference; R250F3, 25th percentile of natural reference with partial lift of flood-control constraints; HMU000, multiple use with full lift of flood-control constraints; HMU0F3, multiple use with partial lift of flood-control-constraints; HMU0F0, multiple use with no lift of flood-control constraints; HMU403, multiple use with partial lift of flood-control constraints plus 49.3 cubic kilometers storage preclude; HMU493, multiple use with partial lift of flood-control constraints and 60.4 cubic kilometers storage preclude; SEC000, social-economic scenario no lift of flood-control constraints.

	Reference regime	Current water-control plan	25th percentile of reference regime		Multiple use, increasing flood-control constraints			Multiple use, increasing storage precludes		Social-economic
	ROR	**NWCP**	**R25000**	**R250F3**	**HMU000**	**HMU0F3**	**HMU0F0**	**HMU403**	**HMU493**	**SEC000**
ROR	*1.00*									
NWCP	**0.00**	*1.00*								
R25000	**0.00**	0.32	*1.00*							
R250F3	**0.00**	0.41	1.00	*1.00*						
HMU000	**0.00**	0.63	0.93	0.93	*1.00*					
HMU0F3	**0.00**	0.74	0.98	0.98	1.00	*1.00*				
HMU0F0	**0.00**	0.74	0.98	0.98	0.98	1.00	*1.00*			
HMU403	**0.00**	0.74	0.98	0.98	1.00	1.00	1.00	*1.00*		
HMU493	**0.00**	0.74	0.98	0.98	1.00	1.00	1.00	1.00	*1.00*	
SEC000	**0.00**	0.74	0.93	0.93	1.00	1.00	1.00	1.00	1.00	*1.00*

Table 8. Comparisons of days per year low-lying agricultural lands are affected by flows, late pulse, Nebraska City, Nebraska.

[Two sided probabilities that distributions are equal, Kolmogorov-Smirnov non-parametric test. Paired comparisons significant at the 0.05 level are shown in bold. Scenarios: ROR, run-of-the-river reference; NWCP, new water-control plan reference; R2500, 25th percentile of natural reference; R250F3, 25th percentile of natural reference with partial lift of flood-control constraints; HMU000, multiple use with full lift of flood-control constraints; HMU0F3, multiple use with partial lift of flood-control-constraints; HMU0F0, multiple use with no lift of flood-control constraints; HMU403, multiple use with partial lift of flood-control constraints plus 49.3 cubic kilometers storage preclude; HMU493, multiple use with partial lift of flood-control constraints and 60.4 cubic kilometers storage preclude; SEC000, social-economic scenario no lift of flood-control constraints.

	Reference regime	Current water-control plan	25th percentile of reference regime		Multiple use, increasing flood-control constraints			Multiple use, increasing storage precludes		Social-economic
	ROR	**NWCP**	**R25000**	**R250F3**	**HMU000**	**HMU0F3**	**HMU0F0**	**HMU403**	**HMU493**	**SEC000**
ROR	*1.00*									
NWCP	**0.00**	*1.00*								
R25000	**0.00**	**0.00**	*1.00*							
R250F3	**0.00**	**0.00**	1.00	*1.00*						
HMU000	**0.00**	**0.02**	0.98	0.98	*1.00*					
HMU0F3	**0.00**	**0.03**	0.93	0.93	1.00	*1.00*				
HMU0F0	**0.00**	0.74	**0.03**	**0.05**	0.19	0.32	*1.00*			
HMU403	**0.00**	**0.03**	0.98	0.93	1.00	1.00	0.32	*1.00*		
HMU493	**0.00**	**0.05**	0.93	0.85	1.00	1.00	0.41	1.00	*1.00*	
SEC000	**0.00**	**0.05**	0.52	0.52	0.98	1.00	0.41	1.00	1.00	*1.00*

Table 9. Comparisons of days per year flood stage is exceeded April–June, St. Joseph, Missouri.

[Two sided probabilities that distributions are equal, Kolmogorov-Smirnov non-parametric test. Paired comparisons significant at the 0.05 level are shown in bold. Scenarios: ROR, run-of-the-river reference; NWCP, new water-control plan reference; R2500, 25th percentile of natural reference; R250F3, 25th percentile of natural reference with partial lift of flood-control constraints; HMU000, multiple use with full lift of flood-control constraints; HMU0F3, multiple use with partial lift of flood-control-constraints; HMU0F0, multiple use with no lift of flood-control constraints; HMU403, multiple use with partial lift of flood-control constraints plus 49.3 cubic kilometers storage preclude; HMU493, multiple use with partial lift of flood-control constraints and 60.4 cubic kilometers storage preclude; SEC000, social-economic scenario no lift of flood-control constraints.

	Reference regime	Current water-control plan	25th percentile of reference regime		Multiple use, increasing flood-control constraints			Multiple use, increasing storage precludes		Social-economic
	ROR	NWCP	R25000	R250F3	HMU000	HMU0F3	HMU0F0	HMU403	HMU493	SEC000
ROR	*1.00*									
NWCP	**0.00**	*1.00*								
R25000	**0.00**	0.93	*1.00*							
R250F3	**0.00**	0.63	0.25	*1.00*						
HMU000	**0.00**	1.00	1.00	0.19	*1.00*					
HMU0F3	**0.00**	0.98	1.00	0.19	1.00	*1.00*				
HMU0F0	**0.00**	0.98	1.00	0.19	1.00	1.00	1.00			
HMU403	**0.00**	0.98	1.00	0.19	1.00	1.00	1.00	*1.00*		
HMU493	**0.00**	0.98	1.00	0.19	1.00	1.00	1.00	1.00	*1.00*	
SEC000	**0.00**	0.98	1.00	0.19	1.00	1.00	1.00	1.00	1.00	*1.00*

Table 10. Comparisons of minimum monthly storage levels in reservoir system.

[Two sided probabilities that distributions are equal, Kolmogorov-Smirnov non-parametric test. Paired comparisons significant at the 0.05 level are shown in bold. Scenarios: ROR, run-of-the-river reference; NWCP, new water-control plan reference; R2500, 25th percentile of natural reference; R250F3, 25th percentile of natural reference with partial lift of flood-control constraints; HMU000, multiple use with full lift of flood-control constraints; HMU0F3, multiple use with partial lift of flood-control-constraints; HMU0F0, multiple use with no lift of flood-control constraints; HMU403, multiple use with partial lift of flood-control constraints plus 49.3 cubic kilometers storage preclude; HMU493, multiple use with partial lift of flood-control constraints and 60.4 cubic kilometers storage preclude; SEC000, social-economic scenario no lift of flood-control constraints.

	Current water-control plan	25th percentile of reference regime		Multiple use, increasing flood-control constraints			Multiple use, increasing storage precludes		Social-economic
	NWCP	R25000	R250F3	HMU000	HMU0F3	HMU0F0	HMU403	HMU493	SEC000
NWCP	*1.00*								
R25000	0.18	*1.00*							
R250F3	0.08	1.00	*1.00*						
HMU000	0.31	**0.01**	**0.00**	*1.00*					
HMU0F3	0.61	**0.02**	**0.01**	1.00	*1.00*				
HMU0F0	0.99	0.13	0.08	0.38	0.76	*1.00*			
HMU403	0.64	**0.02**	**0.01**	1.00	1.00	0.76	*1.00*		
HMU493	0.71	**0.02**	**0.01**	0.99	1.00	0.85	1.00	*1.00*	
SEC000	1.00	0.12	0.07	0.50	0.79	1.00	0.85	0.88	*1.00*

The late-pulse magnitudes have a similar pattern, except that the NWCP differs significantly from all other alternatives, and the R 25000 scenario is significantly different from the HMU series.

Early-pulse durations of the ROR differ significantly from all alternatives, and the NWCP and R series scenarios differ significantly from the HMU series (table 5). In contrast, late-pulse durations of the ROR and NWCP are significantly different from each other, but no significant differences exist among the other alternatives (table 6).

The ROR differs significantly from all alternatives for the distributions of days of flooding of low-lying agricultural land in the flood plain during the early pulse near Nebraska City, Nebraska. The alternatives, however, do not differ significantly among themselves (table 7). For the late pulse, many of the alternatives are significantly different from the NWCP, as well as from the ROR. There is little significant difference among alternatives (table 8).

Not surprisingly, the ROR distribution of days above flood stage at St. Joseph, Missouri, is significantly different from the NWCP and all alternatives (table 9). There are no significant differences among the NWCP and alternatives, probably because rare flood events are affected minimally by management of the mainstem reservoir system.

There are no comparisons of minimum monthly storage levels under the ROR because the reservoirs are modeled as continuously full under that scenario. The NWCP distribution is not significantly different from the alternatives, and only the R series differs significantly from some HMU series scenarios (table 10).

Summary

The graphical, tabular, and statistical data presented in this report resulted from analysis of alternative flow regime designs considered by the Missouri River plenary group during the summer of 2005. The plenary group consisted of managers, stakeholders, and scientists, who were charged with designing an alternative flow regime for the Lower Missouri River. The flow regime was intended to provide increased seasonal variability with an emphasis on spring flow pulses that were thought to support reproduction and survival of the endangered pallid sturgeon. The plenary group attempted to increase variation in the flow regime, while minimizing negative effects to social and economic benefits of river management. Environmental flow components (EFCs) extracted from the reference natural flow regime were used to design and assess performance of alternative flow regimes.

This analysis is based on modeled flow releases from Gavins Point Dam near Yankton, South Dakota, for nine alternative designs and two reference scenarios; the reference scenarios are the run-of-the-river (ROR) and the water- control plan (NWCP) implemented in 2004. The alternative designs were developed by the plenary group with the goal of providing pulsed spring flows while retaining traditional social and commercial uses of the river. Flow regime time series were developed by the U.S. Army Corps of Engineers using the Missouri River daily routing model (U.S. Army Corps of Engineers, 1998; 2005).

All of the alternative flow-regime designs were statistically different from the reference flow regime for environmental flow components and for measures of flooding. Most alternative flow-regime designs had distributions of late-pulse (May-June) magnitude and duration that were statistically different from the current water-control plan. Few of the alternatives were statistically different for the early-pulse (March) magnitude and duration. Among the alternative flow-regime designs, statistical differences were more common in comparisons involving alternatives that were based on the reference flow regime (RF series).

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