Simplifying the Complex: Pool Stage-Frequency Analysis of USACE's Largest Reservoir

Simplification du complexe : analyse de la fréquence d'élévation du plus grand réservoir d'USACE

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Abstract. Lake Sakakawea in North Dakota, U.S.A., was formed following the closure of Garrison Dam in 1953 and is the largest U.S. Army Corps of Engineers (USACE) reservoir. It is the second of six mainstem reservoirs located in series on the Missouri River operated as a system by USACE. Critical for dam safety risk analysis, a pool stage-frequency curve, extending to water levels above the top of dam, was developed for an Issue Evaluation Study using a combination of tools, including Monte Carlo simulation with the recently released USACE reservoir frequency analysis software, RMC-RFA. This paper describes the hydrologic tools leveraged to expedite the pool stage-frequency analysis and discusses the challenges overcome during the study. The methods used to reduce a complex reservoir system to a simplified single reservoir model are presented, and statistical challenges associated with mixed population rain/snow floods, paleofloods, and regulated basin data are discussed. The simplified approach was capable of incorporating a variety of hydrology inputs, while providing a reasonable approximation for the complex reservoir operations. The results were transparent and easily understood by decision makers tasked with making portfolio-wide investment decisions.

Résumé. Le lac Sakakawea, dans le Dakota du Nord, aux États-Unis, a été formé à la suite de la fermeture du barrage Garrison en 1953 et est le plus grand réservoir du Corps des ingénieurs de l'armée américaine (USACE). Il s'agit du deuxième des six réservoirs principaux situés en série sur le fleuve Missouri et exploités en tant que système par l'USACE. Critique pour l'analyse des risques liés à la sécurité des barrages, une courbe de fréquence d'étage de piscine, s'étendant jusqu'aux niveaux d'eau au-dessus du sommet du barrage, a été développée pour une étude d'évaluation des problèmes en utilisant une combinaison d'outils, y compris la simulation de Monte Carlo

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avec le logiciel d'analyse de fréquence des réservoirs USACE récemment publié, RMC-RFA. Cet article décrit les outils hydrologiques mis à profit pour accélérer l'analyse de la fréquence d'étape de la piscine et aborde les défis surmontés au cours de l'étude. Les méthodes utilisées pour réduire un système de réservoir complexe à un modèle de réservoir unique simplifié sont présentées, et les défis statistiques associés aux inondations de pluie / neige dans une population mixte, aux inondations passées et aux données de bassin réglementé sont discutés. L'approche simplifiée était capable d'incorporer une variété d'entrées hydrologiques, tout en fournissant une approximation raisonnable pour les opérations complexes du réservoir. Les résultats étaient transparents et faciles à comprendre par les décideurs chargés de prendre des décisions d'investissement à l'échelle du portefeuille.

1 Introduction

1.1 Role of pool stage-frequency in dam safety

In the risk assessment of dams, the annual peak reservoir stage is typically the primary loading parameter for evaluating a potential failure mode. The probability of failure is often conditional on the magnitude of the hydrologic loading. The consequences of failure are also a function of the reservoir stage, outflow, and corresponding reservoir volume. Therefore, the annual probability of exceeding a given reservoir stage, commonly referred to as stage-frequency, is a critical consideration in performing a risk analysis and is represented as a graph of estimated annual exceedance probability (AEP) versus peak reservoir pool stage [1]. The guiding principles, policy, organization, responsibilities, and procedures for implementation of risk-informed dam safety program activities and dam safety portfolio risk management process within the U.S. Army Corps of Engineers (USACE) is described in detail within the USACE engineering regulation ER 1110-2-1156 [2].

1.2 General concepts

Various techniques are available for determining pool stage-frequency for a reservoir. The selection of the most applicable strategy generally considers factors such as the type of risk study, data availability, basin size, basin hydrology (seasonal runoff, runoff type, etc.), regulation, project schedule, and budget. Sample methods range from basic empirical techniques leveraging plotting positions of observed annual peak stages to complex Monte Carlo simulation including precipitation frequency, paleofloods, and complex reservoir operations.

The stage-frequency analysis described herein was in support of a USACE Issue Evaluation Study (IES) requiring advanced understanding of pool stage-frequencies out to elevations above the top of dam with uncertainty reduced as much as reasonably possible. Various approaches were considered during initial scoping phases; ultimately an inflow volume-based approach was selected and is described in detail in later sections. Recent advances in dam safety hydrologic risk software, strategic simplifications of complex system reservoir operations, and creative stage-frequency curve combination techniques were leveraged for this study to expedite development.

2 Study area

2.1 Reservoir, dam, and watershed

Lake Sakakawea in North Dakota, U.S.A., was formed following the closure of Garrison Dam on the Missouri River in 1953. The Garrison Dam – Lake Sakakawea Project is a multiple purpose project consisting of a rolled earthfill dam and impounded reservoir, a hydroelectric generating plant, three flood tunnels, and a spillway with 28 Tainter gates. Design discharge capacity for the project is 23,500 cms. Garrison Dam is the second-most upstream dam along the Missouri River mainstem system of dams and reservoirs (
Fig. 1) operated by the USACE for flood control, navigation, hydropower, irrigation, water supply, recreation, fish and wildlife, and water quality purposes. Lake Sakakawea has a gross storage of approximately 2900 million cubic meters (MCM). It is the largest USACE reservoir and the third largest reservoir in the United States. Lake Sakakawea has approximately 2200 km of shoreline at normal operating pool, and the length of the reservoir extends for 290 km along the valley of the Missouri River. The total drainage area above Garrison Dam is 470,000 km2, which includes the 149,000 km2 upstream of Fort Peck Dam, the first of the six mainstem Missouri River dams. The majority of the Garrison Dam watershed is drained by the Yellowstone River, which enters the Missouri River just upstream of Lake Sakakawea. The watershed is characterized by the Rocky Mountains in the western Yellowstone River headwaters and the Great Plains sloping eastward from the mountains.

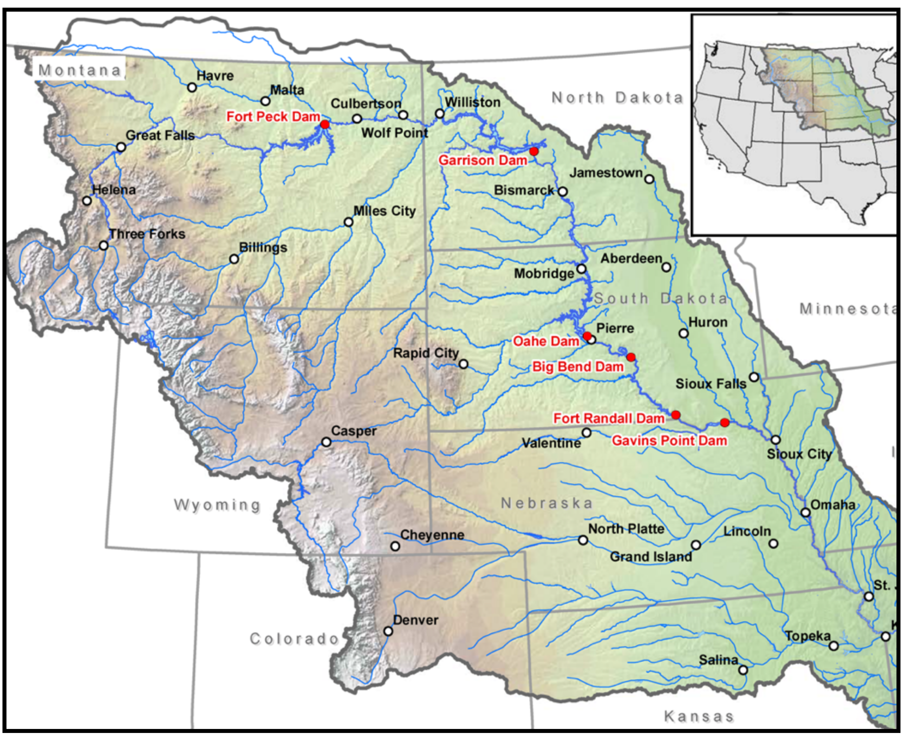

Fig. 1. Mainstem Missouri River dams (red) and Missouri River watershed (shaded relief).

2.2 Seasonal runoff

Inflow into Lake Sakakawea generally occurs in two distinct runoff seasons generally referred to as “early spring” and “late spring” [3]. Early spring is marked by a rapid melting of winter-accumulated snow and ice on frozen ground, usually in March or April, in the plains area as temperatures rise, potentially accompanied by rainfall. The rapid release of water from melting snow and ice jams results in a flashy early spring rise in flow. Peak stages and flows usually occur at this time along lower Yellowstone River tributaries and other streams tributary to the Missouri River through the region. Snowmelt in the mountains also usually begins in this period but contributes little to runoff until later in the year.

The late spring season consists generally of the months of May, June and July. During this period, extensive general rains may occasionally occur in the plains, sometimes accompanied by severe local rainstorms. Plains area runoff is usually quite low unless these rains occur. This is the season of rapid melting of the mountain snow accumulations and results in the highest flows of the year over headwater tributaries of the Yellowstone River. Since this headwater area is normally the major contributing area in the Fort Peck to Garrison reach of the Missouri River, incremental flow volume during this period normally exceeds that occurring during any other period of the year.

2.3 Operations overview

Garrison Dam water control operations are managed by the USACE Northwest Division’s Missouri River Basin Water Management office. As noted previously, Garrison Dam is one of six mainstem dams; these dams are operated as an integrated system for the authorized purposes, and the system regulation is guided by the Missouri River Mainstem Reservoir System Master Water Control Manual [4] and the six individual water control manuals (seven volumes in total). Typical annual system operations include the following: full flood storage evacuated each year, generally around mid-January; increased releases mid-March through late November determined by “service level”, a function of actual system storage, forecast runoff, and tributary reservoirs storage, which sets flow targets downstream; and reduced winter releases. System flood operation objectives include to: prevent/mitigate flooding downstream of the system; prevent/mitigate flooding downstream of each project; evacuate surcharge storage as first priority with risk informed release decisions.

Garrison-specific regulation water management functions include to: capture incremental runoff and meter it out for system requirements while reducing reach flood damages; provide secondary storage to alleviate large downstream reservoir level increases when flooding downstream; and provide extra water for the authorized purposes during low-water years. During extreme floods, final release selection is based on factors such as anticipated inflows, the effects of releases through downstream reaches, and the anticipated max pool level as reflected in additional system regulation studies performed at that time. During unprecedented flood inflows or if reservoir levels exceed or are expected to exceed approximately 30 cm into the surcharge pool zone, the emergency regulation curves, which for the season of the flood provide discharge given the elevation and inflow at the time, can be used as a guide for release scheduling.

3 Methods

3.1 Pertinent complexities, limitations and solutions

Scoping discussions for developing pool stage-frequency for Lake Sakakawea revealed numerous complexities that had potential to cause significant delays and greatly increase the study budget. Rather than succumb to costly delays, the study team was able to develop and implement creative simplifying solutions that led to a final product that adequately informed the risk assessment. Table 1 below provides a number of those complexities identified prior to and during the study, the limitations on the study, and the solution implemented in order to keep the study within budget and on schedule.

Table 1. Study complexities, limitations, and simplifying solutions.

#	Complicating Factor	Limitation on the Study	Simplifying Solution
1	Limited observed extreme events; highest pool of record is vastly less than design dam crest	Empirical data does not significantly inform infrequent stage-frequency	Incorporate inflow volume-based techniques with Monte Carlo simulation to produce stage-frequency out beyond the top of dam
2	Two flood seasons yield flood data from two populations	A single annual maximum series cannot be used and individual years must be separated by hydrologic flood mechanism	Identify threshold date to distinguish seasons, place seasonal maximums into two populations, and perform mixed population analysis
3	Drainage basin is vast	Precipitation frequency informed inflow has limited applicability; snowmelt/rainfall dual flood drivers makes development of precipitation frequency more complex	Focus on inflow data development including incorporation of historical and paleoflood information
4	Observed data is regulated	Fitting an analytical distribution to regulated discharges or volumes is not recommended, especially when extrapolation to rare events is needed	Apply multiple techniques including empirical analysis with observed data and analytical analysis on unregulated and regulated data to develop a composite stage-frequency curve
5	Individual dam release decisions are impacted by hydrology in the entire system	Complex system reservoir operations and significant data development are needed to best simulate Garrison operations for Monte Carlo simulation of varying size flood events	Leverage emergency release decision curves to define infrequent events; use empirical data to define more frequent events
6	Traditional Monte Carlo software with abilities to incorporate spillway gate operations are very time and cost intensive	Schedule delays and budget overruns	Use newly developed Risk Management Center Reservoir Frequency Analysis (RMC-RFA) software, which is capable of performing Monte Carlo analysis more efficiently
7	RMC-RFA (current version) is limited to a single elevation-discharge reservoir model	Emergency release decision curve operation cannot be used explicitly	Develop simplified reservoir model by bracketing elevation-discharge relationships within a more complicated reservoir simulation software; test sensitivity; verify adequacy

The primary study sequence, implementing the above solutions to address model complexities, consisted of the following:

1. Development of stage and flow data, including historical events and paleofloods.
2. Seasonal inflow volume duration frequency analysis
3. Monte Carlo statistical sampling and reservoir model development using Risk Management Center Reservoir Frequency Analysis (RMC-RFA) [5] with simulations to produce seasonal stage-frequency curves and full uncertainty
4. Seasonal stage-frequency curve combination to produce annual stage-frequency
5. Sensitivity analysis
6. Composite stage-frequency curve development

3.2 Monte Carlo analysis with RMC-RFA

3.2.1 Overview of the RMC-RFA methodology

As described in RMC-TR-2018-03 [1], the USACE RMC-RFA software was developed to facilitate hydrologic hazard assessments within the USACE Dam Safety Program. RMC-RFA produces a reservoir stage-frequency curve with uncertainty bounds by utilizing a deterministic flood routing model while treating the inflow volume, the inflow flood hydrograph shape, the seasonal occurrence of the flood event, and the antecedent reservoir stage as uncertain variables rather than fixed values. In order to quantify both the natural variability and knowledge uncertainty in reservoir stage-frequency estimates, RMC-RFA employs a two looped, nested Monte Carlo methodology. The natural variability of the reservoir stage is simulated in the inner loop defined as a realization, which comprises many thousands of simulated flood events. Knowledge uncertainty in the inflow volume-frequency distribution is simulated in the outer loop, which comprises many realizations.

An RMC-RFA simulation requires the six primary model inputs listed in the bullets below. The most labor-intensive inputs for the Garrison study were Inflow Volume-Frequency Curve and Reservoir Model development.

- Inflow Volume-Frequency Curve
- Flood Seasonality Analysis
- Reservoir Starting Stage Duration Analysis
- Reservoir Model
- Inflow Hydrograph Shapes
- Empirical Stage-Frequency Curve

RMC-RFA has been used to model a wide range of dam safety problems within USACE, including the evaluation of dam safety modification alternatives [6]. Smith [7] compared stage-frequency curves from RMC-RFA with curves derived from more complex, precipitation-based stochastic simulation software and showed that RMC-RFA can produce very similar results with much less computational effort.

3.2.2 Data discussion

Key datasets for Garrison Dam included both regulated and unregulated stage and flow datasets. These datasets were both from external models representing a period of record with no mainstem reservoirs and no basin depletions (unregulated) and a period of record with consistent regulation and depletions of the present day (regulated). Both of these datasets were supplemented with additional historical event data developed from various sources. It was desirable to perform analytical frequency analysis using both flow datasets as each provide context to parts of the stage-frequency curve while carrying their own limitations.

Paleoflood data were gathered and developed as part of the IES study. Key output of the paleoflood study included a non-exceedance bound (NEB) in the early spring season and both a NEB and a paleoflood event in the late spring season. Paleoflood data were only used with unregulated data as no determination of mainstem system hydrology could be made to develop regulated flows from the paleoflood information.

3.2.3 Inflow volume-frequency

Inflow volume-frequency analyses of inflows into Garrison Dam were performed with regulated inflows and unregulated inflows with historical and paleoflood data for early spring and late spring seasons for the critical inflow duration. Critical inflow duration is defined here as the inflow duration that results in the highest water surface elevations for the reservoir of interest0F. The seasonal critical durations for Garrison Dam were determined to be 25 days in the early spring season and 60 days in the late spring. The frequency analysis used the seasonal critical duration (25 or 60) day peak average flow for computation. Annual or seasonal peak (instantaneous or daily) data without additional time-series information were converted to volume duration peak data using peak to volume ratios developed from observations. Inflow volume-frequency analyses were conducted using Bulletin 17C techniques [8] within HEC-SSP software [9]. Fig. 2 provides a sample output of a seasonal inflow volume-frequency analysis. Similar analyses were conducted for the various datasets for both seasons.

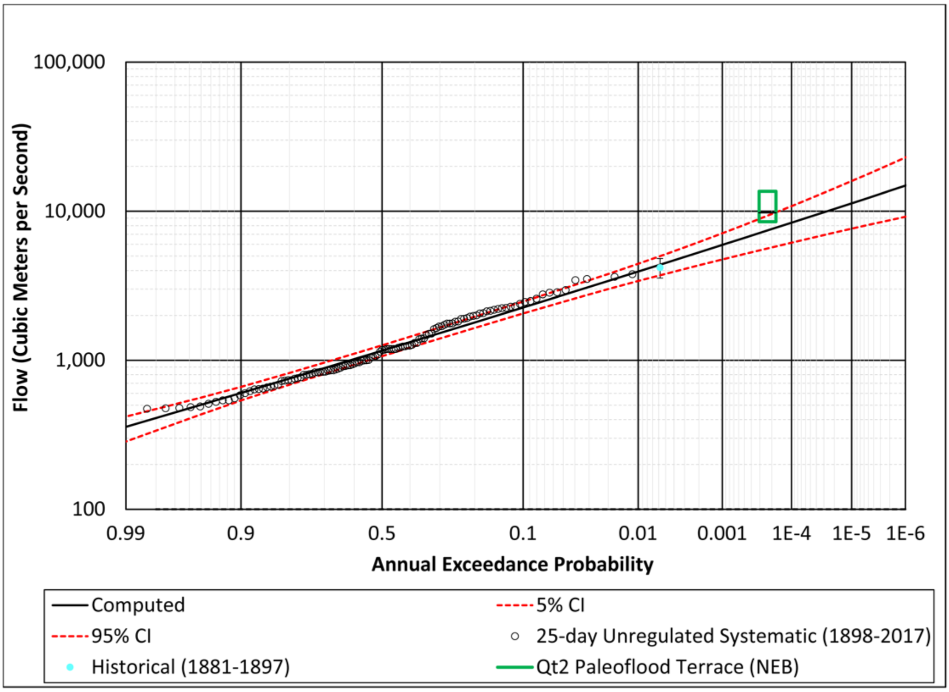

Fig. 2 Inflow volume-frequency results for the early spring season using unregulated data for the 25-day critical duration.

3.2.4 Reservoir model

RMC-RFA version 1.1 requires a simplified stage-discharge curve and uses mod-puls routing to approximate the effect of reservoir operations on stage and outflow. However, Garrison Dam operations are highly complex as it has a gated spillway and is operated as part of the Missouri River mainstem system. Even under simplifying single reservoir operations using emergency release decision curves (seasonal discharge a function of pool stage and inflow), additional approximation was necessary for input into RMC-RFA. In order to determine if a Monte-Carlo analysis using RMC-RFA was sufficient to represent reservoir operations, more detailed modeling was performed. An HEC-ResSim model [10], which is a rule-based reservoir routing software that can model a variety of operational goals and constraints, was developed for Garrison Dam. A family of elevation-discharge curves was developed using HEC-ResSim with scaled historic inflows and varying combinations of spillway gate and flood tunnel operations. The simplified rating curves were then verified in HEC-HMS [11] against the original spillway design floods to ensure the simplified operations produced reasonable outflow and pool stage hydrographs. It was found that a family of reservoir elevation-discharge functions, described as best, average, and worst case release scenarios in this study, was sufficient at enveloping the possible reservoir releases which allowed the stage-frequency analysis to be carried forward using RMC-RFA. Fig. 3 displays the developed elevation discharge curves with various routed scaled events' rising limb elevation discharge points. Elevation is provided in the local project datum (LPD).

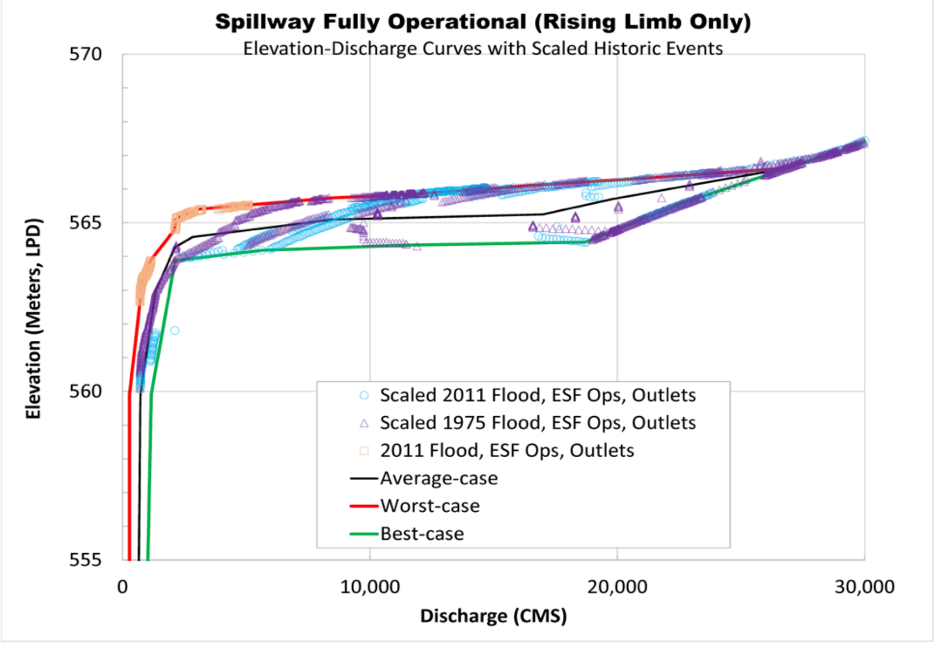

Fig. 3. Simplified early spring elevation discharge curves developed for use in RMC-RFA Monte Carlo simulation model.

3.2.5 Other RMC-RFA inputs

As noted previously, additional input is required by RMC-RFA for simulation in addition to the inflow volume-frequency and reservoir model. Observed stage data was entered into

RMC RFA in order to generate empirical frequency curves for later comparison to modeled results. Monthly starting pool stage duration data were entered along with flood seasonality in terms of monthly flood relative frequency based on observed and modeled pool elevation data. In general terms, these RMC-RFA inputs are used to determine the starting pool prior to a randomly sampled flood event. Once a peak flood is sampled, a flood hydrograph is sampled from a user-entered set and the hydrograph is scaled to maintain the desired duration volume before being routed through the reservoir model.

At Garrison Dam, most early spring floods begin in March while most late spring floods begin in May. Starting pool tends to be lower in the early spring than the late spring. Seasonal observed and design floods were entered in the hydrograph sets.

3.2.6 Model simulation

Within RMC-RFA, three simulation types are available: simulate full uncertainty; simulate expected frequency curve only; and simulate median frequency curve only. Selecting one of the latter two options enables rapid sensitivity analysis. Because multiple simplified operations datasets were developed for Garrison Dam to bracket a range of operations, assessment was performed to determine a most applicable operations rating curve. Fig. 4 provides the early season expected stage-frequency curves for the "best, average, and worst-case" operations sets, terms used for this study but are not to be treated in a literal sense. The "worst-case" curve was determined to be the best representation of actual reservoir operations at Garrison Dam for both seasons. In other words, the dam operators tend to hold back releases within the permitted release rules.

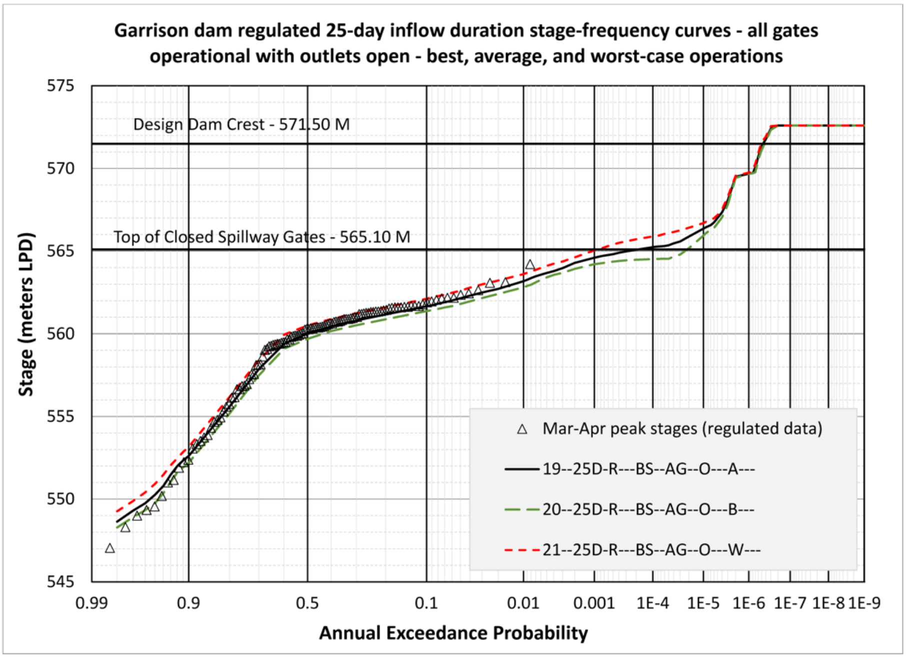

Fig. 4. Expected early spring stage-frequency curves using the family of early spring simplified operations sets. Within the plot, the red dashed, solid black, and green dashed lines represent the RMC-RFA expected stage frequency produced assuming worst, average, and best-case operations, respectively.

Full uncertainty was simulated for both early spring and late spring seasons and for both regulated and unregulated volume duration frequencies using the most applicable operations set. When RMC-RFA finished computing, stage-frequency plots were created including a median, expected, and 90% uncertainty bound curves. The median curve represents the uncertainty in stage-frequency due to natural variability; the 90% uncertainty bounds represent the uncertainty in stage-frequency due to knowledge uncertainty; the expected curve represents the combined uncertainty due to both natural variability and knowledge uncertainty.

3.3 Curve combinations

Neither the early spring nor late spring curve alone completely described the annual stage-frequency at Garrison Dam. Therefore, it was necessary to combine regulated and unregulated seasonal curves into annual stage-frequency curves by means of the Probability of Union theorem as presented in the USACE Engineer Manual 1110-2-1415 [12] shown in Equation 1 below:

$$P(c) = P(a) + P(b) - P(a)*P(b) \tag{1}$$

where $P(c)$ is the combined probability; $P(a)$ is the probability of peak stage 'a' in season 'a'; and $P(b)$ is the probability of peak stage 'b' in season 'b'.

4 Results

The most reasonable approximation of the pool stage-frequency curve for Garrison Dam was determined to be a composite of the graphical, regulated, and unregulated with paleoflood data stage-frequency curves, with the graphical and regulated curves describing the range of observed data and the unregulated curve describing the infrequent range where upstream regulation would be expected to have insignificant impact. The transition between the regulated and unregulated expected curves occurred over minimal elevation and, therefore, was able to be developed by gradually transitioning from the regulated curve to the paleoflood-informed unregulated curve using weighting techniques between AEPs of 0.01 to 0.0001. The same procedure was applied to the median curve and confidence intervals. The final composite stage-frequency curves (expected, median, lower and upper confidence intervals) are shown in Fig. 5.

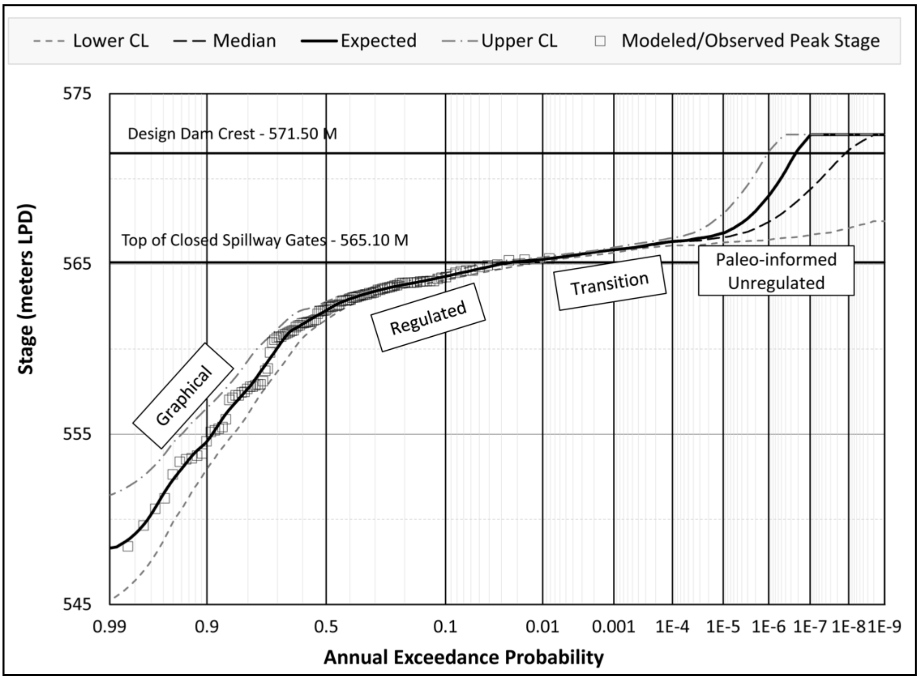

Fig. 5. Garrison Dam construction of final composite pool stage-frequency with expected, median, and 90% confidence curves.

5 Conclusions

Garrison Dam and impounded Lake Sakakawea pose multiple complexities for development of the pool stage-frequency out above the top of dam due to the heterogeneous hydrology within the watershed, lack of observed extreme flood events since the dam's closure, complex mainstem dam system operations, and multivariable emergency release individual dam operations. The implementation of Monte Carlo simulation with a reservoir model was required; however, it was determined that recently developed and publicly available USACE RMC-RFA software with built-in efficiencies for reducing simulation run times was capable of developing pool stage-frequency, that when combined strategically, adequately portrayed the hydrologic loading probability for the dam. The simplified approach was capable of incorporating a variety of hydrology inputs, while providing a reasonable approximation for the complex reservoir operations. The results were transparent and easily understood by decision makers tasked with making portfolio-wide investment decisions.

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