SECWCD - Fryingpan-Arkansas Storage Recovery Study

Phase II Final Report

August 2021

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Phase I Final Report

August 2021

Issue and revision record

Revision	Date	Originator	Checker	Approver	Description
01	7-21-2021	PM KB	JD	WJP	Draft Final Storage Allocation Assessment and Forecasting Analysis
02	8-24-2021	PM KB	JD	WJP	Revised Draft Final Storage Allocation Assessment and Forecasting Analysis

Document reference: 507102411 | TR-04-01 |

Information class: Standard

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Executive summary

Storage capacity loss within reservoirs is both a nationwide and worldwide issue. As reservoir life decreases due to storage capacity loss, federal agencies, public and private operators, and owners are faced with the challenge of meeting current and future water distribution demands, while mitigating the environmental, social, and economic impacts associated with the potential implementation of storage recovery alternatives.

The Phase II, Task 1 work summarized herein is a continuation of the Phase I – Fryingpan-Arkansas Storage Recovery Study. The purpose of the Phase II work is to expand upon the results of the Phase I study through an assessment of Pueblo Reservoir storage allocation impacts and a storage capacity loss forecasting analysis. The work has been conducted by Mott MacDonald on behalf of the Southeastern Colorado Water Conservancy District (District). This work facilitates the District's goals and objectives of quantifying the impacts of Pueblo Reservoir storage capacity loss on District operations and storage contracts and provides order of magnitude estimates as to when storage loss becomes critical or limiting to Fryingpan-Arkansas operations. Additionally, Mott MacDonald has developed next steps for the District's consideration that may be incorporated into future phases of work.

The Phase II, Task 1 study work included the execution of the following Tasks:

1. **Project Management.** This task included an update to the Project Management Plan developed during the Phase I study, project status meetings, and additional coordination with the District and Storage Recovery Strategy Committee throughout the duration of the work.
2. **Phase II Study Initiation Workshop.** This task included a coordination meeting between the District and Mott MacDonald team members to discuss project objectives and goals, schedule, and available data sources. This meeting was held on May 7th, 2021.
3. **Data Collection and Basis of Assessment**. This task included data requests, supplemental document review, data processing, identification of data gaps and the development of a Basis of Assessment technical memorandum submitted to the District on 21 May 2021 (included as Attachment C).
4. **Storage Allocation Impacts Assessment and Storage Capacity Loss Forecasting Analysis.** This task included the engineering work and analysis necessary to quantify impacts of Pueblo Reservoir storage capacity loss on District storage and operations. The results of Task 4 are documented herein.
5. **Review Meeting**. Following completion of Task 4, Mott MacDonald held a virtual review meeting/workshop to present and discuss the Phase II study findings and any recommendations for future work that have arisen during the execution of the study. This meeting was held on July 7th, 2021.
6. **Phase II Study Report and Meeting.** Mott MacDonald will prepare, submit and present the final draft of the Phase II, Task 1 study works at District headquarters in Pueblo, CO in August of 2021.

The Phase II study report includes the following subsections:

Introduction

Section 1 provides an overview of document purpose, goals and objectives, and content. The purpose of this document is to estimate historical storage loss and develop future projections of

Pueblo Reservoir storage capacity to assess impacts on District operations and storage contracts. Mott MacDonald notes that the estimates provided in this memorandum are order of magnitude estimates, and that future studies and data collection should be conducted to refine any estimates provided in this document.

Data Collection and Processing

Mott MacDonald utilized various U.S. Bureau of Reclamation (Bureau) provided data pertaining to storage capacity to conduct this assessment. Mott MacDonald signed a Non-Disclosure Agreement (NDA) with the Bureau to receive the 2012 bathymetric survey and topographic data included herein. Post-processing of the data was required prior to initiating the engineering assessment. This included digitizing the 1974 and 1993 bathymetric rangeline survey data, as well as verifying the datum and converting the 2012 contour data survey provided by the Bureau. Following this, Mott Macdonald generated elevation surfaces based on the 1974, 1993, and 2012 surveys for the purpose of determining storage capacity estimates. It should be noted that the surfaces that were created contain certain levels of error due to the sparse nature of the data provided within the 1974 and 1993 rangeline surveys. We recommend that future surveys be conducted using modern topographic and bathymetric surveying techniques. These updated surveys will refine any storage capacity projections made in this document. Additional information regarding recommended future survey programs is included within Section 4.2 herein.

Storage Allocation Impacts Assessment and Storage Loss Forecasting Analysis

Using the data collected and processed by Mott MacDonald, an engineering assessment was conducted to produce qualitative estimates of projected Pueblo Reservoir storage capacity loss. This assessment included an operations analysis, sedimentation assessment and forecasting, and future storage allocation projections as detailed below.

- Operations Analysis: The operations analysis investigated historical reservoir elevations since dam closure in 1974. The analysis noted seasonal trends, which showed lower water surface elevations in summer and early fall months, with higher elevations in late winter and early spring. A cyclical trend in long term water surface elevations was also noted, with low water elevations within the reservoir occurring on an approximate 10 to 11-year interval due to periods of what appears to be drought.
- Sedimentation Assessment & Forecasting: The sedimentation assessment used the bathymetric and topographic surfaces compiled by Mott MacDonald and first compared them to storage calculations provided in the 2012 Bathymetric Survey Report prepared by the U.S. Bureau of Reclamation, 2015. The two sets of calculations showed similar results, with differences ranging between 0.5 to 1.7% relative to the Bureau's estimates. The historical data was then used to project spatially variable reservoir sedimentation 2, 5, 10, and 25 years into the future. Projected sedimentation within the reservoir was projected relative to the year 2021. The projections for future reservoir capacities were developed to aid the District in future planning efforts. Projected sedimentation estimates were then used with the compiled reservoir elevation data to develop a range of projected future storage allocation capacities.
- Future Storage Allocation Projections: Qualitative analysis was conducted for the purposes of projecting future capacities for all storage allocations 2, 5, 10, and 25 years into the future. The range of estimates considers varying water levels as well as prediction bounds that account for uncertainty in the projections due to the sparse historical rangeline data (1973 and 1993). The projected future storage allocation capacity ranges are shown below in

Table 1.1. Note that only the 10%, 50%, and 99% exceedance levels are shown. For a full summary of the projected allocation ranges, see Attachment A.

Table 1.1: Projected range of future capacities of selected storage allocations.

		Year 2 (2023)			Year 5 (2026)		
Allocation	**Top of Pool [ft]**	**10th % [AF]**	**50th % [AF]**	**99th % [AF]**	**10th % [AF]**	**50th % [AF]**	**99th % [AF]**
Active Cons.	4,880.5	60,000-70,000	148,000-158,000	209,000-219,000	60,000-70,000	147,000-157,000	207,000-217,000
Inactive Pool	4,796.7	21,000-23,000	17,000-23,000	17,000-23,000	16,000-22,000	16,000-22,000	16,000-22,000
Dead	4,764.0	400-2,400	400-2,400	400-2,400	300-2,300	300-2,300	300-2,300
		Year 10 (2031)			**Year 25 (2046)**		
Allocation	**Top of Pool [ft]**	**10th % [AF]**	**50th % [AF]**	**99th % [AF]**	**10th % [AF]**	**50th % [AF]**	**99th % [AF]**
Active Cons.	4,880.5	59,000-69,000	146,000-156,000	205,000-215,000	56,000-66,000	140,000-150,000	197,000-207,000
Inactive Pool	4,796.7	16,000-22,000	16,000-22,000	16,000-22,000	13,000-19,000	13,000-19,000	13,000-19,000
Dead	4,764.0	0-2,100	0-2,100	0-2,100	0-1,700	0-1,700	0-1,700

Discussion and Next Steps

This assessment provides planning level estimates to identify future storage capacity loss to aid the District in assessing impacts on future storage contracts. The analytical calculations provided in this document contain uncertainty that should be refined to better understand future storage capacity loss. Continuation and refinement of this assessment along with further data collection programs will improve our understanding of the distribution of sedimentation throughout Pueblo Reservoir and refine the storage capacity projections provided in this document. We recommend future data collection programs and refinement studies that include, but are not limited to, the following:

- Updated bathymetric and topographic surveying programs.
- Geomorphologic and hydrological analyses to assess sediment loading and distribution within the Upper Arkansas River Basin, including quantifying sediment load from unregulated tributaries upstream of Pueblo Reservoir.
- Numerical modeling to refine the storage capacity estimates provided in this document. . The revised sedimentation and storage capacity projections developed through the numerical modeling will serve to better quantify impacts to Pueblo Reservoir storage contracts. The models could then be used to evaluate the effectiveness of proposed storage recovery alternatives such as direct sediment removal, sediment diversion, and/or other feasible reservoir sustainability alternatives.

1 Introduction

This engineering assessment has been developed by Mott MacDonald for the Fryingpan-Arkansas Storage Recovery Study on behalf of the District. This document provides a storage allocation impact assessment and storage capacity loss forecasting analysis pertaining for Pueblo Reservoir.

1.1 Document Purpose

This document details the results of the Phase II, Task 1 engineering assessment conducted by Mott MacDonald for the purposes projecting future Pueblo Reservoir storage capacity losses and providing estimates as to when storage loss becomes critical to Fryingpan-Arkansas operations.

1.2 Document Objectives

The objective of this document is to provide the District with the results of the storage allocation impact assessment and storage capacity loss forecasting analysis. The primary goals and objectives of the study were to assess the impacts of storage capacity loss on District operations and contracts, and to provide updated information to facilitate future decision making, study phases/tasks, and other work aimed at the evaluation of potential reservoir storage recovery options.

1.3 Document Summary

The following sections summarize the work and results pertaining to Phase II, Task 1 of the Fryingpan-Arkansas Storage Recovery Study. These sections include data collection and processing, an engineering assessment, discussion, and next steps.

A summary of all data collected, verification of survey datums, and post-processing efforts is provided in Section 2 of this report. Processing of the data was conducted to identify potential trends in reservoir water surface elevation data, digitize non-electronic survey data, and develop bathymetric and topographic surfaces of historic reservoir elevations that were then used in the engineering assessment.

The engineering assessment is summarized in Section 3 and documents the results from both the sedimentation assessment as well as the future storage allocation and contract storage capacity analysis. This analysis uses curve fitting relationships based on historical data, combined with reservoir elevation data to project future reservoir capacity.

Section 4 summarizes the limitations associated with the analysis and projected reservoir capacities provided in the engineering assessment. In addition, Section 4 provides recommendations for the continuation and refinement of the results of this assessment along with recommendations for further data collection programs and ancillary works.

2 Data Collection and Processing

Site-specific data was collected and processed by Mott MacDonald in order to conduct this engineering assessment. Both publicly available and District-provided data was utilized for the sedimentation and storage-capacity analyses. This section provides a summary of the data collection effort included as part of the engineering assessment, including data collection, datum verification, post-processing, and survey digitization.

2.1 Summary of Data Collected

All data utilized within this engineering assessment was produced by the Bureau and was either collected online within the public domain and/or provided to Mott MacDonald by the District or Bureau. Table 2.1 summarizes all data collected and processed for this assessment.

Table 2.1: Summary of Collected Data.

Source	Description	Year(s)
Bureau – Hydromet Website	Water Surface Elevation	1974 – 2021
Bureau – Hydromet Website	Storage Content	1974 – 2021
Bureau – Hydromet Website	Daily Mean Inflow	1984 – 2021
Bureau – Hydromet Website	Daily Mean Discharge	1984 – 2021
Bureau – Hydromet Website	Snow Water Equivalent	2004 – 2021
1993 Sedimentation Survey Report	Bathymetric Survey Profiles	1974
1993 Sedimentation Survey Report	Bathymetric Survey Profiles	1993
2012 Bathymetric Survey Report	Digital Bathymetric Survey	2007 (Topographic, IFSAR), 2012 (Bathymetric)

2.2 Datum Verification

Similar to other reservoirs, reported elevations pertinent to Pueblo Reservoir are referenced to a site-specific vertical datum. This “Project Datum” was verified by Mott MacDonald to be tied to the Bureau water surface elevation data, as well as the 1974 and 1993 bathymetric surveys. However, verification was required with regards to the vertical datum of the 2012 survey data. Following a literature review and point comparison, it was confirmed that the 2012 survey provided by the Bureau was provided in the National Vertical Datum (NAVD88).

The contour elevations provided in the 2012 survey data were decreased by 3.2 feet to convert to Pueblo Reservoir project datum per the datum conversion provided in U.S. Bureau of Reclamation, 2015. For this report, all water surface elevation data elevations, topographic and bathymetric survey data, and other data are reported in the project datum.

2.3 Data Processing

2.3.1 Bureau Operations Data.

Following the collection of all pertinent operations data, inclusive of reservoir elevation, historical storage capacity, and inflow and outflow data, Mott MacDonald processed the data to identify any potential trends and to utilize the information within the engineering assessment. This processing included generation of historical timeseries and statistical distributions of the Bureau - Hydromet data (U.S. Bureau of Reclamation, 2021). The Bureau provided data spans from dam closure in 1974 until present day and is reported as daily-average values. This data analysis review was performed to identify any seasonal and/or long-term trends in inflows, reservoir elevations, and storage capacity. Figure 2-1 shows the monthly distributions of reservoir water surface elevations since dam closure provided online as part of the Bureau hydromet data (U.S. Bureau of Reclamation, 2021). Colored areas shown within Figure 2-1 are indicative of the different storage allocation elevation ranges within the reservoir. Reservoir elevation exceedance data is also shown at the 10th percentile (green line), 50th percentile (blue line), and 90th percentile (black line) as indicated within the figure legend.

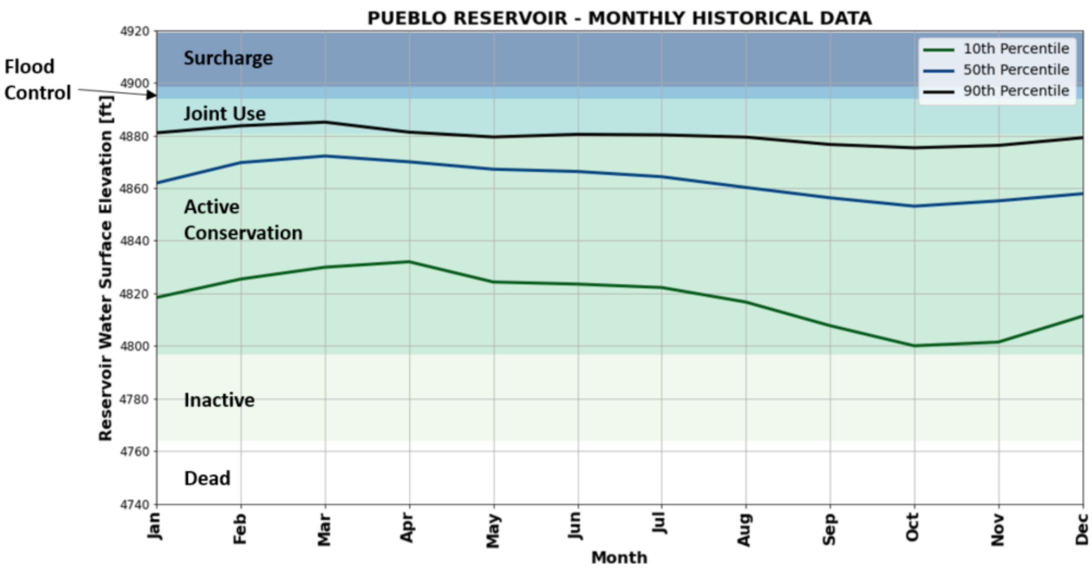

Figure 2-1: Distribution of monthly reservoir elevations showing 10th percentile (green), 50th percentile (blue), and 90th percentile (black).

The monthly distribution of reservoir elevation exceedance data shows a few notable trends as summarized below:

- The highest elevations are typically in late winter to early spring months, which is a typical trend for reservoirs operated within the Western United States.
- Reservoir elevations are typically lower over the summer to early fall months before typically increasing in the early winter months.
- The majority of water surface elevation fluctuations (10th – 90th percentile) fall within the Active Conservation storage allocation.

Yearly distributions were also developed to identify any long-term trends in the data and to evaluate low and high bounds for the operating reservoir elevations. A summary of the historical elevations since dam closure in 1974 is shown below in Figure 2-2. These reservoir elevations were used for the capacity forecasting analysis summarized in Section 3.1 herein. Colored areas shown within Figure 2-2 are indicative of the different storage allocation elevation ranges within the reservoir.

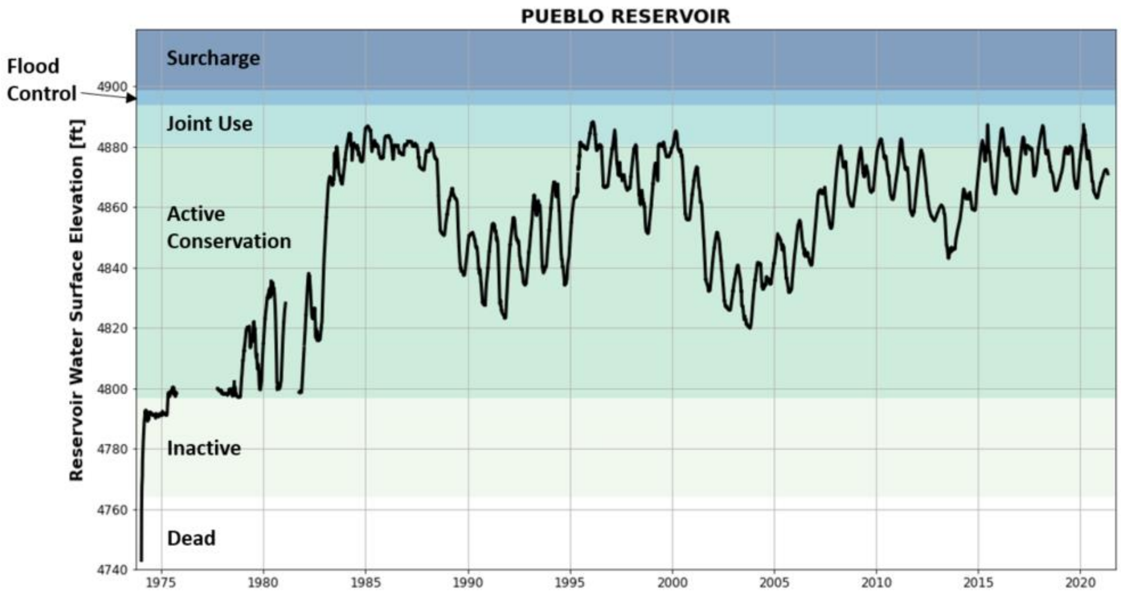

Figure 2-2: Historical Pueblo Reservoir Water Surface Elevation timeseries.

The historical timeseries data shows a few notable trends as summarized below:

- High reservoir elevations were noted in the mid-late 1980s, consistent with documented periods of high snow water equivalents. The District also noted that the only time water was physically spilled outside of dam safety work was during this time period.
- A cyclical trend is noted, with periods of low elevations occurring at approximate 10 to 11-year intervals..
- Large variations in reservoir elevations occur mostly within the elevation range of the Active Conservation storage allocation.

This data was used to develop regression trends and equations to determine future storage availability, sedimentation, and capacity limits as described later in Section 3.1 herein.

2.3.2 Survey Data Digitization & Processing

As previously mentioned, a digital form of the 2012 bathymetric contour survey data provided by the Bureau was used in this assessment. However, the 1974 and 1993 surveys were only available as rangelines in PDF format (U.S. Bureau of Reclamation, 1994). This required digitization and subsequent smoothing of the U.S. Bureau of Reclamation, 1994 data so that it could be properly utilized within the engineering assessment. Thirty-one (31) elevation profiles taken along georeferenced rangelines were digitized and processed by Mott MacDonald. Figure 2-3 shows the locations of the 31 rangelines that were digitized and used to develop the 1974 and 1993 surfaces as well as an example of the digitization process.

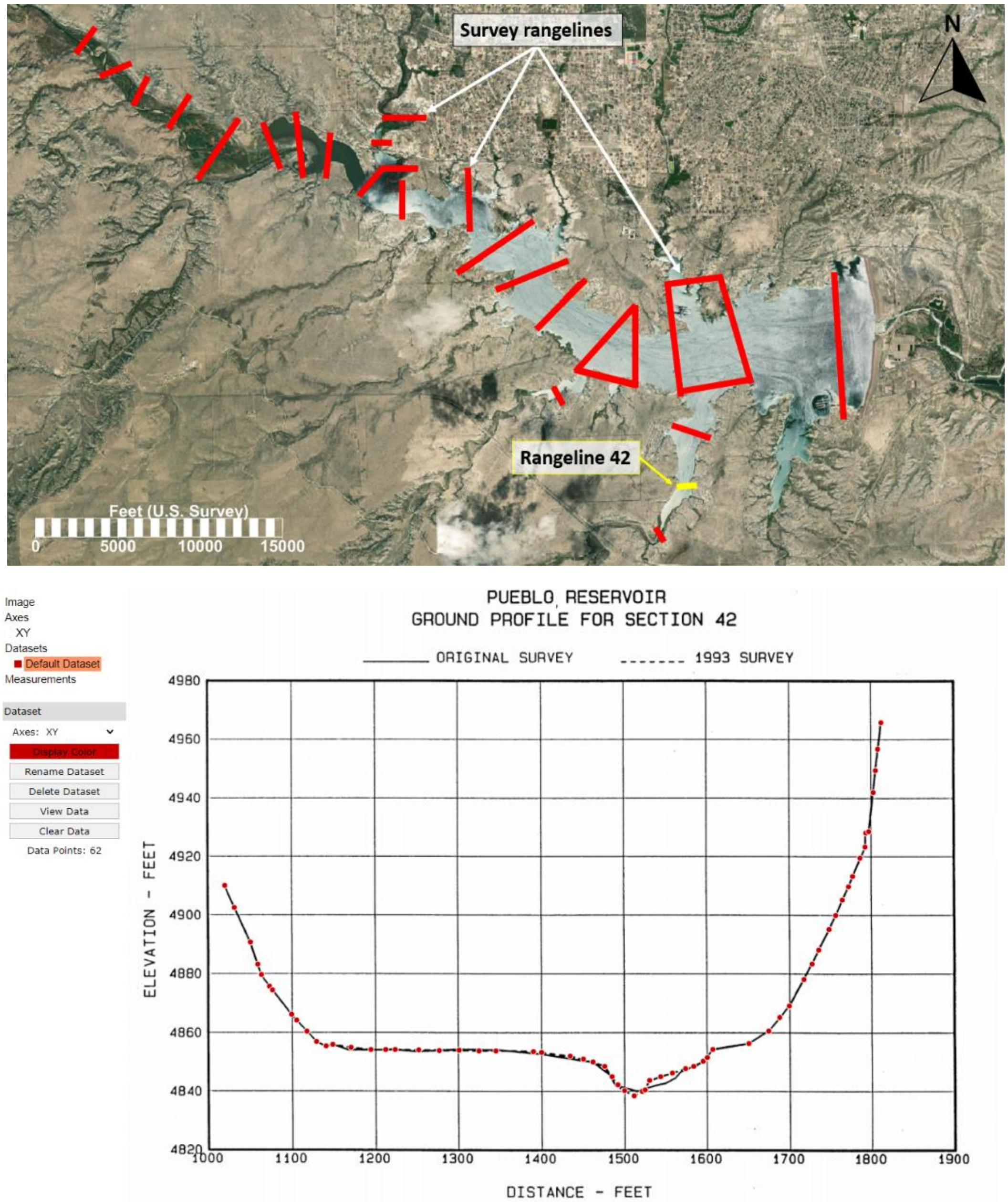

Figure 2-3: Locations of the 31 rangelines (top) and example digitization of the 1974 bathymetric survey profile along range line 42 (bottom).

The digitized 1974 and 1993 transects were then combined with the above water (assumed as top of spillway at 4,898.7 ft) topography provided by the Bureau. Topography data provided by the Bureau (U.S. Bureau of Reclamation, 2015) was referenced to a 2007 IFSAR (Interferometric Synthetic Aperture Radar) survey conducted within the project area limits. Once combined, additional smoothing and bathymetric interpolation was conducted to merge the two datasets and to extrapolate contour elevations for the 1974 and 1993 surfaces that were not covered within the interstitial space of the rangeline surveys. The final 1974, 1993, and 2012 elevation surfaces used for the engineering assessment described in Section 3 herein are shown in series in Figure 2-4 below.

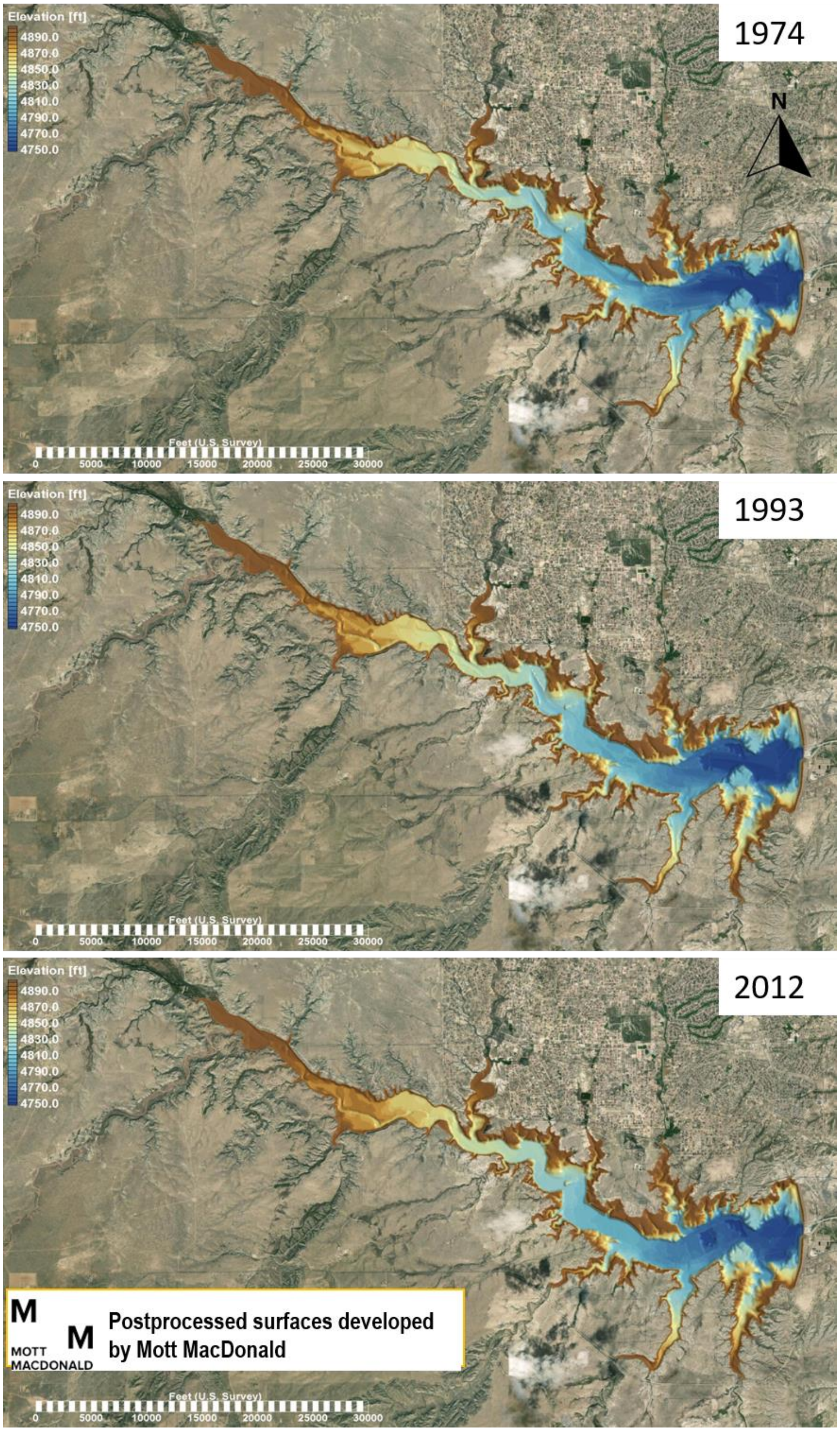

Figure 2-4: Post-processed Pueblo Reservoir bathymetric surfaces for years 1974, 1993 and 2012.

While best engineering judgement was used to develop the 1974 and 1993 surfaces, there is inherent error and subjectivity involved in the process of extrapolating contour elevations. Therefore, when these surfaces were used to develop regression equations to predict future storage capacity, higher prediction bounds were used to quantify the inherent error in the digitization and bathymetric surface development process. In future phases of work, it is recommended that additional elevation survey programs be conducted using modern survey technologies such as multi-beam bathymetric and Light Detection And Ranging (LiDAR) to more accurately capture present day elevations throughout the project area limits. This additional survey would serve to refine any capacity estimates provided in the following sub-sections.

3 Engineering Assessment

An engineering assessment was conducted to quantify the impacts of storage capacity loss on District operations and develop storage capacity projections that can be used by the District to assess when storage loss may become critical or limiting to District operations. The following Sections describe the operations analysis, sedimentation assessment, and future storage allocation projections developed by Mott MacDonald.

3.1 Historical Sedimentation Assessment

A sedimentation analysis was conducted using the bathymetric and topographic surfaces described in Section 2.3.2. Before the sedimentation forecasting analysis was conducted, Mott MacDonald compared the computed historical storage allocation capacities to those developed by the Bureau (U.S. Bureau of Reclamation, 2015). A summary of the volume comparisons, inclusive of Bureau estimates using the Area Capacity Computer Program (ACAP), Mott MacDonald estimates using surface comparisons, and differences (+/-) between the two estimates, is shown below in Table 3.1.

Table 3.1: Comparison of historical storage allocation capacity estimates developed by the Bureau of Reclamation and Mott MacDonald

		1974			1993			2012[1]		
Storage Allocation	Top of Pool [ft]	Bureau [AF]	MM [AF]	Diff. [MM – Bureau]	Bureau [AF]	MM [AF]	Diff. [MM – Bureau]	Bureau [AF][2]	MM [AF]	Diff. [MM – Bureau]
Flood Control	4,898.7	26,992	26,456	-536	27,044	26,443	-601	26,990	26,439	-551
Joint Use	4,893.8	66,266	65,145	-1,121	65,716	64,998	-718	66,011	64,704	-1,307
Active Conservation	4,880.5	234,210	238,957	4,747	229,059	230,438	1,379	219,772	218,850	-922
Inactive Pool	4,796.7	26,895	28,252	1,357	25,792	25,673	-119	23,706	23,469	-237
Dead	4,764.0	3,758	5,537	1,779	2,329	4,327	1,998	1,895	1,796	-99
	Total	358,121	364,347	6,226	349,940	351,878	1,938	338,374	335,258	-3,116

Notes and references

[1] 2012 Bureau results reflect the updated 2015 calculations presented in U.S. Bureau of Reclamation, 2015.

[2]The 1974 and 1993 Mott MacDonald surfaces were developed from digitized rangeline data provided by the U.S. Bureau of Reclamation, 1994. 2012 electronic contour data provided by the Bureau was used in for developing the 2012 volume calculation estimates developed by Mott MacDonald.

[3]Differences in calculated storage allocation capacity estimates are likely due to discrepancies in the bathymetric and topographic surfaces used by MM and the Bureau, surface development, and inherent differences in volume calculation methodologies.

[4]Differences between the Bureau and Mott MacDonald calculations were incorporated into the storage capacity projections as error bounds.

Overall, the total difference in estimated capacity is likely due to differences in calculation methodology. The Bureau used the Area-Capacity (ACAP) program, while Mott MacDonald used a surface volumetric calculation to determine the volumes within each storage allocation. In addition, Mott MacDonald had to digitize rangeline data to develop the 1974 and 1993 surfaces, which could contribute to the differences in the calculated storage allocation capacities. Total differences in storage allocation capacity estimates range from 0.5 to 1.7%

relative to the total available storage within the reservoir. Differences in volume within individual storage allocations are in the same order of magnitude. Therefore, the methodology employed by Mott MacDonald for volume calculations is appropriate for the purposes of a planning level analysis. These percent errors will be incorporated into the forecasting analysis described in the following Section as prediction error bounds.

An analysis of the historical surfaces was conducted to determine the spatial distribution of sedimentation and debris accumulation within Pueblo Reservoir since dam closure based upon the historical 1974, 1993, and 2012 bathymetric and topographic data. Figure 3-1 shows the spatial distribution of historical sedimentation based on the surfaces compiled and developed by Mott MacDonald. In general, the analysis shows the highest sedimentation rates along the reservoir thalweg (original Arkansas River Channel), with higher sedimentation noted in the upper reaches of Pueblo Reservoir near the delta formation. In general, this matches the analysis provided in U.S. Bureau of Reclamation, 2015 which showed sedimentation along the thalweg, with the highest sedimentation rates located in the upper segment of the reservoir towards the delta.

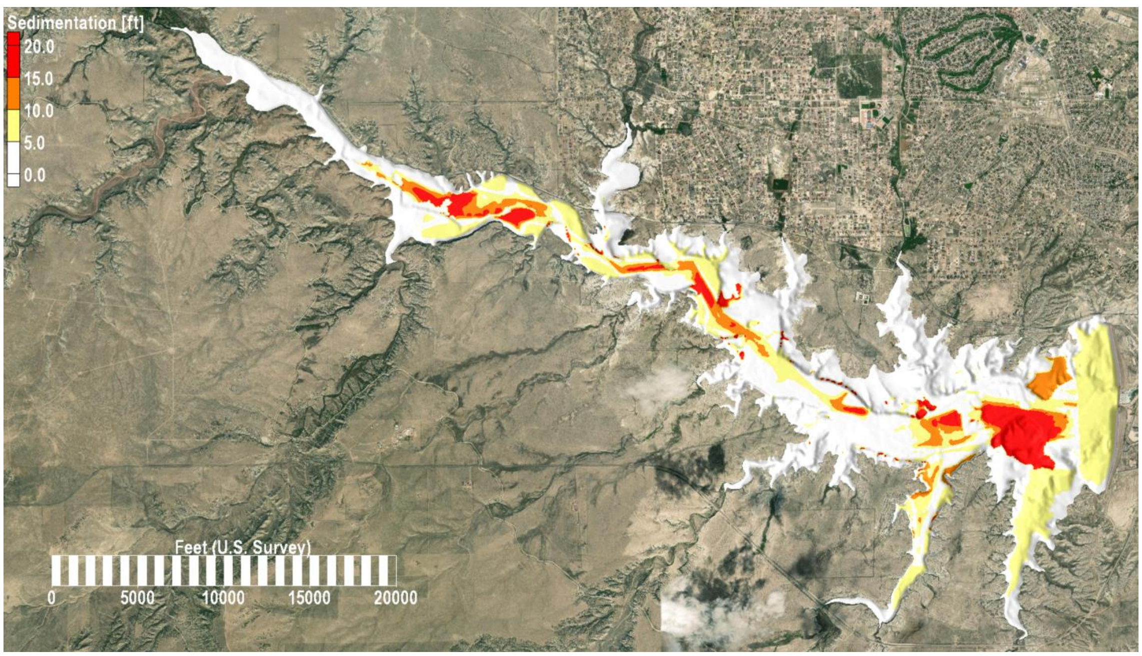

Figure 3-1: Historical Pueblo Reservoir sedimentation and debris accumulation from dam closure (1974) to 2012 survey based on surfaces compiled and developed by Mott MacDonald.

Additionally, to better assess general sedimentation patterns within Pueblo Reservoir, Mott MacDonald analyzed four "sedimentation zones" to examine large-scale patterns in sedimentation and debris accumulation since dam closure in 1974 to 2012. Figure 3-2 shows the four designated zones, while Table 3.2 tabulates the relative percentage of total sedimentation from 1974 to 2012 in each zone.

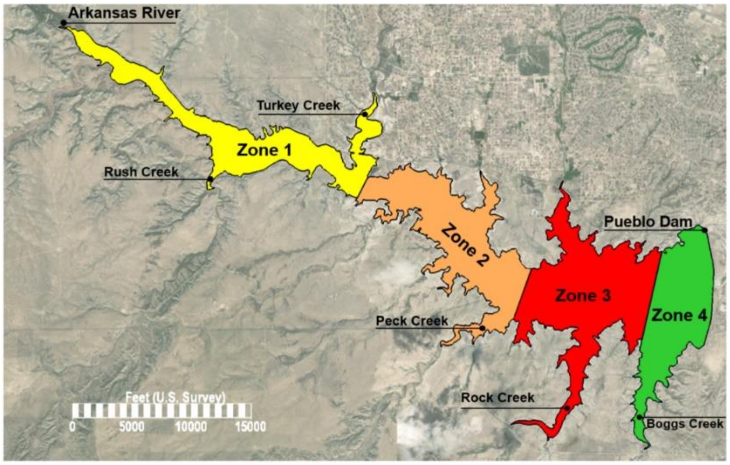

Figure 3-2. Large scale sedimentation zones used to analyze 1974 to 2012 sedimentation patterns.

Table 3.2: Comparison of historical sedimentation distribution from 1974 to 2012.

Zone	Percent of Total Sedimentation [%]
1	18
2	20
3	32
4	30
Total	100

Notes and references

[1] These sedimentation estimates are based on Mott MacDonald bathymetric and topographic surfaces developed from 1974 rangelines, and 2012 contour data provided by the Bureau

[2] These sedimentation distributions show historic sedimentation patterns based on the surfaces developed by Mott MacDonald. Future sedimentation patterns may change based on changes to hydraulics, sediment inflow, and other factors.

[3] Numerical modeling and additional surveys are recommended to refine the sedimentation distributions estimates.

The historical sedimentation analysis shows similar conclusions to the thalweg sedimentation analysis presented in U.S. Bureau of Reclamation, 2015. Both analyses show a relatively uniform distribution of sedimentation throughout the reservoir. However, sediment and debris accumulation in zones 3 and 4 mostly impacts the Inactive Pool and Dead Pool storage allocations. Sedimentation in zones 1 and 2, while less in terms of total sedimentation volume, contributes more to storage capacity loss of the Active Conservation and Joint Use storage allocations.

It should be noted that this analysis relies on rangeline data for the 1974 and 1993 historical surveys. Therefore, the spatial resolution of the data limits the precision of this assessment and the estimates of storage capacity loss presented herein. To facilitate increasing the accuracy of the estimated projections provided in this document and aid in the development and scoping of future work, it is recommended that a comprehensive survey program be conducted to refine and compare annual storage capacity loss estimates developed by the Bureau and Mott MacDonald.

3.2 Sedimentation Forecasting Methodology

For the purposes of this assessment, processed elevation survey data was interpolated to a meshed grid containing over 75,000 points distributed within the approximate project area limits of Pueblo Reservoir. Once interpolated, a linear regression analysis of the data was conducted at each point to approximate future sedimentation and reservoir elevations. The results of the linear regression analysis were then used to assess potential future impacts to existing storage allocations within the reservoir. An example of the regression analysis is shown in Figure 3-3.The results of this analysis are documented within Section 3.2.

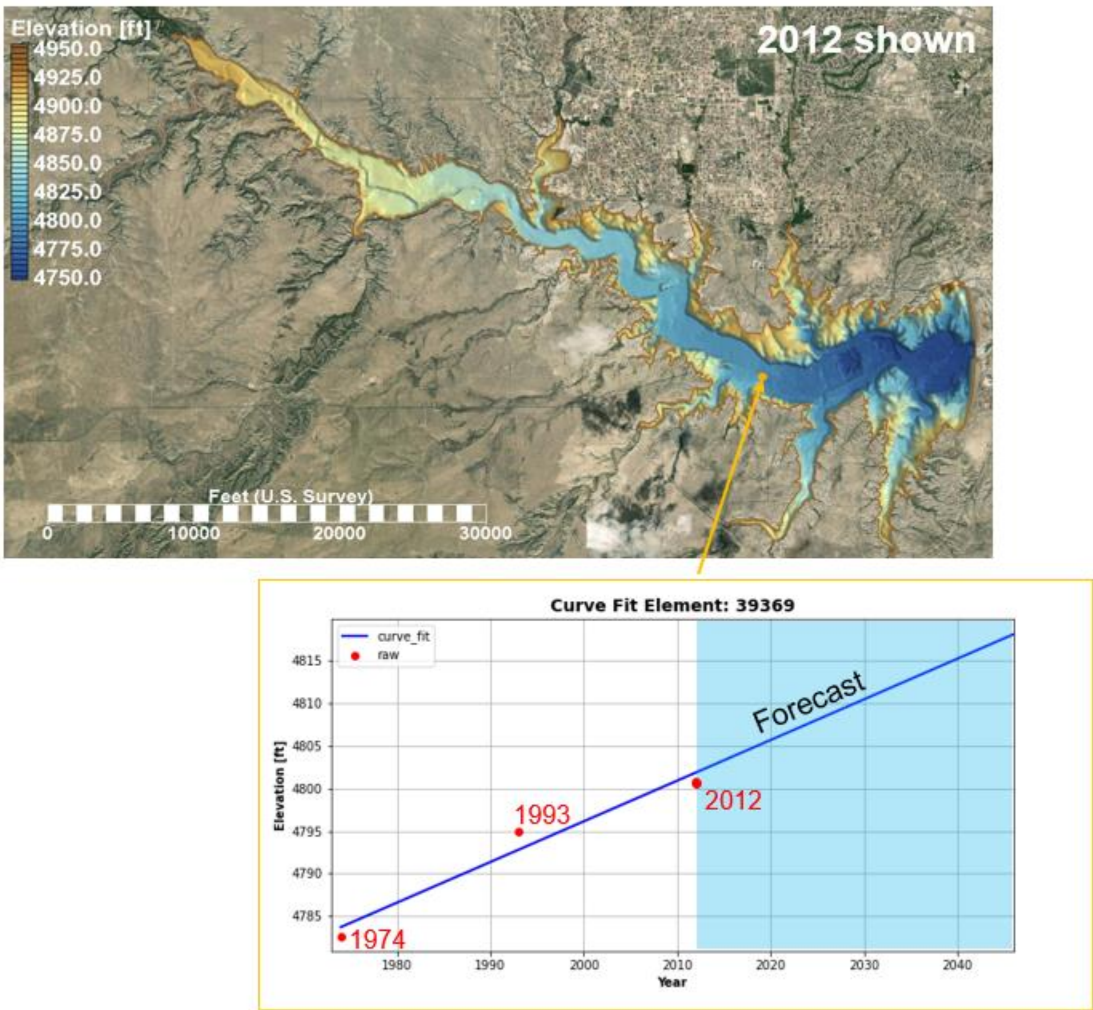

Figure 3-3: Linear Regression relationship example at point 39369.

It is important to note that this approach relies on historical sedimentation rates and does not account for future changes to hydrodynamics due to sedimentation. Therefore, a numerical modeling study is recommended in future phases of the project to refine results from this analysis.

3.3 Future Storage Allocation Capacity Estimates

The linear regression relationships developed in the previous Section were used to project future reservoir elevations. These projected reservoir elevations were used in conjunction with historical water surface elevation data to develop projected capacity statistics. The process for developing future storage allocations is detailed below:

- Forecasting regression curves are developed at over 75,000 points located throughout the reservoir.
- These forecasting curves are used to project and estimate future elevations and sedimentation.
- The projected future elevations are used in combination with the historical water surface elevation data (post 1985 to avoid including elevations when the reservoir was filling up) to develop a range of statistical capacities.
- Projected future capacities were analyzed at the 10% non-exceedance level (i.e. 10% of the time capacity is expected to be lower than this value), the 50% non-exceedance level, and the 99% non-exceedance level (representing the projected maximum storage capacity available within the reservoir).
- An analysis was conducted for overall reservoir capacity, as well as a separate analysis broken down by individual storage allocation. The analysis focused on the projected storage available in the Active Conservation.

Figure 3-4 shows an example of the capacity calculations for the year 2023 in the Active Conservation storage allocation (Elevation: 4796.7 to 4880.5'). This analysis process is repeated to develop future projected reservoir capacities for all years analyzed.

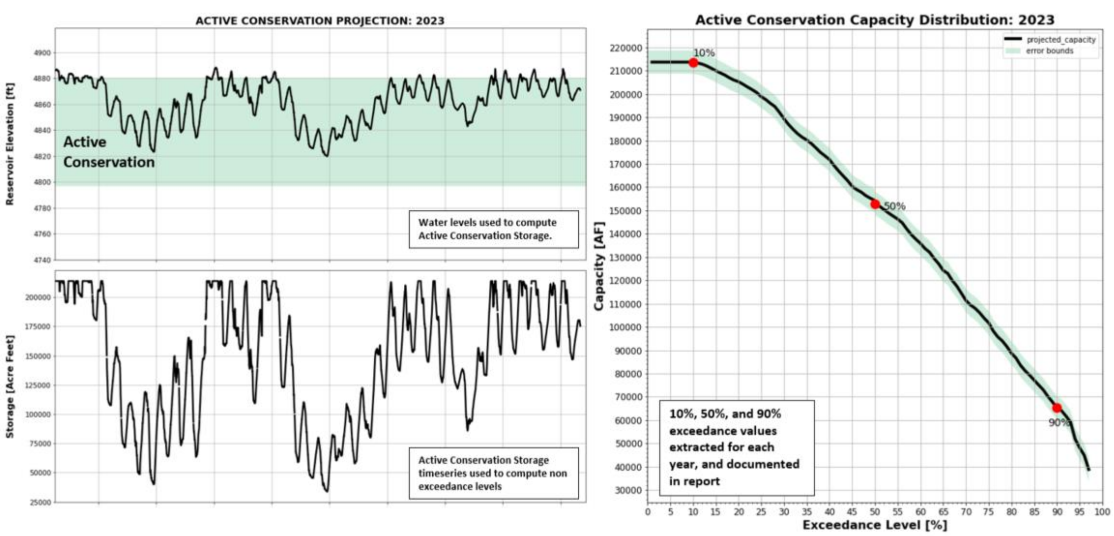

Figure 3-4: Example figures showing storage capacity projection calculations in year 2023. Top left shows the distribution of water surface elevations used to compute storage capacity. Bottom left shows distribution of storage capacities considering the water surface elevation and projected sedimentation. Right shows exceedance plot of reservoir capacity, with 10%, 50%, and 90% values highlighted in red. Note: 99% also extracted and reported in tables to represent the max capacity of Active Conservation Pool.

The projected storage capacity considering water surface elevation and projected sedimentation was calculated for 1, 2, 5, 10, and 25 years into the future (relative to 2021). Note that bathymetric elevations in 2021 are based on the regression analysis described in the previous Section, as the most recent survey is from 2012. An example plot showing the projected distribution of storage capacity within the Active Conservation Pool (Elevation: 4796.7 to 4880.5') in 10 years (2031) is shown below in Figure 3-5.

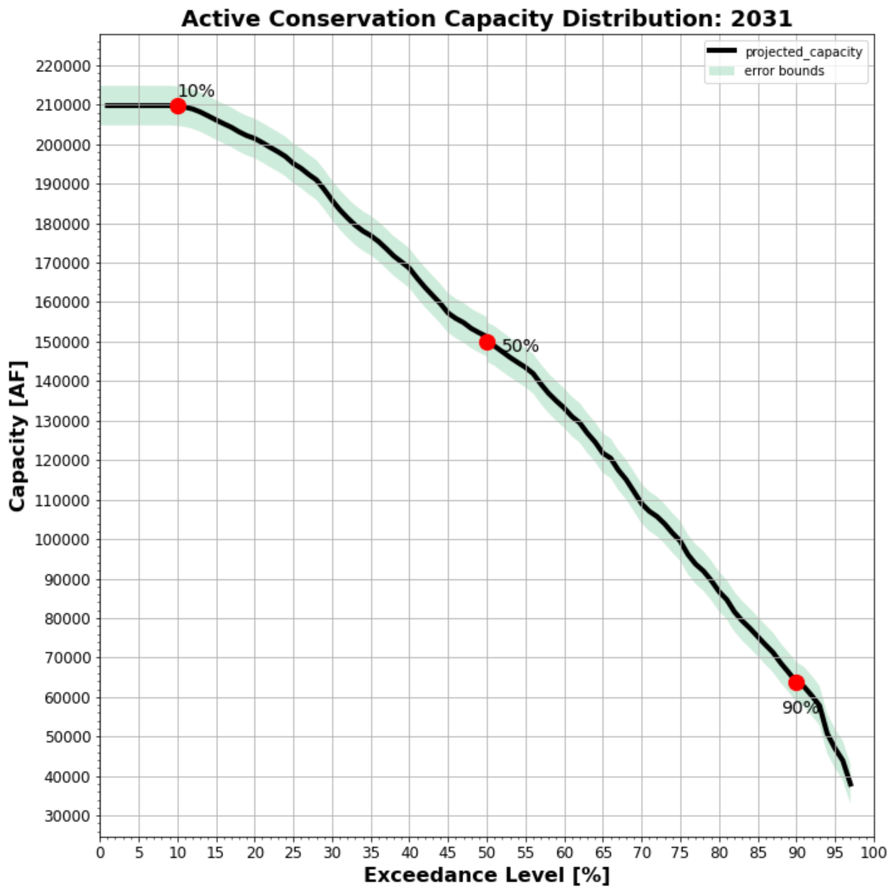

Figure 3-5: Exceedance plot showing storage capacity projection calculations in year 2031 within the Active Conservation Pool.

Figure 3-5 shows the distribution of potential storage capacity considering historical water surface elevations since 1985, and projected sedimentation in year 2031 (10 years into the future). The exceedance values on the x-axis represent the amount of time in a year that given storage capacity is available. For example – the 10% exceedance value in 2031 for the active conservation pool is projected to be approximately 205,000 – 215,000 considering the error bounds shown. A full summary of distribution curves is shown in Attachment B.

Table 3.3 shows the projected yearly capacity loss ranges from the sedimentation analysis. Note that these ranges are based on historical trends and the linear regression analysis described in Section 3.1 herein. Future analysis and numerical modeling is required to refine these sedimentation estimates for planning purposes. Table 3.4shows the computed range of capacities within the Active Conservation, Inactive, and Dead Pool storage allocations for 2, 5, 10, and 25 years into the future. The projections for future reservoir capacities are developed to aid the District in future planning efforts. Please note that any projections are based on the linear regression methodology described in the previous sub-section which is based on historical survey data collected in 1974, 1993, and 2012. Please also note that these projections assume that the top and bottom elevation of each storage allocation pool (as tabulated in Table 3.1) stay constant in the future. If these elevations are altered at any point, the analysis shown in this section and associated capacity projections must be re-analyzed.

The projected capacity for the Active Conservation Pool is also shown in Figure 3-6. Figures showing projected future capacities for each storage allocation are provided in Attachment A.

Table 3.3: Projected future yearly capacity loss range for Dead to Joint Use Allocations.

Allocation	Projected Annual Future Capacity Loss [AF/YR]
Joint Use	50-180
Active Conservation	350-625
Inactive Pool	125-200
Dead Pool	5-55
Total	530-1,060

Notes and References

[1] The Bureau provides estimates in U.S. Bureau of Reclamation, 2015 on sedimentation in the Active Conservation through Dead Pool Allocations.

[2] U.S. Bureau of Reclamation, 2015 estimate a historical average annual rate of 496.1 AF/yr. This matches general range of estimated sedimentation calculated by Mott MacDonald in the Active Conservation through Dead Pool Allocations of 480-880 AF/yr.

[3] Additional surveys are needed to refine the sedimentation projections.

Table 3.4: Projected range of future capacities of selected storage allocations, considering historical water level fluctuations.

		Year 2 (2023)			Year 5 (2026)			Year 10 (2031)			Year 25 (2046)		
Storage Allocation	Top of Pool El. [ft]	10th % [AF]	50th % [AF]	99th % [AF]	10th % [AF]	50th % [AF]	99th % [AF]	10th % [AF]	50th % [AF]	99th % [AF]	10th % [AF]	50th % [AF]	99th % [AF]
Active Cons.	4,880.5	60,000-70,000	148,000-158,000	209,000-219,000	60,000-70,000	147,000-157,000	207,000-217,000	59,000-69,000	146,000-156,000	205,000-215,000	56,000-66,000	140,000-150,000	198,000-208,000
Inactive Pool	4,796.7	21,000-23,000	17,000-23,000	17,000-23,000	16,000-22,000	16,000-22,000	16,000-22,000	16,000-22,000	16,000-22,000	16,000-22,000	13,000-19,000	13,000-19,000	13,000-19,000
Dead	4,764.0	400-2,400	400-2,400	400-2,400	300-2,300	300-2,300	300-2,300	0-2,100	0-2,100	0-2,100	0-1,700	0-1,700	0-1,700

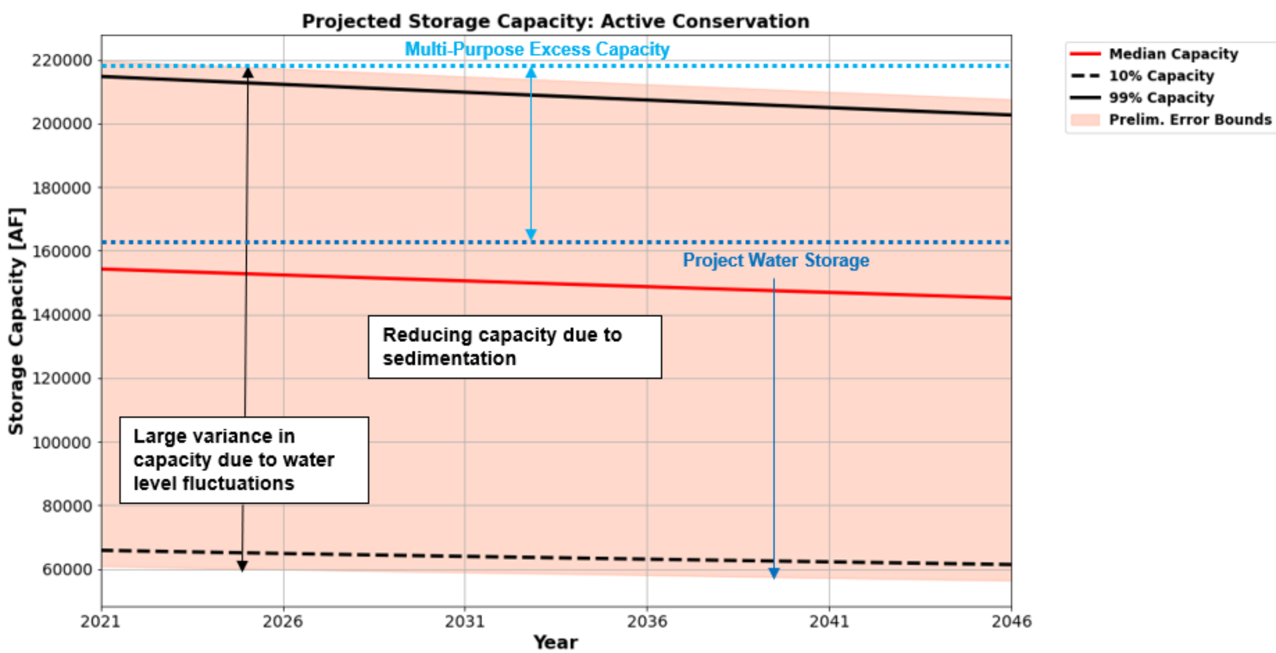

Figure 3-6. Projected storage capacity for active conservation pool considering sedimentation. Project water storage (163,100 AF assumed) and Multi-Purpose Excess Capacity (56,672 AF assumed) shown for reference

Based on the analysis conducted in this engineering assessment, the following qualitative conclusions are made regarding the Pueblo Reservoir storage allocation impacts assessment and storage capacity loss forecasting analysis. Additional data collection, analysis, and numerical modeling is recommended as described in Section 4 herein to refine the conclusions provided below.

Water Level Analysis:

- The highest elevations are typically in late winter to early spring months. Reservoir elevations are typically lower over the summer to early fall months before typically increasing in the early winter months. This observed behavior generally matches the District's water year (November 1 to October 31).
- The majority of water surface elevation fluctuations fall within the Active Conservation storage allocation. This means that water level fluctuations greatly impact the water available for the District's operations and contracts.

Sedimentation Analysis:

- Sedimentation analysis relied on digitization, smoothing, and interpolation of the 1974 and 1993 rangeline data. To refine the accuracy of estimates provided in this assessment, additional topographic and bathymetric survey programs are recommended.
- Since dam closure in 1974, the spatial distribution of sedimentation and debris accumulation within the reservoir has occurred in the thalweg and in the upper reservoir Arkansas River delta area. Sedimentation within the delta area is expected to progress into the future.
  - As such, available storage capacity within the Active Conservation pool is expected to continue to reduce. .
- Projected future sedimentation is based on historical data, and therefore shows sedimentation in the thalweg and upper delta. To refine this spatial analysis of sedimentation and account for changes to flow patterns affecting sedimentation, numerical modeling is recommended in future phases of work.

Storage Allocation Capacity Projections:

- Storage allocation impacts due to long term sedimentation and debris accumulation within Pueblo Reservoir will continue to increase with time. The more that sedimentation impacts the reservoir, the more frequent/common spilling will be. It is understood that spilling will occur in accordance with the water use by allocation shown in Figure 3.4 of Attachment C. Multi-purpose excess capacity contracts (Spill priorities 1 through 3) will likely be impacted when the reservoir water surface elevation is below the top elevation of the Active Conservation storage allocation. Spilling of Project Water (Spill priority 4) may occur when reservoir levels are at or below the median reservoir water surface elevation (50% exceedance).
- Impacts to the Active Conservation storage allocation may impact project water storage when the reservoir is below its median water surface elevation.
- Impacts to multi-purpose excess capacity contracts within the active conservation pool are likely to be exacerbated as the overall storage capacity within the reservoir reduces due to sedimentation and debris accumulation.
- Future sedimentation is likely to worsen the impact of water level fluctuations on available storage within the Active Conservation storage allocation pool.

4 Discussion and Next-Steps

4.1 Discussion & Limitations

The results of this engineering assessment indicate, at a planning level, the projected future sedimentation, and its impact on future storage allocations and reservoir capacity in Pueblo Reservoir. The sedimentation and capacity projections developed by Mott MacDonald used digitized rangeline data (U.S. Bureau of Reclamation, 1994) to develop the 1974 and 1993 bathymetric surfaces. The 2012 surface was developed from detailed contour data provided by the Bureau. Acknowledging that there is inherent subjectivity when developing surfaces from sparse rangeline data, large prediction bound ranges have been provided for all future storage capacity projections provided in this document. Therefore, it is recommended that new survey data be collected in order to refine the storage capacity projections provided in this assessment. The projections provided in this document rely on analytical regression equations developed from historical bathymetric data and the associated sedimentation. Sedimentation of a water body inherently changes the hydrodynamics of the system and can therefore influence future sedimentation of the reservoir. This is a known limitation of using historical data to project future sedimentation. Therefore, to refine the planning level projections provided in this estimate, detailed numerical modeling studies are recommended before developing any additional storage recovery alternatives.

4.2 Next Steps

Continuation and refinement of this assessment along with further data collection programs will improve our understanding of the distribution of sedimentation throughout Pueblo Reservoir and refine the storage capacity projections provided in this document. The recommended next steps will also aid the District in assessing and optimizing the storage recovery alternative design concepts proposed and assessed as part of the Phase I – Fryingpan-Arkansas Storage Recovery Study. Recommended future data collection programs and refinement studies include, but are not limited to, the following:

- Updated bathymetric and topographic surveying programs. A detailed survey using combined modern LiDAR and Multibeam survey methodology will refine the sedimentation and storage capacity loss estimates provided in this memorandum. In addition, further surveys are necessary to develop accurate numerical models that are used to develop storage recovery alternatives.
- Geomorphologic and hydrological analyses to assess sediment loading and distribution within the Upper Arkansas River Basin, including quantifying sediment load from unregulated tributaries upstream of Pueblo Reservoir. Identification of unregulated tributaries carrying the greatest sediment load is vital to understanding the sedimentation processes within Pueblo Reservoir. Once identified, alternative measures can be designed and implemented for these "problem" tributaries to reduce sediment load into the Arkansas River and ultimately within Pueblo Reservoir.
- Numerical modeling to refine the storage capacity estimates provided in this document. Hydraulic and hydrologic models would be coupled to provide more refined estimates of reservoir sedimentation than the analytical analysis provided in this assessment. The revised sedimentation and storage capacity projections developed through the numerical modeling will serve to better quantify impacts to Pueblo Reservoir storage contracts. The models could then be used to evaluate the effectiveness of proposed storage recovery

alternatives such as direct sediment removal, sediment diversion, and/or other feasible reservoir sustainability alternatives.

4.3 Closure

This engineering assessment was conducted to provide guidance on assessing the impacts of Pueblo Reservoir storage capacity loss on District storage, operations & storage contracts. The considerations and future studies detailed in this document can be used to guide further assessments of storage capacity loss and aid in developing storage recovery alternatives and designs. Comprehensive data collection, analysis, and numerical modeling programs should be implemented in future studies if sustainability measures are to be investigated further. Most critical to any future assessments or storage recovery alternatives analysis is to conduct updated bathymetric and topographic surveys within the project area limits of Pueblo Reservoir.

5 References

U.S. Bureau of Reclamation. 1994. *Pueblo Reservoir 1993 Sedimentation Survey*. Sedimentation Section Surface Water Branch Division of Earth Sciences. Denver, Colorado.

U.S. Bureau of Reclamation. 2015. *Pueblo Reservoir 2012 Bathymetric Survey*. Technical Report No. SRH-2014-15. Denver, Colorado: Sedimentation and River Hydraulics Group of the Technical Service Center.

U.S. Bureau of Reclamation. 2021. *USBR Hydromet ARC050 Data*. https://www.usbr.gov/gp-bin/arc050_form.pl?PUER

A. Attachment A – Storage Allocation Projection Curves

Description: This attachment presents the allocation projections for each storage allocation, as well as the entire reservoir. These projections present capacity for each year at different exceedance levels (which consider the variability in water surface elevation). For example, reservoir levels are higher than the 10% level 90% of the time, higher than the 99% level 1% of the time, etc. Note that individual projections are not shown for the Flood Control or Surcharge storage allocations because the historical reservoir elevation data used in these calculations never rose above these allocation's bottom of pool elevation.

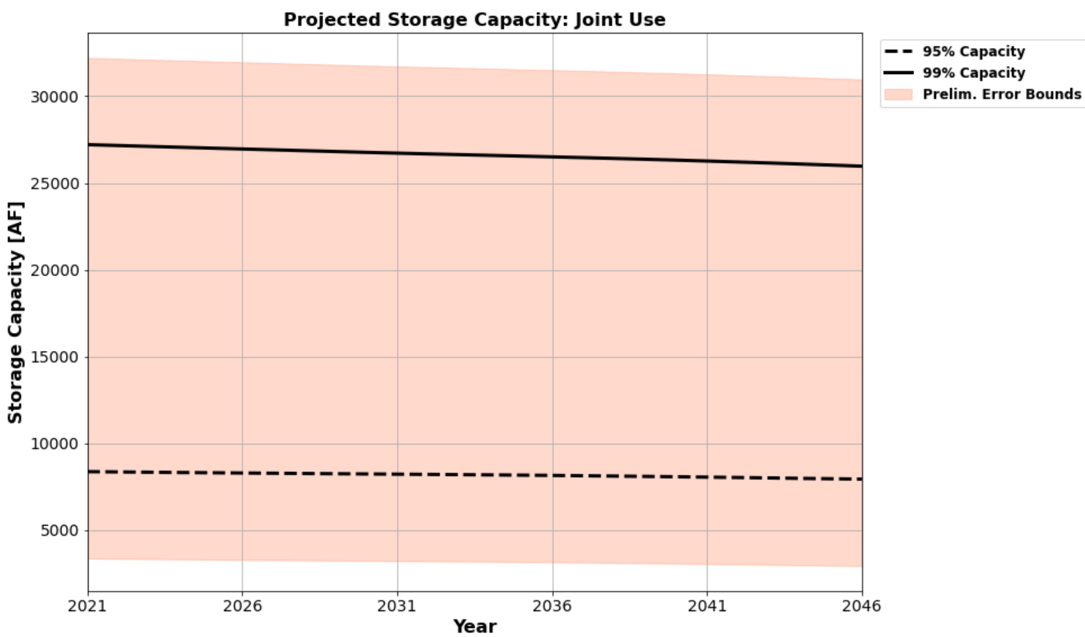

Figure A- 1: Projected storage capacity at the 95% and 99% exceedance levels for the Joint Use storage allocation

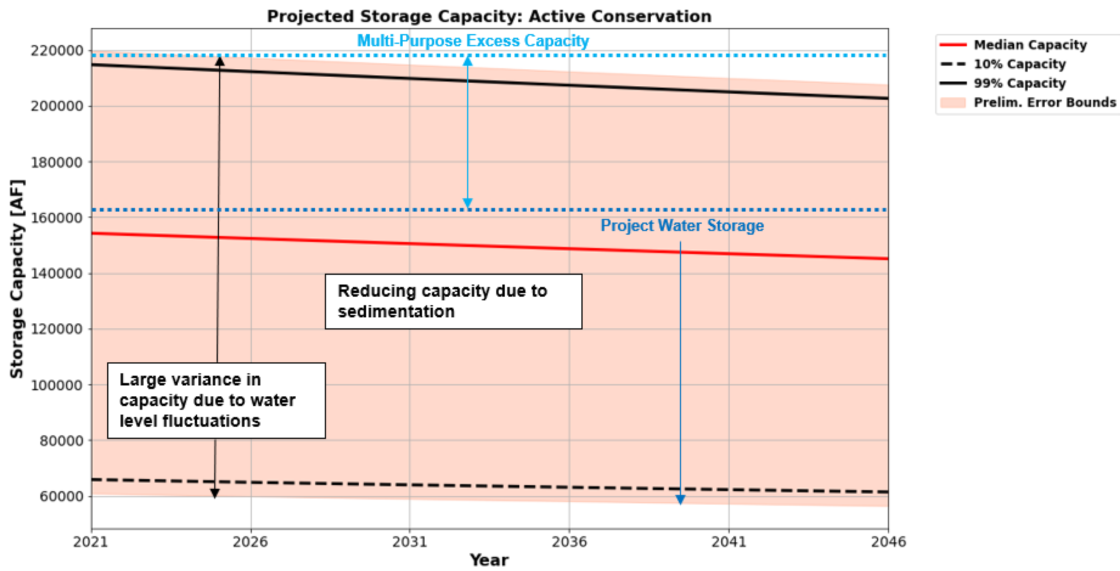

Figure A- 2: Projected storage capacity at the 10%, 50%, and 90% exceedance levels for the Active Conservation storage allocation

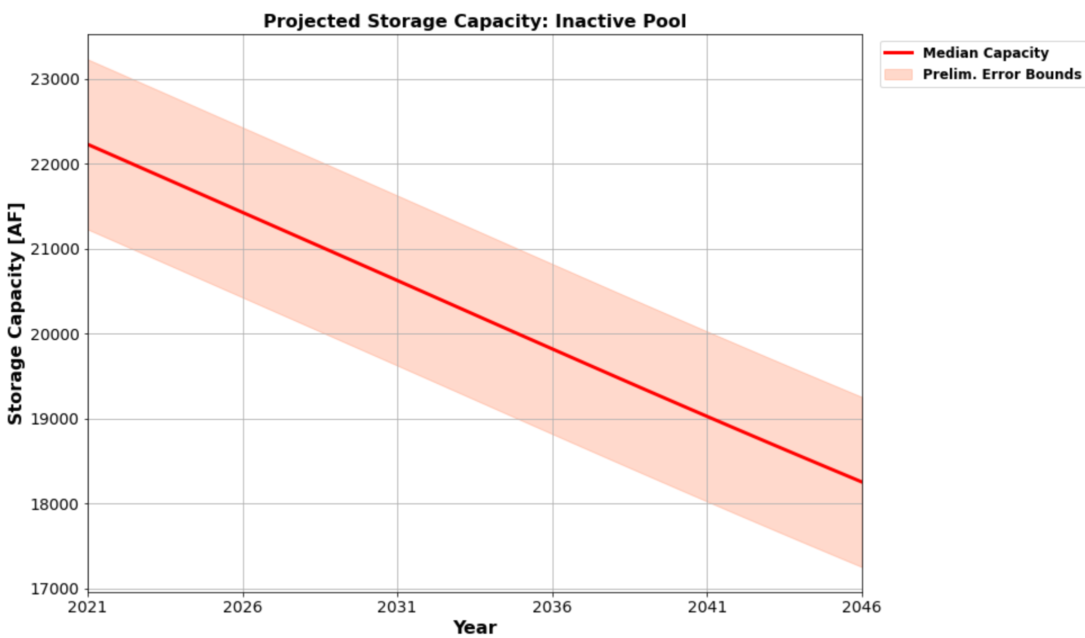

Figure A- 3: Projected storage capacity at the 50% (median) exceedance levels for the Inactive Pool storage allocation. Note that because the water level never drops below the top of Inactive Pool, capacity is only a factor of projected sedimentation and therefore all projected exceedance level estimates (0-100%) for the Inactive Pool Storage allocation are the same.

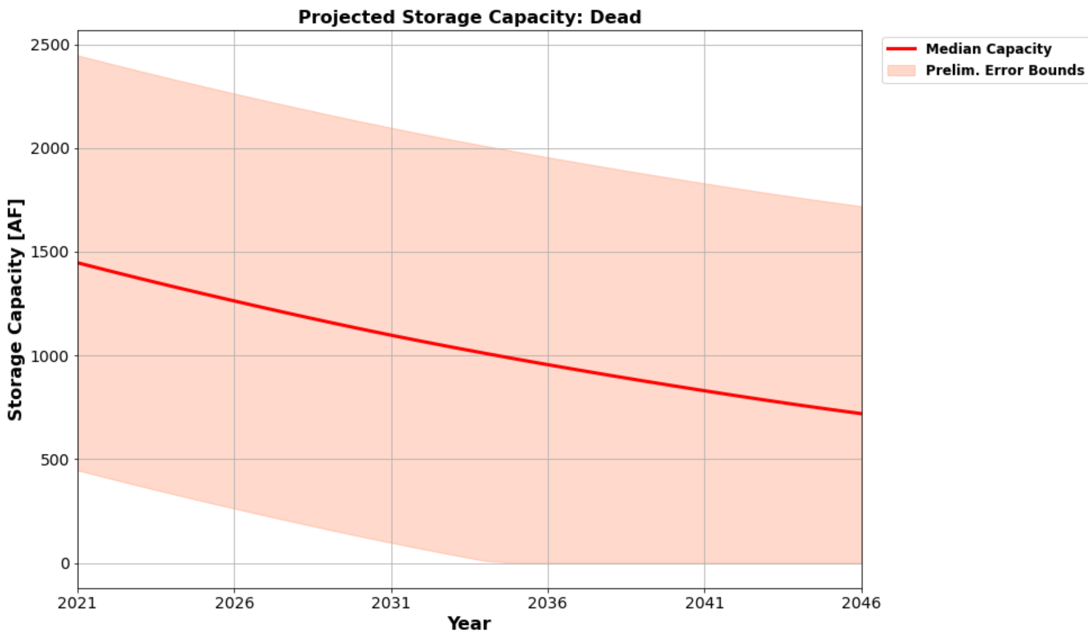

Figure A- 4: Projected storage capacity at the 50% (median) exceedance levels for the Dead Pool storage allocation. Note that because the water level never drops below the top of Dead Pool, capacity is only a factor of projected sedimentation and therefore all projected exceedance level estimates (0-100%) for the Dead Pool Storage allocation are the same.

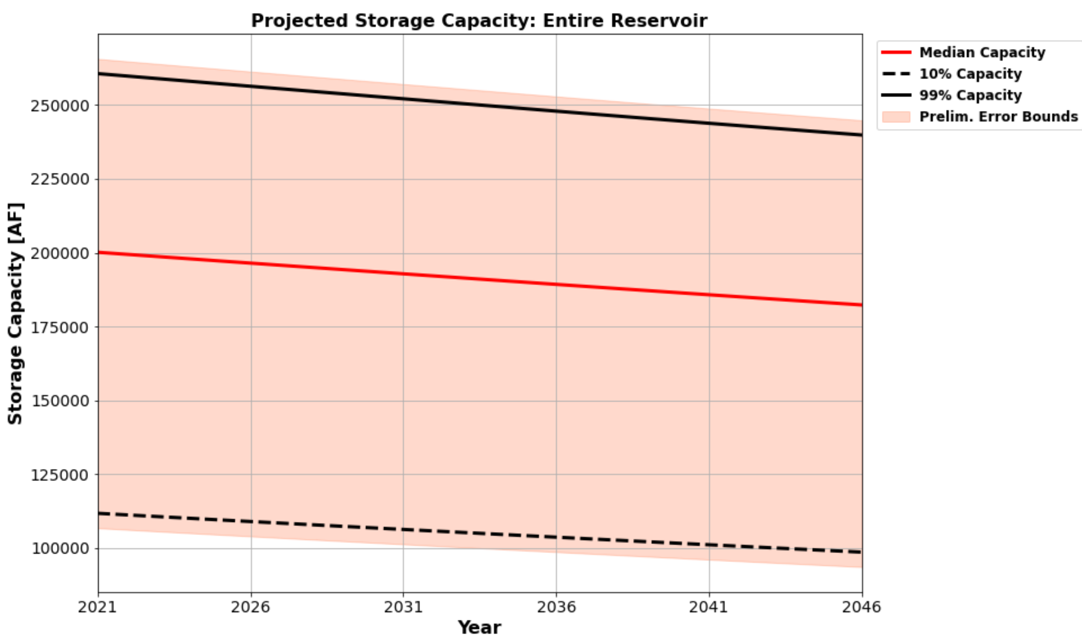

Figure A- 5: Projected storage capacity at the 10%, 50%, and 99% exceedance levels for the entire reservoir. Note that these exceedance levels consider the historical variability in water surface elevations as discussed in the document.

B. Attachment B – Projected Storage Allocation Distributions

Description: This attachment presents the projected storage allocation distributions for the Active Conservation and the entire reservoir. Note that the distribution of capacity is based on historical water levels (post 1985 to avoid including elevations when the reservoir was filling up). Since the vast majority of historical water levels fall within the Active Conservation level, distributions were only developed for the Active Conservation and Entire Reservoir. The capacity of other storage allocations almost entirely relies on sedimentation, and projected capacity of these allocations is documented in Attachment A.

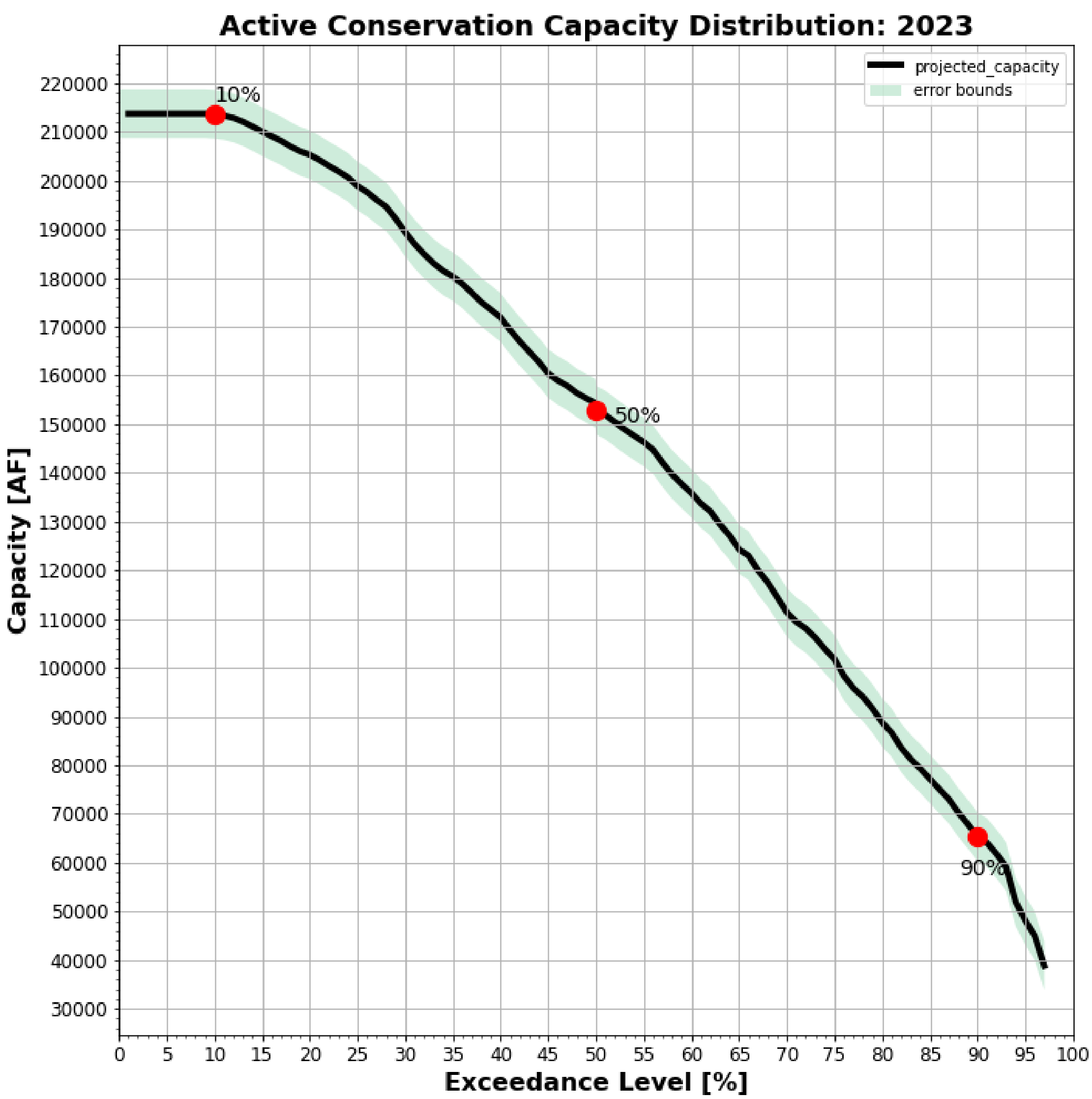

Figure B- 1: Active Conservation Pool projected storage in 2023. Note that these exceedance levels consider projected sedimentation in 2023 and the historical variability in water surface elevations as discussed in the document.

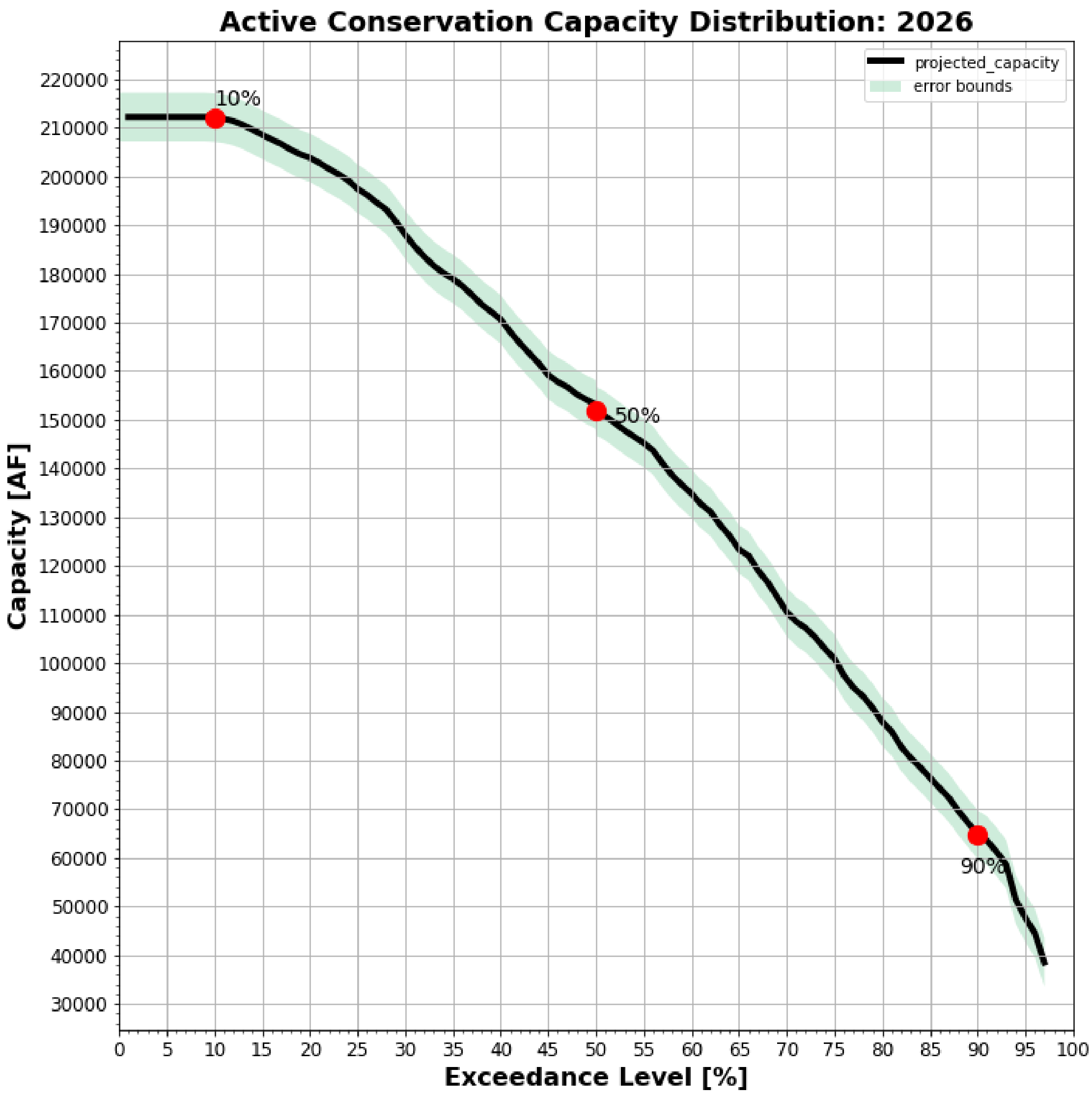

Figure B- 2: Active Conservation Pool projected storage in 2026. Note that these exceedance levels consider projected sedimentation in 2026 and the historical variability in water surface elevations as discussed in the document.

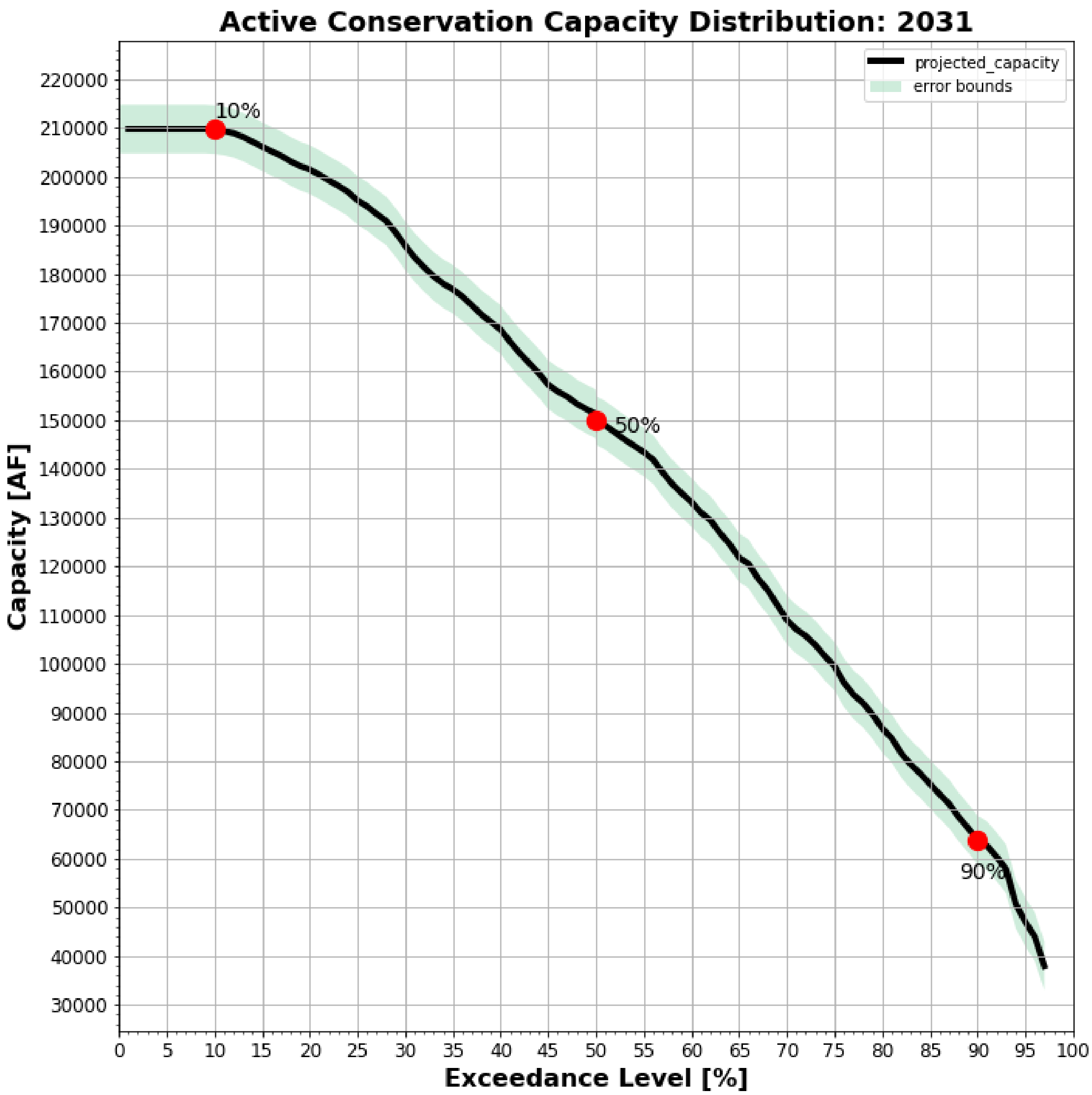

Figure B- 3: Active Conservation Pool projected storage in 2031. Note that these exceedance levels consider projected sedimentation in 2031 and the historical variability in water surface elevations as discussed in the document.

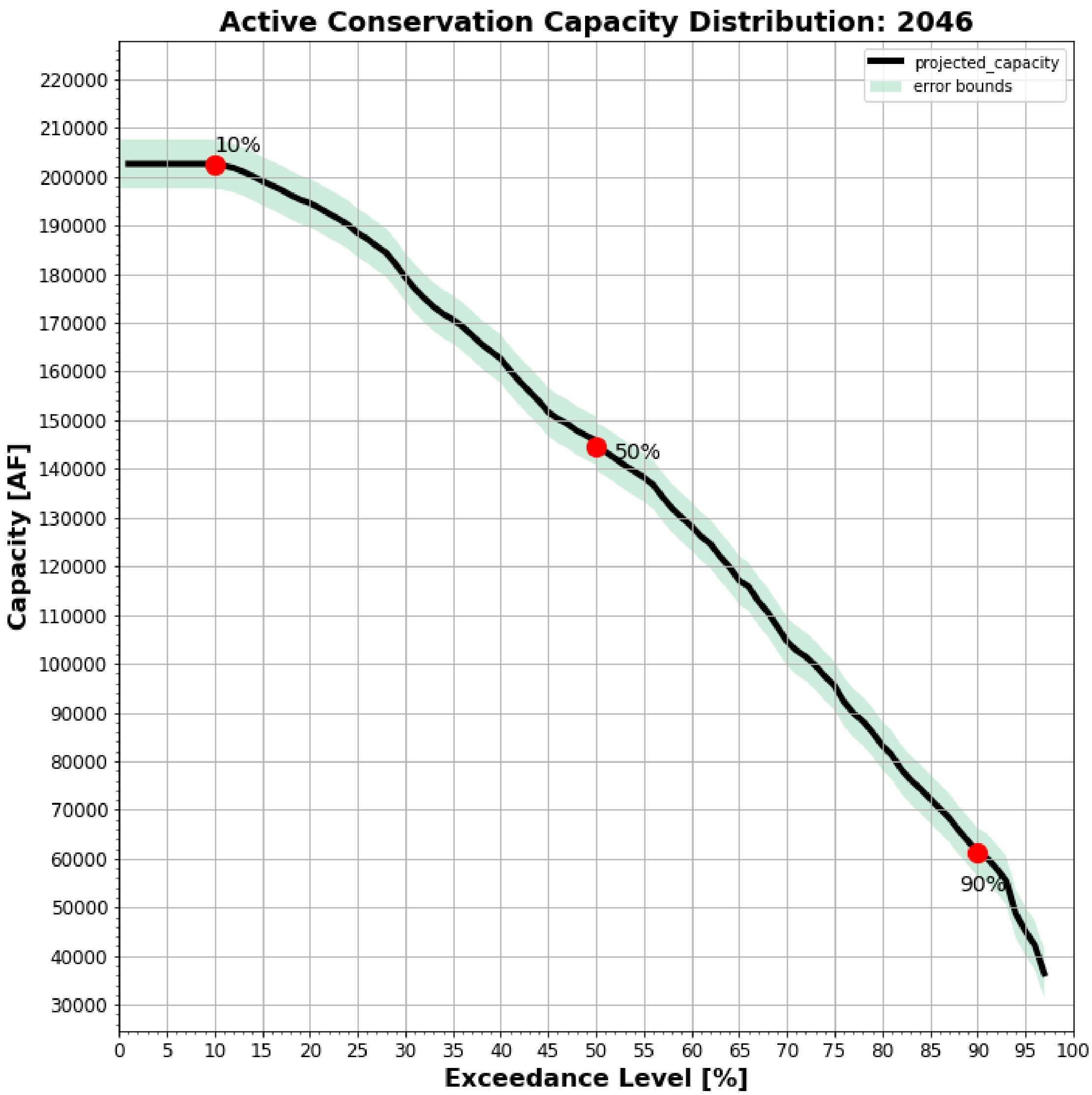

Figure B- 4: Active Conservation Pool projected storage in 2046. Note that these exceedance levels consider projected sedimentation in 2046 and the historical variability in water surface elevations as discussed in the document.

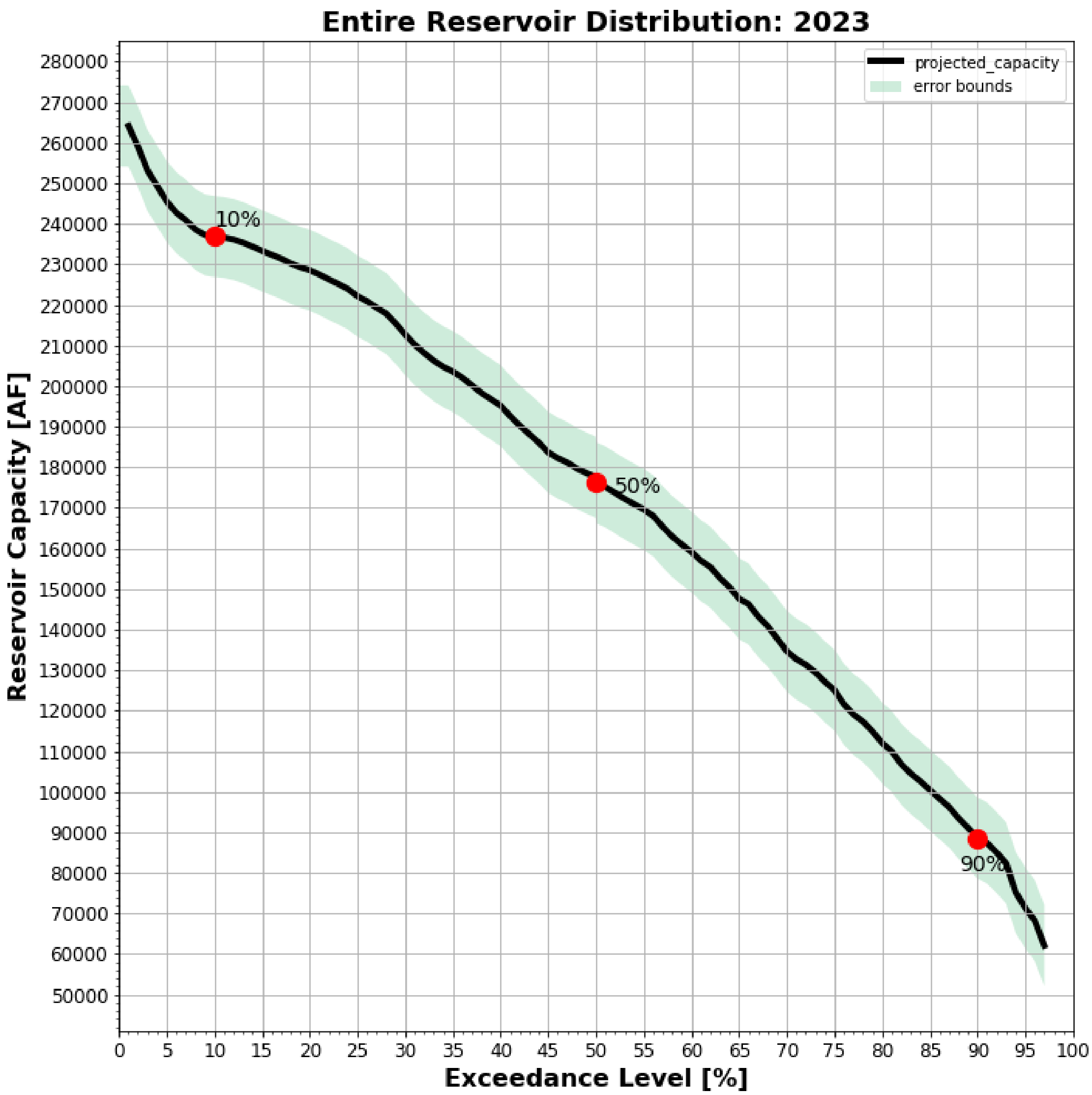

Figure B- 5: Entire Reservoir projected storage in 2023. Note that these exceedance levels consider projected sedimentation in 2023 and the historical variability in water surface elevations as discussed in the document.

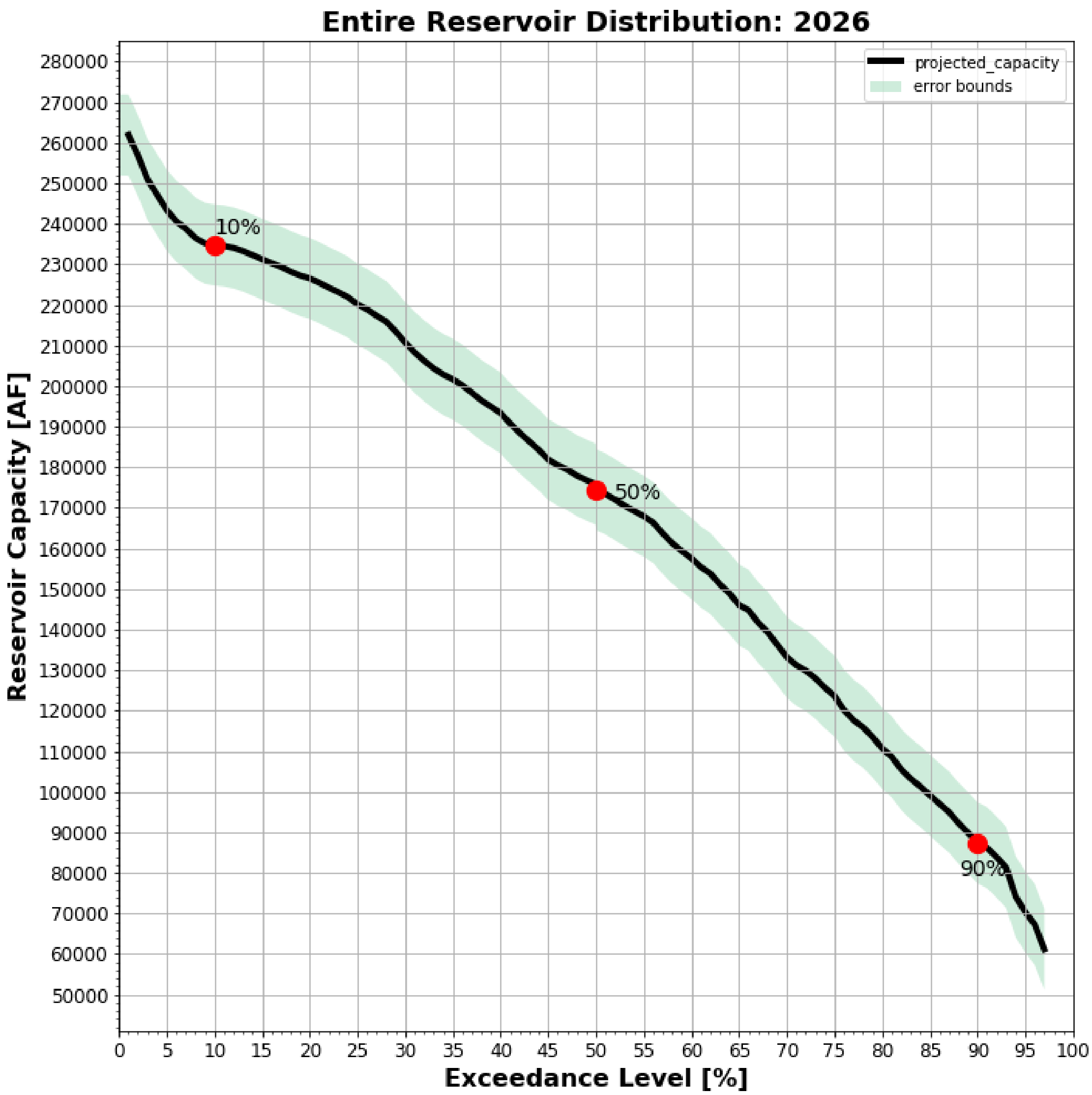

Figure B- 6: Entire Reservoir projected storage in 2026. Note that these exceedance levels consider projected sedimentation in 2026 and the historical variability in water surface elevations as discussed in the document.

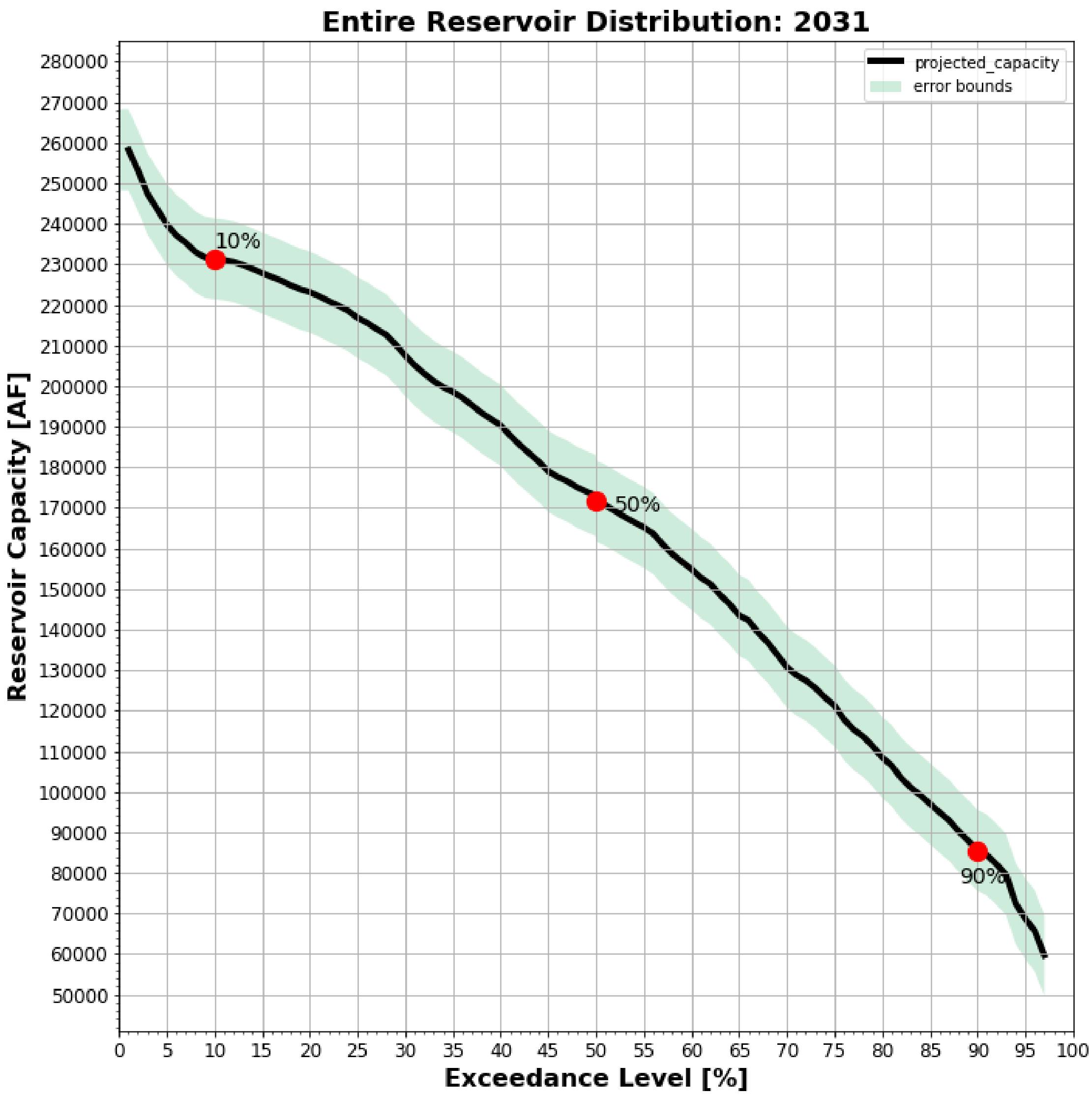

Figure B- 7: Entire Reservoir projected storage in 2031. Note that these exceedance levels consider projected sedimentation in 2031 and the historical variability in water surface elevations as discussed in the document.

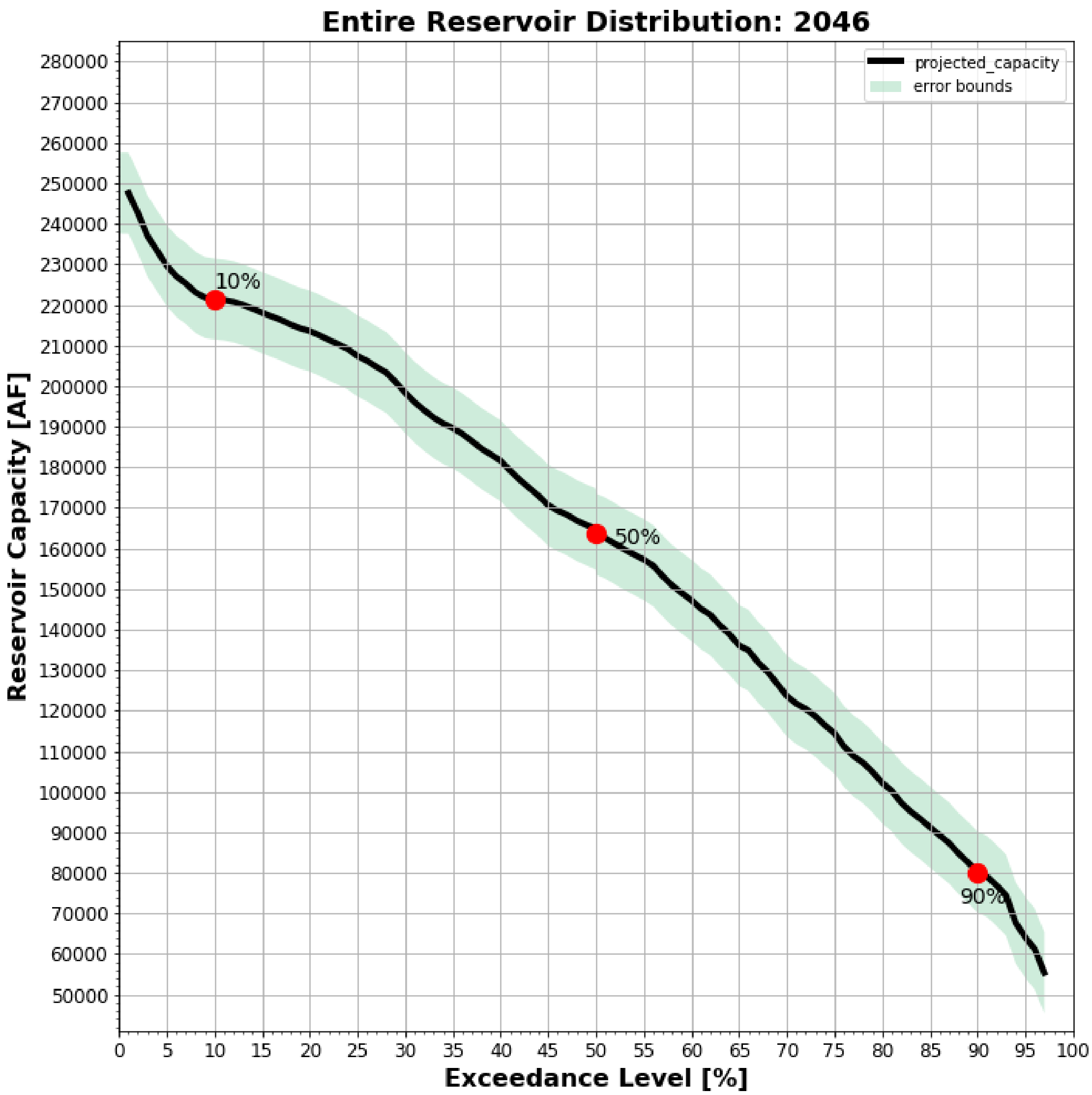

Figure B- 7: Entire Reservoir projected storage in 2046. Note that these exceedance levels consider projected sedimentation in 2046 and the historical variability in water surface elevations as discussed in the document.

C. Attachment C – Basis of Assessment

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