US Army Corps of Engineers ®
Omaha District

CLIMATE CHANGE ASSOCIATED SEDIMENT YIELD IMPACT STUDY: GARRISON DAM SPECIFIC SEDIMENT AND OPERATION EVALUATIONS

HYDROLOGIC ENGINEERING BRANCH

ENGINEERING DIVISION

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EXECUTIVE SUMMARY

Climate change could affect water resources in the Missouri River Basin through alterations in the hydrologic cycle. Warmer temperatures accompanied by more precipitation could lead to a larger snowpack and an earlier spring melting of the snowpack, which would lead to an increase in runoff within the basin. Conversely, lower temperatures accompanied by less precipitation could decrease the snowpack and delay the spring melting of the snowpack, which would lead to a decrease in runoff within the basin. Both scenarios, along with other climate-change scenarios, could alter the basin runoff, changing the sedimentation rate for the Missouri River reservoirs and operation of the Missouri River dams.

This study considers the potential impact of climate-induced hydrologic changes to the Missouri River at the Garrison Dam, the largest of the main stem reservoirs and located in the upper Missouri River Basin. The specific impact examined in this study is the relationship between changing climate and basin runoff that could change reservoir sedimentation or influence the flood control capabilities of the dam.

Five different climate scenarios: drier and cooler, drier and warmer, wetter and cooler, wetter and warmer, and a median future precipitation and temperature, were developed by the US Bureau of Reclamation from one hundred twelve downscaled climate projections. Each climate scenario contained two different periods: 2010-2039 (Near Future) and 2040-2069 (Distant Future).

The US Bureau of Reclamation used the data from the projected climate scenarios as input for a Variable Infiltration Capacity (VIC) model and derived values for runoff, infiltration, and contributions to groundwater from precipitation falling on a particular subset of the region. New elevation-storage relationships and reservoir inflows for each climate scenario were developed using the VIC runoff values. The new elevation-storage relationships and reservoir inflows were then incorporated into Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) and the Daily Routing Model (DRM) in order to model changes in stream flow and amount of sediment transported to the Garrison Reservoir, Lake Sakakawea.

The modeling results showed an increase in pool elevations and releases for all climate scenarios with respect to the historical pool elevations and releases; a majority of the affect was attributed to the increased inflows and not the increased sediment loads. The DRM provided results that were more realistic because the six main stem reservoirs are simulated as a system; as the pool elevations and releases increase at the Garrison Dam, the other five reservoirs adjusted their operations to compensate, which helped reduce the overall effect of the increased flows.

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1 INTRODUCTION

Climate change, as defined by the Intergovernmental Panel on Climate Change, refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer (Bernstein, et al., 2007). Between 1995 and 2006, eleven of those years rank among the twelve warmest years since 1850. The average increase of 0.13^{o}C per decade over 50 years (1956 to 2005) is nearly twice that for the 100 years from 1906 to 2005. Because of this temperature increase, hydrologic systems in portions of the Missouri River basin are experiencing increased runoff and earlier spring peak discharge. This study assesses the effects of climate change concerning sedimentation of Lake Sakakawea and operation of the Garrison Dam located on the Missouri River in North Dakota.

1.1 STUDY AREA

The Missouri River flows 2,341 miles beginning in southwestern Montana and ending in St. Louis, MO as it drains into the Mississippi River making it the longest river in North America. Before the 1960's, the Missouri River would regularly leave its banks and fill the wide floodplain with water. In 1967, all of the six main stem reservoirs were operational: Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point. The Garrison Dam is located in the upper portion of the Missouri River Basin in North Dakota approximately 75 miles north of Bismarck (shown in Figure 1-1). The reservoir behind the Garrison Dam, Lake Sakakawea, is the largest Corps reservoir in the U.S. The lake is 178 miles long and 14 miles wide at its widest point. It has a maximum capacity of 23 million acre-ft, which is one third of the total water stored by the Missouri River main stem dam system. The Garrison Dam drains 181,400 square miles including 57,500 square miles that are downstream of Fort Peck, shown in Figure 1-2; the Yellowstone River, which flows into the Missouri River directly upstream of the Garrison Dam, drains a majority of this incremental drainage area.

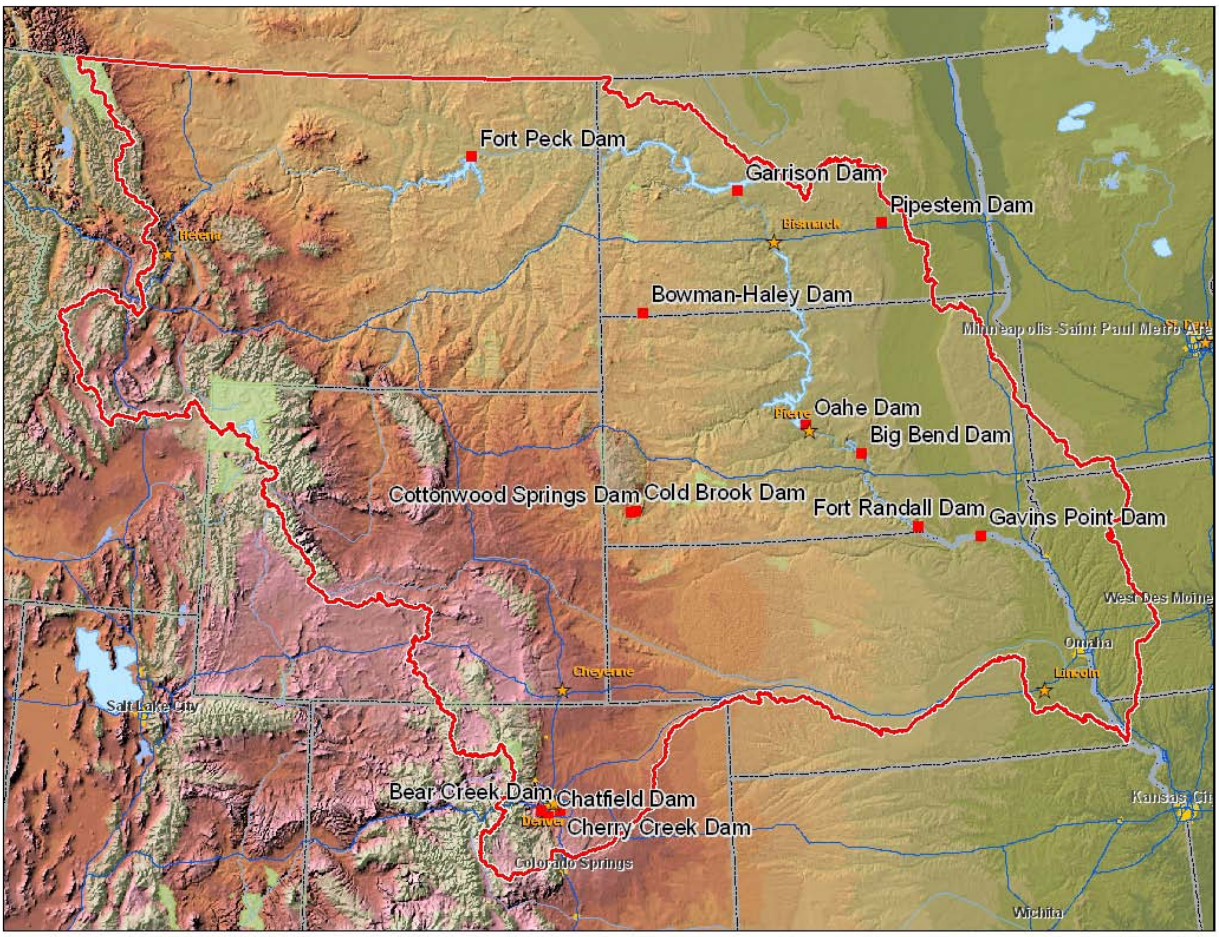


Figure 1-1: Map of the Missouri River basin.

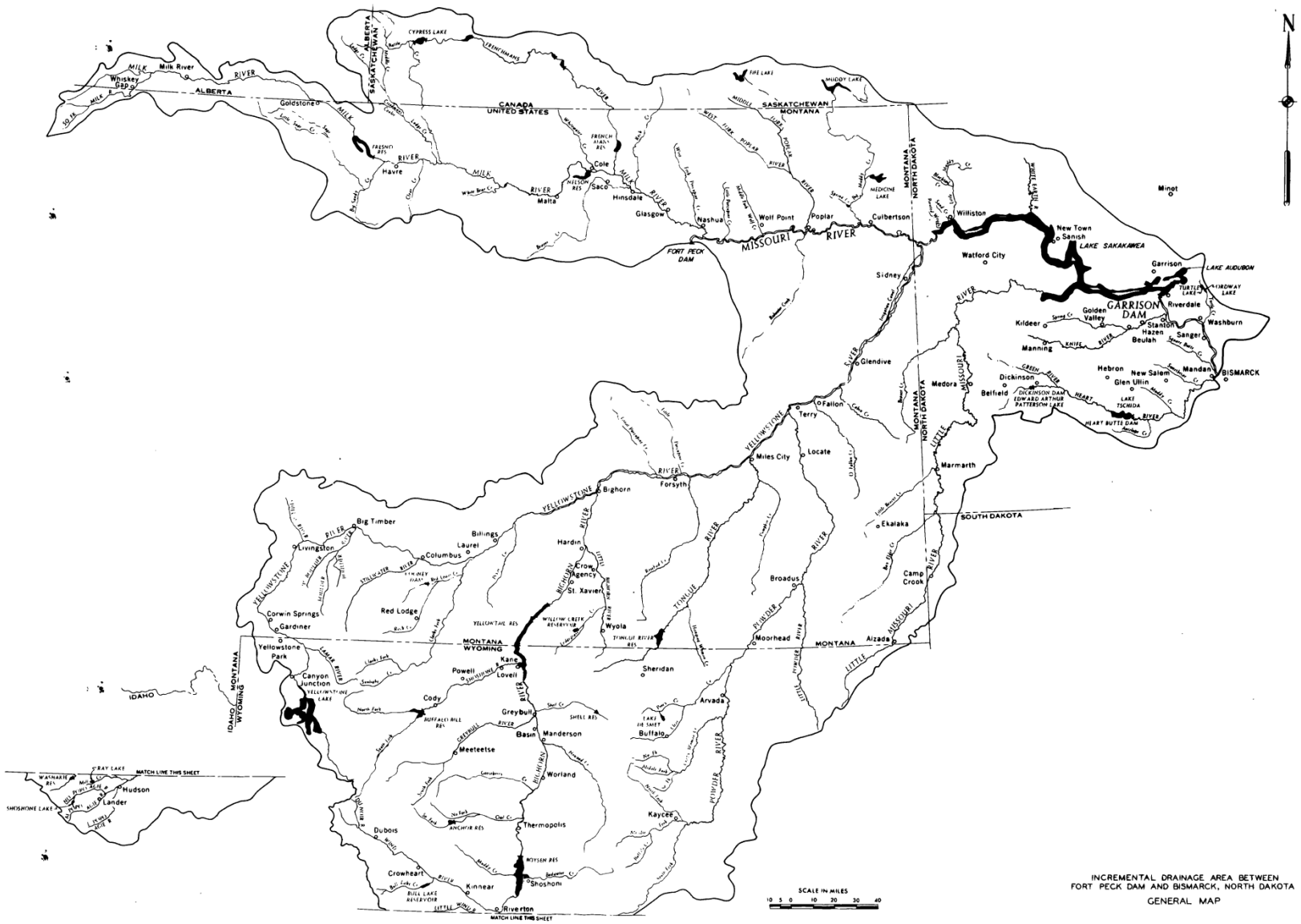


Figure 1-2: Garrison Dam incremental drainage area (USACE, 1978).

1.2 CLIMATE OF THE UPPER MISSOURI RIVER BASIN

The upper Missouri River Basin consists primarily of Montana east of the Continental Divide and North Dakota. The topography rises to over 8,000 ft beginning at the headwaters of the Missouri River in western Montana and falls to approximately 1,800 ft as the Missouri River flows through North Dakota and crosses into South Dakota.

The climate of the Upper Missouri River Basin is characterized as continental with cold winters and mild/hot summers, but temperatures and precipitation can vary widely because of the vast difference in elevation. During the winter months, temperatures are influenced by cold Canadian air moving south into the northern portions of the basin causing temperatures to frequently drop below 0°F. In contrast, warm Chinook winds blowing from the southeast can warm the eastern slopes of the Rocky Mountains in Montana to western North Dakota, sometimes causing temperatures to rise up to 50°F during the winter. Snow is the primary source of precipitation from November to March in the upper Missouri River Basin, but snow can fall as early as September and as late as May. While the average annual precipitation is approximately 15 inches, the higher elevations in Montana can receive as much as 50 to 60 inches annually due to snowstorms. Summer temperatures rise to 80°F in July and August across the upper Missouri River Basin. The rising temperatures and humidity levels in eastern North Dakota allow for the formation of thunderstorms during the summer months; however, western North Dakota and Montana are typically less humid and do not receive as much summer precipitation.

2 PURPOSE AND SCOPE

This study is being completed in partnership with the US Bureau of Reclamation as a pilot study for the USACE Responses to Climate Change program in order for the US Army Corps of Engineers to develop guidance for evaluating climate change effects on reservoir sedimentation and operations for various water resource projects. This pilot study will address the effect of inflows and alterations in sediment yield associated with climate change for Lake Sakakawea in North Dakota shown in Figure 1-1.

Reservoir sedimentation depends on streamflow variability in the reservoir's tributary basin. Under climate change conditions, hydrologic and land cover variation can be used to develop revised sediment load conditions. A watershed sedimentation evaluation was performed with a range of parameters to examine climate change impacts. The sediment yield parameters were adjusted to develop reservoir inflow sediment rating curves that were calibrated to match the sediment loads determined from historical reservoir survey data. Results of the sedimentation analyses are contained in (USACE, 2012).

Existing reservoir regulation practices were assessed to evaluate how projected changes in inflows and reservoir sedimentation would affect reservoir levels and releases. Historic data were used to estimate the likely impact on the elevation-storage relationship. Current operating practices were reviewed with a revised elevation-storage relationship and inflows to evaluate the effect on operations. Comparisons of results can be used to predict the life of a reservoir

and to apply better management of the reservoir to extend its life expectancy under climate change. These comparisons may also assist in decisions on whether additional analysis is needed, such as better forecasting of variable hydrologic loading or changes in operating rules and upstream sediment management.

Two different types of reservoir simulation analyses were completed for Lake Sakakawea. The first was an event-based simulation that routed the Spillway Design Flood and the second type was a period of record simulation of the Garrison Dam operations. The period of record simulation used two separate models, HEC-HMS and DRM, to simulate dam operations from 1967 to 2009 for existing and ten different future climate scenarios.

3 METHODOLOGY

Several different research groups have produced numerous simulations of past and future climates for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). The WCRP Working Group on Coupled Modeling helped to organize and coordinate the modeling efforts in phase three of the Coupled Model Intercomparison Project (CMIP3) effort.

3.1 BIASED CORRECTED SPATIALLY DOWNSCALED CLIMATE PROJECTIONS

Three scenarios for future greenhouse gas emissions were selected for CMIP3: SRES A2, SRES A1B, and SRES B1. The SRES A2 scenario represents a higher emissions path where technological changes and economic growth in relation to emissions is slow and population growth is high. SRES A1B scenario represents a median emissions path where technological changes and economic growth in relation to emissions is balanced between fossil fuels and non-fossil fuels (not heavily reliant on either form of fuel). The SRES B1 scenario represents a lower emissions path where a rapid change in technological and economic growth in relation to emissions occurs (US Bureau of Reclemation, et. al., 2011). The various future emissions are shown in Figure 3-1.

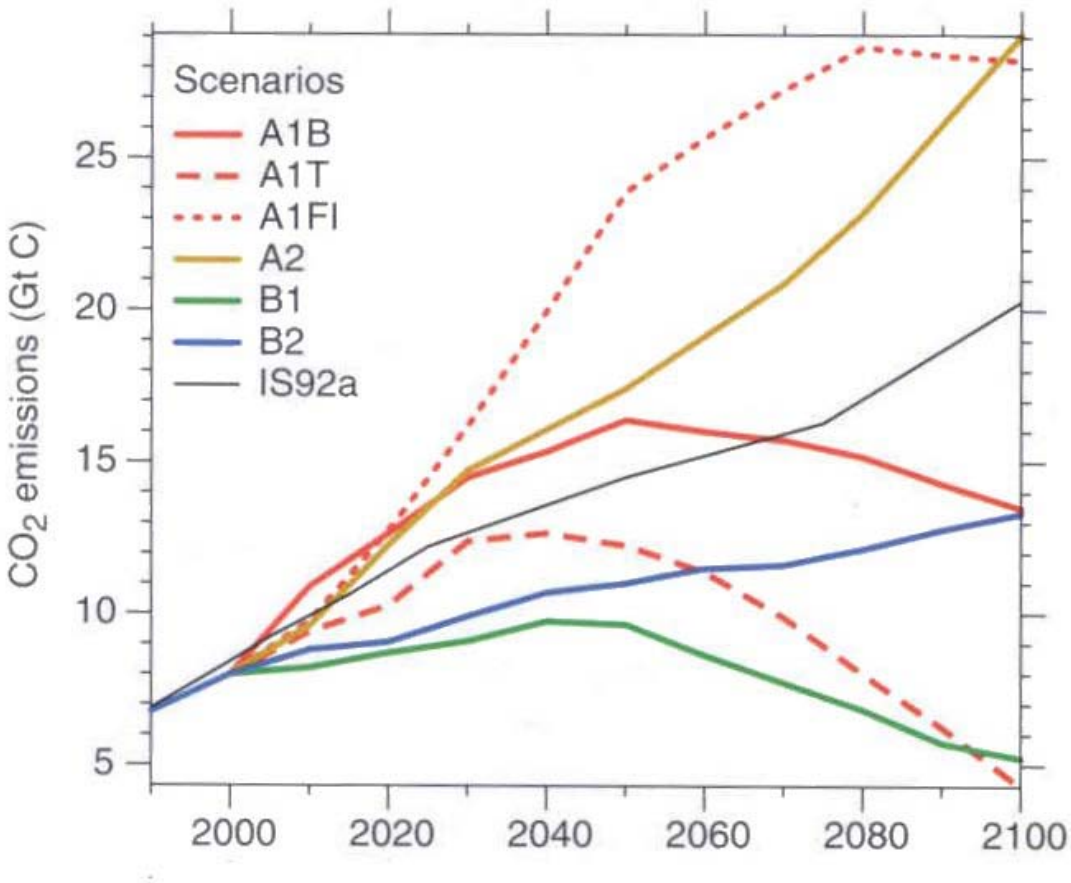


Figure 3-1: SRES future greenhouse gas emission scenarios.

The original output scale of the climate models was not adequate for some watershed and basin-scale studies, so various techniques were used to downscale the original outputs to a finer scale that would be adequate for watershed or basin assessments. One method of statistically downscaling the climate data, which was developed for hydrologic impact studies (Wood, Leung, Sridhar, & Lettenmaier, 2004), was easily applied to ensembles of projections and compared favorably to the other downscaling methods in (Wood, Leung, Sridhar, & Lettenmaier, 2004). A detailed downscaling methodology of the climate projections can be found at the following website: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/#About (US Bureau of Reclemation, et. al., 2011). Table 3-1 lists the sixteen CMIP3 models that produced the Biased Corrected Spatially Downscaled (BCSD) projections that were used in this study to estimate the future changes in runoff due to climate change. One or more simulations for each model was completed that featured a unique set of initial atmospheric and oceanic conditions for the 20th century simulations, which were used to define the initial conditions for the 21st century projections. Once all of the simulations were completed, one hundred twelve different future climate projections had been created.

Table 3-1: CMIP3 BCSD projections used in this study.

Model abbreviations, emissions pathways, and projection run numbers					
Modeling Group, Country	WCRP CMIP3 I.D.	SRES A2	SRES A1b	SRES B1	Primary Reference
Bjerknes Centre for Climate Research	BCCR-BCM2.0	1	1	1	(Furevik, et al., 2003)
Canadian Centre for Climate Modeling & Analysis	CGCM3.1 (T47)	1...5	1...5	1...5	(Flato & Boer, 2001)
Centre National de Recherches Meteorologiques, France	CNRM-CM3	1	1	1	(Salas-Melia, et al., 2005)
CSIRO Atmospheric Research, Australia	CSIRO-Mk3.0	1	1	1	(Gordon, et al., 2002)
NOAA / Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	1	1	1	(Delworth, et al., 2006)
NOAA / Geophysical Fluid Dynamics Laboratory USA	GFDL-CM2.1	1	1	1	(Delworth, et al., 2006)
NASA / Goddard Institute for Space Studies, USA	GISS-ER	1	2, 4	1	(Russell, et al., 2000)
Institute for Numerical Mathematics, Russia	INM-CM3.0	1	1	1	(Diansky & Volodin, 2002)
Institut Pierre Simon Laplace, France	IPSL-CM4	1	1	1	(Marti, et al., 2006)
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	MIROC3.2 (medres)	1...3	1...3	1...3	(K-1 Model Developers, 2004)
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA	ECHO-G	1...3	1...3	1...3	(Legutke & Voss, 1999)
Max Planck Institute for Meteorology, Germany	ECHAM5/ MPI-OM	1...3	1...3	1...3	(Jungclaus, et al., 2006)
Meteorological Research Institute, Japan	MRI-CGCM2.3.2	1...5	1...5	1...5	(Yukimoto, et al., 2001)
National Center for Atmospheric Research, USA	CCSM3	1...4	1...3, 5...7	1...7	(Collins, et al., 2006)
National Center for Atmospheric Research, USA	PCM	1...4	1...4	2...3	(Washington, et al., 2000)
Hadley Centre for Climate Prediction and Research UK	UKMO-HadCM3	1	1	1	(Gordon, et al., 2000)

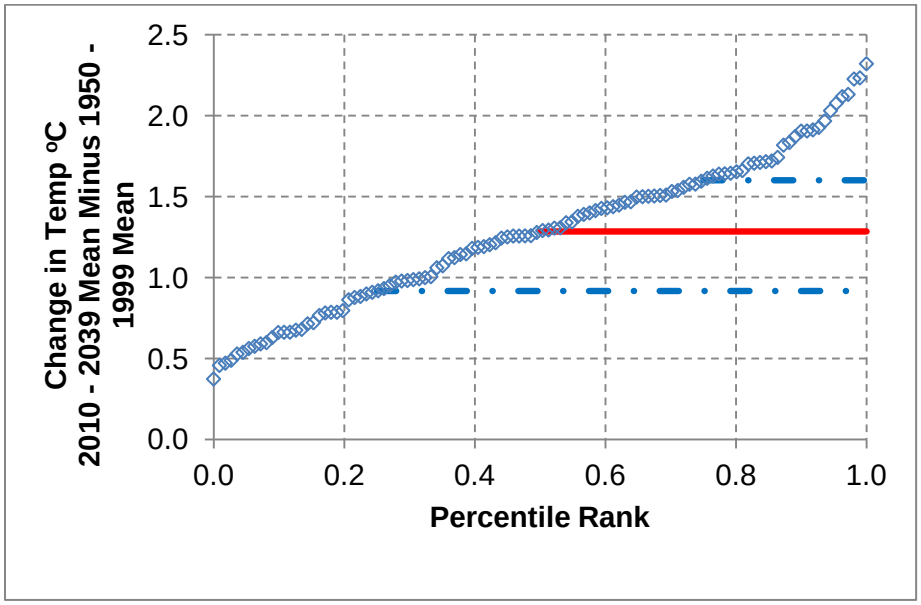
Each BCSD climate projection contains (US Bureau of Reclemation, et. al., 2011):

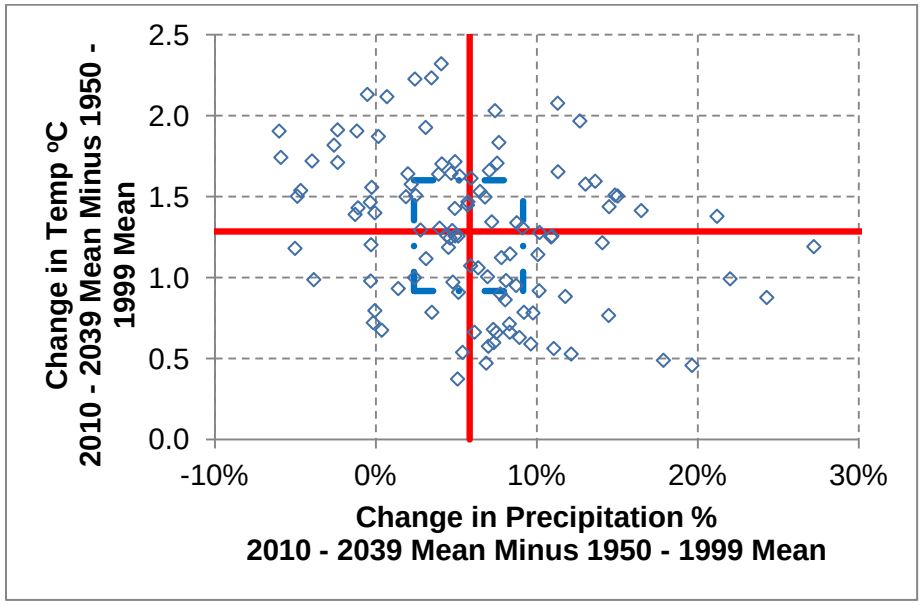
1. Variables
    a. Precipitation, mean daily rate during each month (mm/day/month)
    b. Surface air temperature, monthly mean (^oC)
    c. Missing value flag: 1E+20
2. Time
    a. Coverage: 1950-2099
    b. Resolution: monthly
3. Space
    a. Coverage: North American Land-Data Assimilation System domain (i.e. contiguous US plus southern Canada and northern Mexico, from 25.125^{o}N to 52.875^{o}N and -124.625^{o}E to -67.000^{o}E
    b. Resolution: 1/8° latitude/longitude (~12 km by 12km)

Two issues must be addressed before the climate projection data are ready for the hydrologic modeling.

1. Which of the 112 climate projections should be used as input for the VIC model?
2. The BCSD climate projections contain monthly averaged values, but the VIC model requires a daily value as input

The ensemble-informed, hybrid-delta method was used in this study to create a climate projection for each of the ten future climate scenarios. The first step in the ensemble informed method was to calculate the change in temperature and precipitation between the simulated future periods (2010-2039 and 2040-2069) and the simulated baseline period (1950-1999) for all the climate projections; the temperature was an incremental difference and the precipitation was a percent difference. The differences were plotted as temperature and precipitation cumulative distribution functions (CDFs), which are displayed in Figure 3-2 as the top left and bottom right plots, respectively. The 25th, 50th, and 75th percentiles were transposed to a plot of the climate projections shown as change in temperature vs. percent change in precipitation, which is displayed in Figure 3-2 as the top right plot. The 50th percentile on the temperature and precipitation CDFs created quadrants one through four. The 25th and 75th percentiles created quadrant five. The upper right quadrant, Q1, contained climate projections with warmer, wetter climates. Climate projections with cooler, wetter climates were contained within the lower right quadrant, Q2. The lower left quadrant, Q3, contained climate projects with cooler, drier climates while the upper left quadrant, Q4, contained climate projections with warmer, drier climates. Climate projections that represented the median temperature and precipitation were contained within the middle quadrant, Q5.


Change in Temp ºC
2010 - 2039 Mean Minus 1950 - 1999 Mean
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Percentile Rank


Change in Temp ºC
2010 - 2039 Mean Minus 1950 - 1999 Mean
2.5
2.0
1.5
1.0
0.5
0.0
-10%
0%
10%
20%
30%
Change in Precipitation %
2010 - 2039 Mean Minus 1950 - 1999 Mean

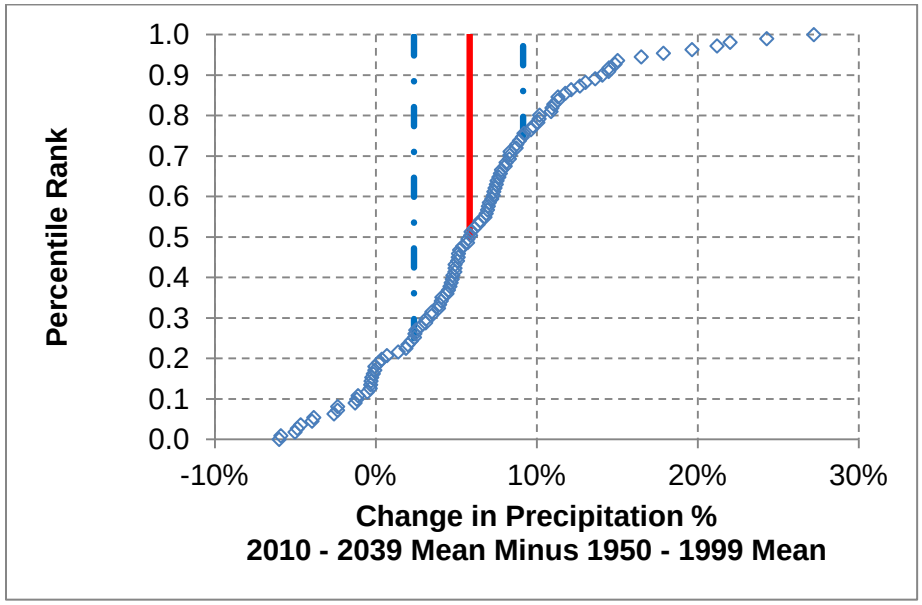

Percentile Rank
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-10%
0%
10%
20%
30%
Change in Precipitation %
2010 - 2039 Mean Minus 1950 - 1999 Mean

Figure 3-2: The top left plot shows the Δ Temperature CDF. The bottom right plot shows the %Δ Precipitation CDF. The top right plot shows all of the climate projections plotted as Δ Temperature vs. %Δ Precipitation with the defined quadrants.

All of the climate projections lying within the different quadrants were used to create a CDF for each month (i.e. each climate projection within quadrant one was used to create a CDF for January, February, March, etc.). These CDFs were compared to CDFs generated from the simulated baseline data and adjustment factors were generated from the ratios. The adjustment factors were then applied to the CDFs generated from observed, mean-monthly temperature and precipitation data to produce the future temperature and precipitation for the different climate scenarios. The future, climate-adjusted temperature and precipitation data were used as input for the Variable Infiltration Capacity (VIC) model.

The VIC model is a gridded hydrologic model developed by the University of Washington that produces surface and subsurface runoff for natural conditions (i.e. no dams or other hydraulic structures altering flow) using climate or meteorological data as input. Spatial variability in precipitation is simulated by dividing the grid cells into a time-varying wet fraction (falling precipitation) and dry fraction (no precipitation). Land cover is simulated by arbitrarily dividing the grid cells into tiles to represent the different types of land cover, but the model does not account for spatial variability of the land cover. It lumps all of the same land cover into one tile. Soil is modeled in layers with infiltration into the top layer controlled by the variable infiltration capacity parameterization. Gravity controls the flow from the top layer to the subsequent lower layers. The VIC model simulates several different forms of snow: ground snow pack, snow within a canopy, and snow on the surface of ice. To accurately model snow accumulation and snowmelt, the VIC model can divide each grid cell into elevation bands that account for changes in temperature due to elevation differences. An important caveat to the VIC model is that each grid cell is computed individually during the simulation so the VIC model treats each cell as an individual system; therefore, runoff between cells is considered negligible and ignored by the model (University of Washington, 2011).

The US Bureau of Reclamation (USBR) conducted the VIC simulations and calibrated them to natural flow conditions. Even after the VIC simulations had been calibrated, the results did not match observed flows. A post process bias-correction was performed to ensure the results matched observed flows using quantile maps. Monthly quantile maps (CDFs) were created for both the VIC simulated future periods (2010-2039 and 2040-2069), the VIC simulated historic period (1950-1999), and the observed historic period (1950-1999). A bias-corrected runoff value was interpreted from these CDFs. Consider the mean monthly runoff for January 2020, which is equal to 15th percentile on the CDF created from the VIC simulated historical January runoff. Switching to observed data, the 15th percentile runoff on the CDF created from observed historical January runoffs is selected. This runoff is considered the new bias-corrected runoff for January 2020. If the runoff exceeded the range of observed runoff, it was assumed that the ratio of the maximum simulated to maximum observed runoff would be applied to all runoffs exceeding the maximum quantile (linear extrapolation). Likewise, it was assumed that the ratio of the minimum simulated to minimum observed runoff would be applied to all runoffs below the minimum quantile. Once the monthly biased-correction was complete, an annual bias-correction is completed using the same procedure except using average annual runoff to create the CDFs. This procedure can only be used when natural conditions exist because the VIC model can only produce runoff for natural conditions. If a hydraulic structure such as a dam exits above the location in question, an additional step must be included. If natural flow

conditions at Gages 1 and 2 exist and bias-correction is completed at those locations, the ratio of the bias-corrected simulated flow to the observed flow at Gage 1 and 2 can be transferred to Gage 3 where natural flow conditions do not exist by means of discharge weighting (see Equation 3-1). See Figure 3-3 for the locations of the gages.

$$CR_{Gage\,3} = \frac{Q_{Gage\,1}}{Q_{Gage\,1}+Q_{Gage\,2}} CR_{Gage\,1} + \frac{Q_{Gage\,2}}{Q_{Gage\,1}+Q_{Gage\,2}} CR_{Gage\,2} \quad \textbf{(3-1)}$$

where CR = monthly biased-correction ratio of observed flow to simulated flow

Q = monthly flow rate

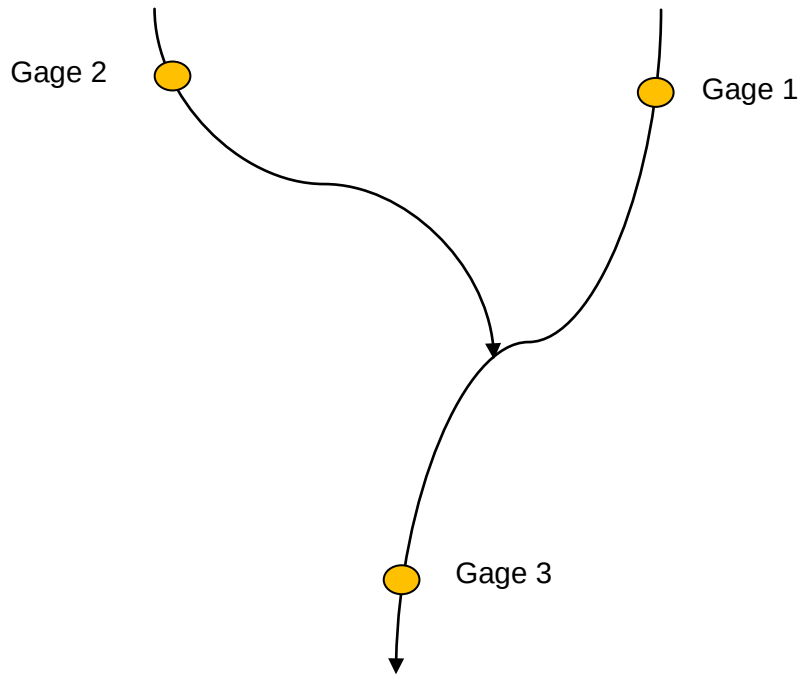


Figure 3-3: Stream and gage alignment.

The USBR provided the Corps with the biased-corrected runoff values for the simulated historic and future periods, which were used to calculate runoff ratios (simulated climate runoff/simulated historic runoff). Since the VIC model is based on natural conditions, the release from Fort Peck Dam was routed to the Garrison Dam and was subtracted from the total inflow to Lake Sakakawea to get the incremental (natural) flow between Fort Peck and Garrison Dams. The incremental flows were multiplied by the VIC runoff ratios to get the climate-adjusted incremental runoff between Fort Peck and Garrison Dams. The total volume of runoff for the VIC calculated data and the climate-adjusted incremental flows between Fort Peck and Garrison were compared on an annual basis to ensure the annual runoff volumes matched. An annual runoff ratio (R1) was calculated from the VIC data by dividing the baseline annual runoff volume into the ten climate scenarios annual runoff volumes (five climate scenarios with two periods). Another annual runoff volume ratio (R2) was calculated from the climate-adjusted, incremental flows and observed incremental flows into Lake Sakakawea. An adjustment ratio (R1/R2) was used to correct the climate-adjusted incremental flows by multiplying it by the

climate-adjusted incremental inflow, ensuring the calculated annual runoff volume was equal to the VIC annual runoff volume. Once the annual runoff volume correction was complete, the climate-adjusted incremental flows were added back to the Fort Peck routed releases to get the total climate-adjusted inflows to Lake Sakakawea. The same procedure was completed for the Fort Peck incremental flows using the Wolf Point VIC data. It was assumed that the operation of the dams upstream of Fort Peck would not change; therefore, the incremental flows are equal to the total inflow to Fort Peck.

Example calculation of the climate-adjusted inflow to Lake Sakakawea

Fort Peck Routed Release (January 1, 1967):	12,800 cfs
Total Lake Sakakawea Inflow (January 1, 1967):	15,200 cfs
Lake Sakakawea Incremental Inflow (January 1, 1967):	15,200 – 12,800 = **2,400 cfs**
VIC Runoff Ratio (January 1967):	1.0753
Climate-Adjusted Inflow (January 1, 1967):	1.0753 * 2,400 = **2,581 cfs**
VIC Baseline Annual Runoff (1967):	24,996,331 acre-ft
VIC Climate Scenario Annual Runoff (1967):	27,697,888 acre-ft
Garrison Observed Incremental Annual Runoff (1967):	12,101,419 acre-ft
Garrison Climate-Adjusted, Incremental Annual Runoff (1967):	13,546,647 acre-ft
VIC Ratio (R1):	27,697,331 / 24,996,331 = **1.1081**
Garrison Ratio (R2):	13,546,647 / 12,101,419 = **1.1194**
Adjustment Ratio (R1/R2):	1.1081 / 1.1194 = **0.9899**
New Climate-Adjusted Inflow (January 1, 1967):	1.0753 * 0.9899 * 2,400 = **2,555 cfs**
Garrison Climate-Adjusted, Total Inflow (January 1, 1967):	12,800 + 2,555 = **15,355 cfs**
Annual Volume Check	
Garrison Observed Incremental Annual Runoff (1967):	12,101,419 acre-ft
Garrison Climate-Adjusted, Incremental Annual Runoff (1967):	13,409,312 acre-ft
Garrison Ratio (R2):	13,409,312 / 12,101,419 = **1.1081**
(R2) = (R1)	1.1081 = 1.1081

An important caveat to the methodology used to adjust flows for climate change is that the bias-correction can change the flows than the climate adjustments. An example of this is shown in Figure 3-4 where the change between the original VIC simulated monthly mean flow and the VIC monthly and annually bias-corrected flow is greater than the change between the VIC monthly and annually bias-corrected flow and the Q1 10-39 (quadrant one climate scenario for 2010-2039) VIC bias-corrected simulated monthly flow.

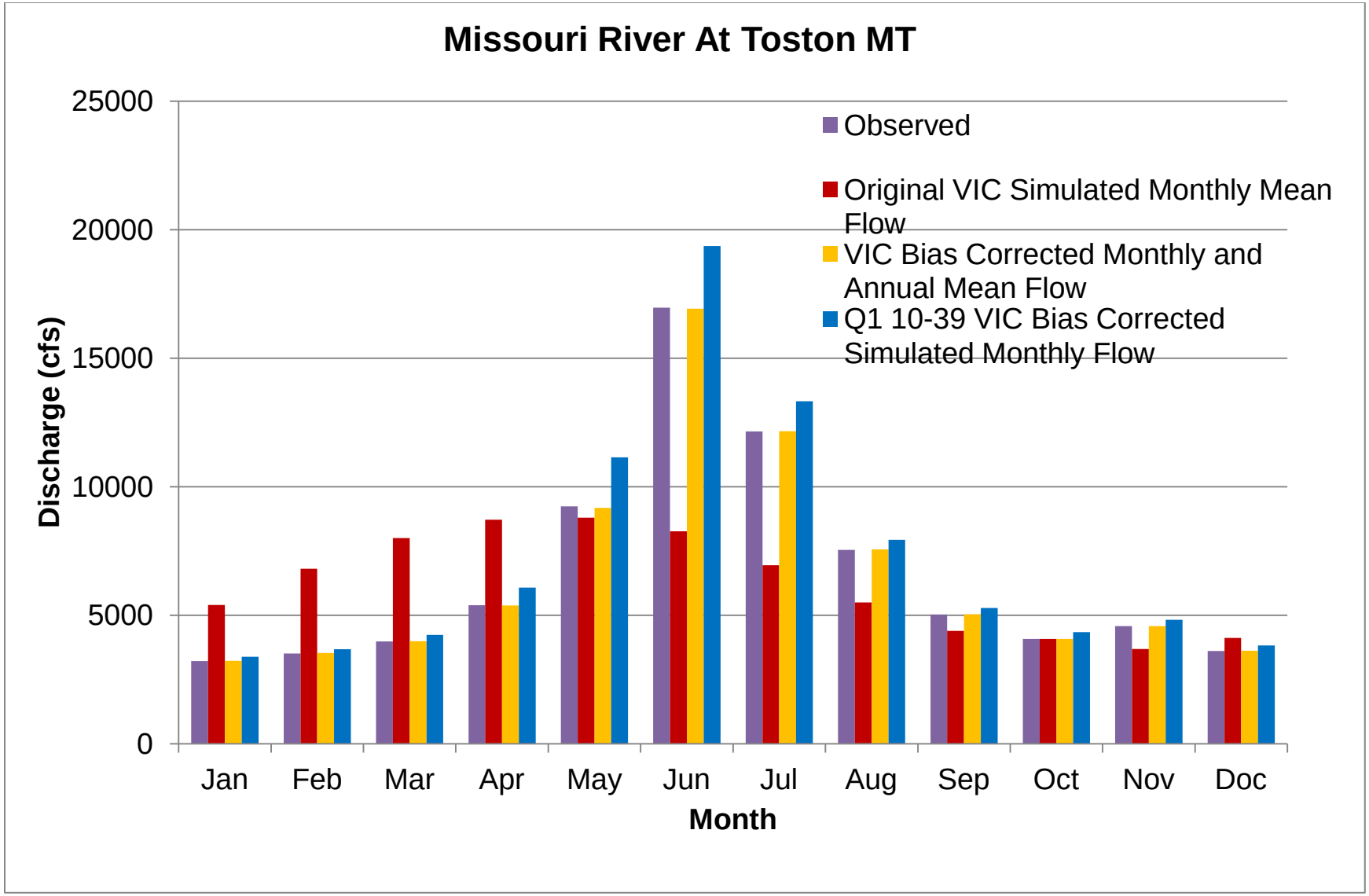


Figure 3-4: Comparison of the bias-correction change vs the climate change at Toston, MT (natural conditions existed at Toston).

3.2 HYDROLOGIC MODELING

Two types of hydrologic analyses were used in this study: a simplified approach that modeled the Garrison Dam using a Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) model and a complex method that modeled all six dams on the main stem of the Missouri River using the Daily Routing Model (DRM). The HEC-HMS model utilized Equation 3-2 and an elevation-storage relationship to calculate pool elevations.

$$\text{Inflow-Outflow}=\Delta\text{Storage} \quad \textbf{(3-2)}$$

The simplified approach included two types of simulations: an event analysis, which used the spillway design flood, and a period of record analysis that used the observed inflows and releases at the Garrison Dam between January 1, 1967 and December 31, 2009. The period of record analysis assumed the Garrison Dam's releases remained unchanged for each future climate scenario and computed the change in pool elevations.

As stated before, the DRM modeled all six dams on the Missouri River, treating the dams as a system. The operation of the Garrison Dam not only depends on the conditions that directly affect it (i.e. incremental flows), but also on the conditions that affect the other five dams on the Missouri River. If a downstream reservoir is experiencing a large incremental inflow and is nearing its flood control pool, the releases from the Garrison Dam can be reduced to reduce the total inflow into the downstream reservoir; however, this would cause Lake Sakakawea's pool elevations to increase. Fort Peck's release would then be reduced to counter the lower releases from the Garrison Dam, minimizing the rise in Lake Sakakawea's pool elevations. The model uses a set of rule curves that provide system limitations and guidance as to how each dam is operated; therefore, the DRM provides a more realistic model of how the Garrison Dam and the rest of the system of dams would be operated.

3.2.1 Spillway Design Flood Methodology

Both the spillway design flood analysis and the period of record analysis used a simple HEC-HMS model that included an inflow source and one reservoir. The spillway design flood analysis set the inflow equal to the spillway design flood, which was taken from the *Missouri River Main Stem Reservoir System Reservoir Regulation Manual: Garrison Manual* (USACE, 1978). Values for the inflows and releases were obtained from a plot of the spillway design flood, shown in Figure 3-5, and entered into HEC-HMS as a time-series, discharge gage.

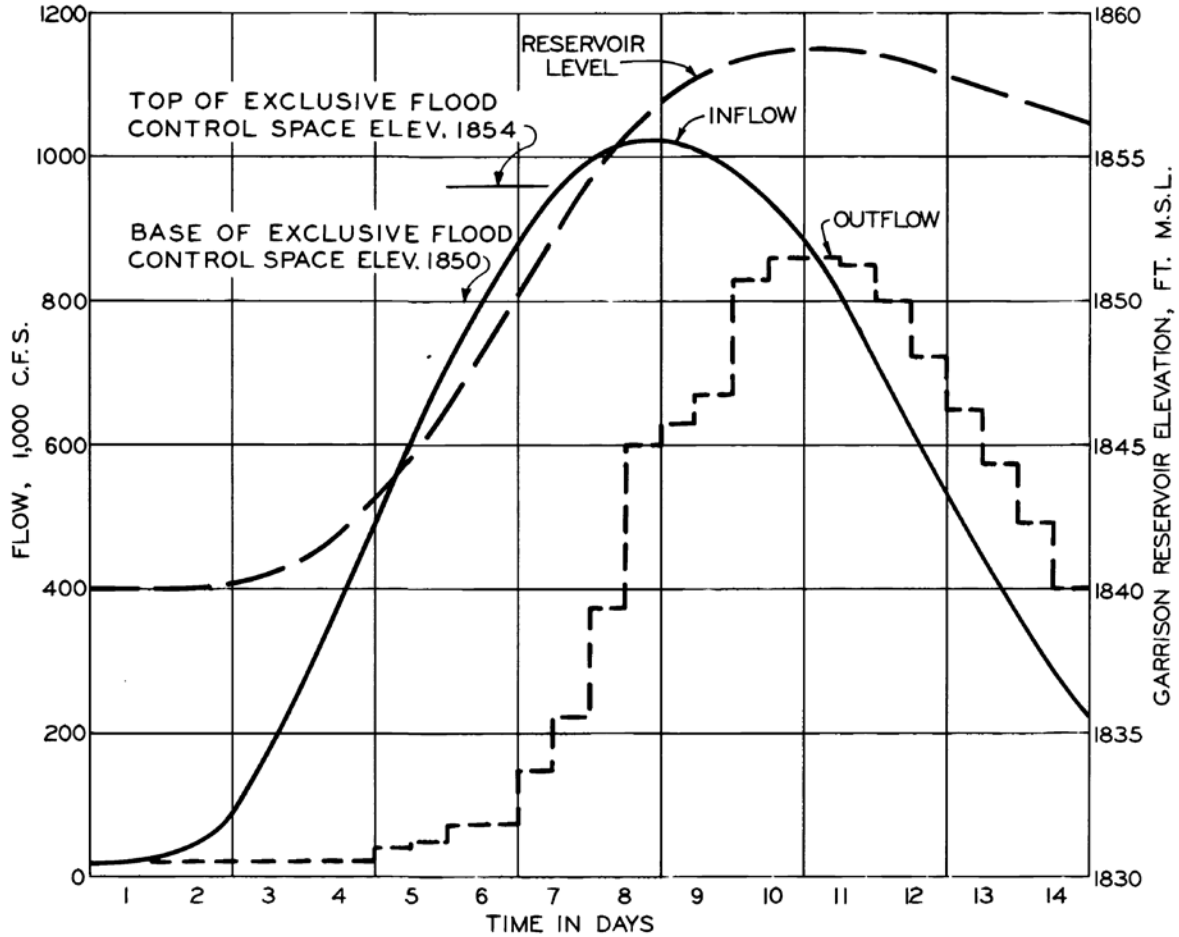


Figure 3-5: Garrison spillway design flood (maximum possible early spring flood) (USACE, 1978).

Since the spillway design flood was originally routed using the 1971 (surveyed in 1969) capacity of Lake Sakakawea, the 1971 elevation-storage relationship was used in the analysis. The plot of the spillway design flood also contained the pool elevations during the flood, so the pool elevations were obtained from the plot and used to calibrate the model. Once the model was calibrated, the 1988 (most recent) elevation-storage relationship was used to model a current baseline scenario. The spillway design inflows and releases were not adjusted for climate change; eleven climate-adjusted, elevation-storage relationships were used in the model to evaluate the effects of climate change on reservoir safety. A future baseline scenario was one of the climate scenarios, which represented a future scenario where the climate continued on its current path. This provided a baseline of comparison for the other ten climate scenarios (five climate scenarios for two periods). The results of the spillway design flood analyses are discussed in Section 4.1.

3.2.2 HEC-HMS Period of Record Methodology

The second part of the simplified method was the period of record analyses, which examined how climate change affected pool elevations if the release remained equal to the observed values (reservoir operations did not change). The HEC-HMS model used for the spillway design flood analyses was altered to include observed inflows and releases as the inputs for the model. The initial methodology set the releases equal to the observed releases; however, after initial simulations caused Lake Sakakawea to exceed the flood storage capacity, a spillway was added to the model to ensure the pool elevations remained below the top of the spillway gates. The spillway was designed to allow uncontrolled flow through the spillway once the pool elevations reached 1854.0 ft (Garrison Dam's spillway top of gates elevation) to ensure the pool elevations remained below 1854.0 ft. The HEC-HMS model used in the period of record analyses was not calibrated, unlike the spillway design flood analyses. During the period of record, January 1, 1967 through December 31, 2009, four different historic elevation-storage relationships were used to calculate the inflows to Lake Sakakawea; however, only one elevation-storage relationship was used in the HEC-HMS model simulations for baseline conditions and each climate change scenario. If only one of the four historic elevation-storage relationships was used with the observed inflows and releases, the calculated pool elevations diverged from the observed pool elevations because the elevation-capacity relationships have changed over time.

The current baseline scenario calculated the pool elevations of Lake Sakakawea using the observed inflow and releases along with the latest elevation-storage relationship, which was based on the 1991 relationship. This scenario provided current-condition baseline pool elevations that could be compared to the future baseline scenario. The future baseline scenario calculated the pool elevations of Lake Sakakawea using the observed inflow and releases along with a future elevation-storage relationship that represented future storage losses based on current sedimentation rates with change in the climate. The future baseline scenario was used as the basis for comparison between the various future climate scenarios.

Several simulations of the different climate scenarios were completed to understand the effects of climate-adjusted sedimentation and climate-adjusted inflows. The first set of simulations assessed the effects of climate-adjusted sedimentation (capacity analyses). The capacity simulations used the climate-adjusted elevation-storage relationships for each climate scenario, future storage losses based on climate-adjusted sedimentation rates, in conjunction with the observed inflows and releases. A second set of simulations assessed the effects of climate-adjusted inflows (flow analyses) using the climate-adjusted inflows for each climate scenario in conjunction with the observed releases and the 1991 elevation-storage relationship. The final set of simulations assessed the combined effects of the climate-adjusted sedimentation and inflows (flow and capacity analyses) using the climate-adjusted inflows and elevation-storage relationships for each climate scenario in conjunction with the observed releases.

3.2.3 DRM Period of Record Methodology

The Daily Routing Model (DRM) used daily flow data, an elevation-storage relationship, and rule curves that govern the operation of the six main stem dams to evaluate the Missouri River system from Fort Peck to St. Louis. The model contained twenty nodes, six dams, and fourteen

gaging stations, but only four gaging stations are located within the reservoir system. The input data was organized into annual, fourteen-month files, which spanned December of the previous year through January of the following year (i.e. 01 Dec, 1966 through 31 Jan, 1968), and included the incremental flow, evaporation, total inflow, releases, storage, pool elevation, depletions, etc. for each of the six main stem reservoirs. These input files also contain gage data for gages downstream of Gavins Point Dam (last dam on the Missouri River). The elevation-storage relationships file contained the elevation-storage relationship for each of the six reservoirs. In addition to the input and elevation-storage relationship files, the DRM used a series of rule curves that govern the dam operations. The rule curves contained the various pool elevations for each reservoir (flood pool, multi-purpose pool, etc.), the channel capacity limits for minor flooding below each dam, maximum and minimum releases for fish and wildlife as well as irrigation, etc. The channel capacity limits for minor flooding below the dams were reduced by five kcfs to account for channel capacity losses due to sedimentation. The model used these limits along with the incremental inflows to calculate the releases for each dam while attempting to meet the requirements established within the rule curves.

The DRM period of record analyses consisted of the same three sets of simulations as the HEC-HMS period of record analyses: capacity, flow, flow and capacity. For the flow and flow and capacity simulations, the only data changed in the fourteen-month input file for the climate simulations was the incremental flow between the dams; the values for Fort Peck and Garrison were changed to the climate-adjusted incremental flows. VIC results were not available for the four remaining dams downstream of Garrison Dam so only climate-adjusted inflows and climate-adjusted elevation-storage relationships for Fort Peck and Garrison were used in the DRM.

4 RESULTS

4.1 SPILLWAY DESIGN FLOOD ANALYSES

This section contains the results of the spillway design flood analyses. The calibrated pool elevations compared well with the design pool elevations found in the Garrison Regulation Manual (USACE, 1978) and are shown in Figure 4-1. A comparison of the current baseline and future baseline scenario shows a small difference in the pool elevations. From the pool elevations displayed in Figure 4-2, it was inferred that dam safety would not be threatened if the climate did not change (sediment rates remained at the current rate). The pool elevations shown in Figure 4-3 also demonstrate that dam safety would not be threatened under any future climate-change scenario as the maximum pool elevation in each climate scenario did not change when compared to the future baseline scenario. Table 4-1 lists the difference in maximum pool elevations for each climate scenario when compared to the future baseline scenario.

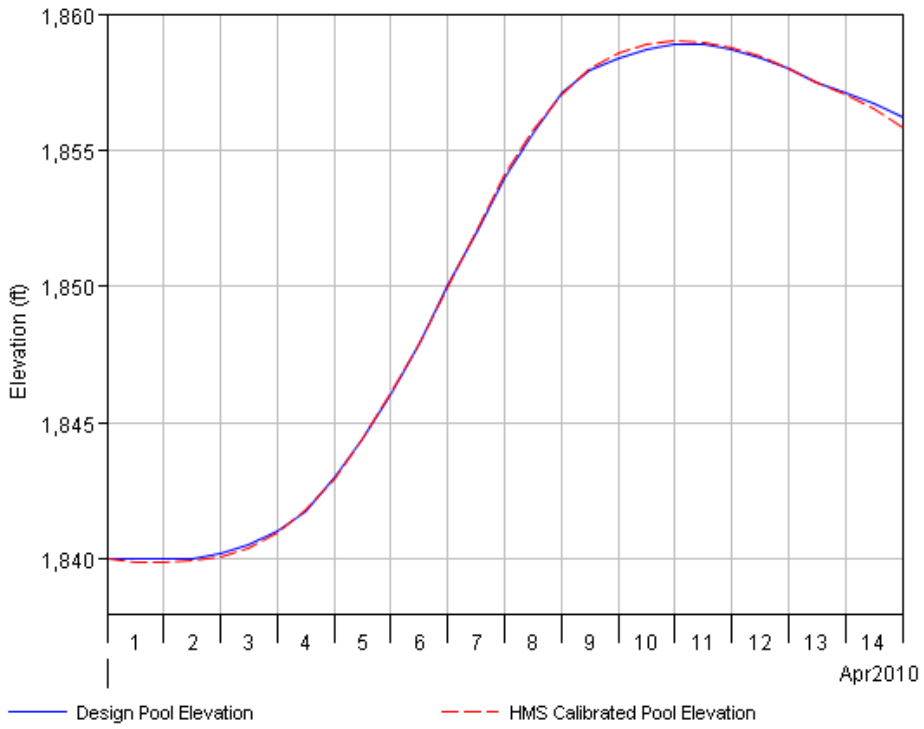


Figure 4-1: The calibrated HMS calculated pool elevation compared to the design pool elevation.

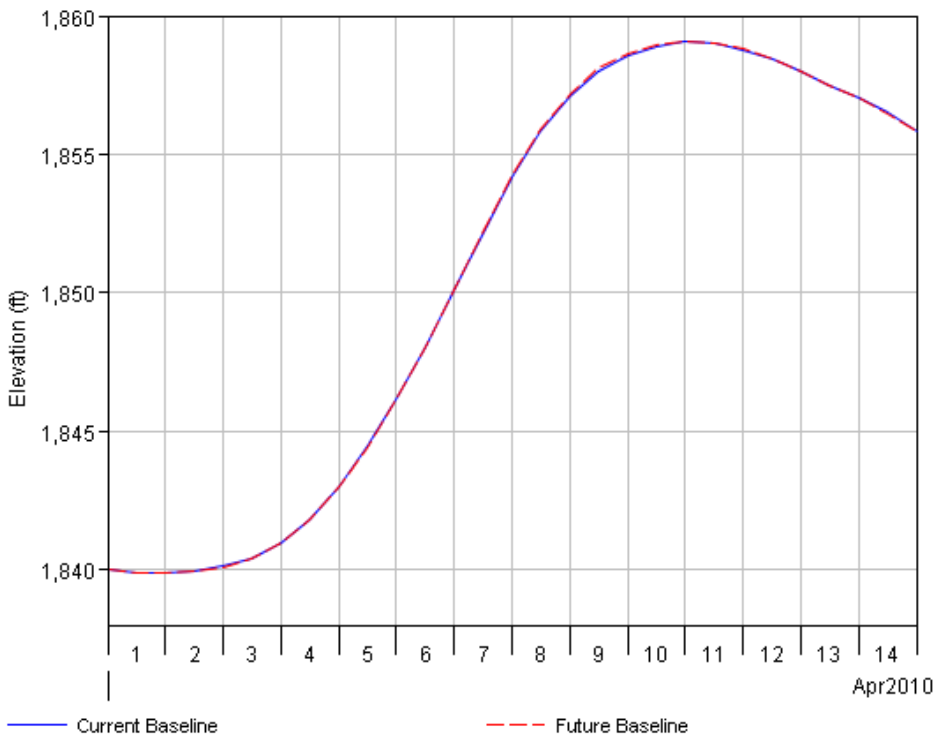


Figure 4-2: The current baseline pool elevation compared to the future baseline pool elevation.

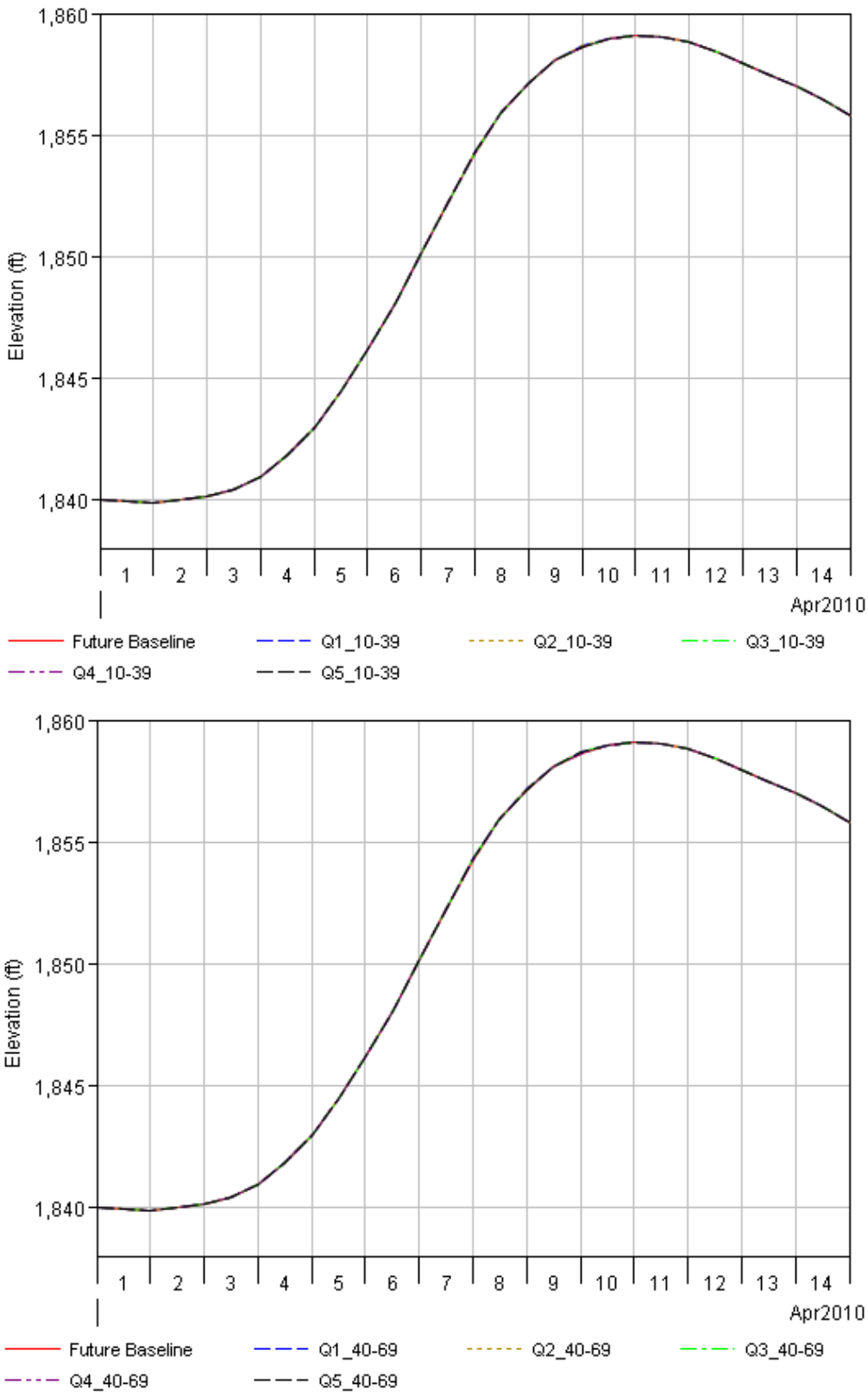


Figure 4-3: The top plot shows the 2010 – 2039 pool elevation comparison. The bottom plot shows the 2040 – 2069 pool elevation.

Table 4-1: Maximum elevation difference compared to the future baseline, climate scenario.

Future Climate Scenario	Maximum Elevation Difference (ft)
Q1_10-39	+0.01
Q2_10-39	+0.01
Q3_10-39	0.00
Q4_10-39	0.00
Q5_10-39	0.00
Q1_40-69	+0.01
Q2_40-69	+0.01
Q3_40-69	+0.01
Q4_40-69	0.00
Q5_40-69	+0.01

4.2 HEC-HMS PERIOD OF RECORD ANALYSES

4.2.1 Capacity Analyses

This section contains the results of the capacity analyses completed using the HEC-HMS model for each of the climate scenarios. The percent exceedance values listed in Table 4-2 and Table 4-3 show that the climate-adjusted elevation-storage relationships had no significant effect on the reservoir operations; the percent exceedance values were similar for each of the simulations. Plots of the duration analyses shown in Table 4-2 and Table 4-3 are located in Appendix A – Duration and displayed in Figure 7-1 through Figure 7-4.

Table 4-2: Percent exceedance values for the HMS Capacity pool-duration analyses.

Percent Exceedance	Future Baseline (ft)	Q1 10-39 (ft)	Q1 40-69 (ft)	Q2 10-39 (ft)	Q2 40-69 (ft)	Q3 10-39 (ft)	Q3 40-69 (ft)	Q4 10-39 (ft)	Q4 40-69 (ft)	Q5 10-39 (ft)	Q5 40-69 (ft)
0.1	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0
0.2	1853.4	1853.4	1853.4	1853.4	1853.4	1853.4	1853.4	1853.4	1853.4	1853.4	1853.4
0.5	1851.9	1851.9	1851.9	1851.9	1851.9	1851.9	1851.9	1851.9	1851.9	1851.9	1851.9
1	1850.5	1850.5	1850.5	1850.5	1850.5	1850.5	1850.5	1850.5	1850.5	1850.5	1850.5
2	1849.3	1849.3	1849.3	1849.3	1849.3	1849.3	1849.3	1849.3	1849.3	1849.3	1849.3
5	1848.1	1848.0	1848.0	1848.0	1848.0	1848.0	1848.0	1848.1	1848.0	1848.0	1848.0
10	1846.5	1846.5	1846.5	1846.5	1846.5	1846.5	1846.5	1846.5	1846.5	1846.5	1846.5
15	1844.9	1844.9	1844.9	1844.9	1844.9	1844.9	1844.9	1844.9	1844.9	1844.9	1844.9
20	1843.7	1843.7	1843.7	1843.7	1843.7	1843.7	1843.7	1843.7	1843.7	1843.7	1843.7
30	1841.3	1841.3	1841.3	1841.3	1841.3	1841.3	1841.3	1841.3	1841.3	1841.3	1841.3
40	1839.4	1839.3	1839.3	1839.3	1839.3	1839.3	1839.4	1839.4	1839.3	1839.4	1839.3
50	1837.4	1837.4	1837.4	1837.4	1837.4	1837.4	1837.4	1837.4	1837.4	1837.4	1837.4
60	1834.3	1834.3	1834.3	1834.3	1834.3	1834.3	1834.3	1834.3	1834.3	1834.3	1834.3
70	1828.4	1828.3	1828.3	1828.3	1828.3	1828.4	1828.4	1828.4	1828.4	1828.4	1828.3
80	1821.6	1821.5	1821.5	1821.6	1821.5	1821.6	1821.6	1821.6	1821.6	1821.6	1821.5
85	1818.9	1818.8	1818.8	1818.8	1818.8	1818.9	1818.8	1818.9	1818.9	1818.9	1818.8
90	1814.5	1814.3	1814.3	1814.4	1814.3	1814.4	1814.4	1814.4	1814.4	1814.4	1814.3
95	1809.8	1809.6	1809.5	1809.6	1809.5	1809.7	1809.7	1809.7	1809.7	1809.7	1809.6
98	1805.7	1805.4	1805.4	1805.5	1805.4	1805.6	1805.5	1805.6	1805.6	1805.6	1805.5
99	1805.0	1804.7	1804.7	1804.8	1804.6	1804.9	1804.8	1804.9	1804.9	1804.9	1804.8
99.5	1804.4	1804.1	1804.1	1804.2	1804.0	1804.3	1804.2	1804.3	1804.3	1804.3	1804.2
99.8	1804.0	1803.8	1803.7	1803.8	1803.7	1803.9	1803.8	1804.0	1803.9	1803.9	1803.8
99.9	1803.4	1803.1	1803.0	1803.2	1803.0	1803.3	1803.2	1803.3	1803.3	1803.2	1803.2

Table 4-3: Percent exceedance values for the HMS Capacity release-duration analyses.

Percent Exceedance	Future Baseline (cfs)	Q1 10-39 (cfs)	Q1 40-69 (cfs)	Q2 10-39 (cfs)	Q2 40-69 (cfs)	Q3 10-39 (cfs)	Q3 40-69 (cfs)	Q4 10-39 (cfs)	Q4 40-69 (cfs)	Q5 10-39 (cfs)	Q5 40-69 (cfs)
0.1	65,100	65,100	65,100	65,100	65,100	65,100	65,100	65,100	65,100	65,100	65,100
0.2	65,000	65,000	65,000	65,000	65,000	65,000	65,000	65,000	65,000	65,000	65,000
0.5	50,147	50,147	50,147	50,147	50,147	50,147	50,147	50,147	50,147	50,147	50,147
1	49,500	49,500	49,500	49,500	49,500	49,500	49,500	49,500	49,500	49,500	49,500
2	38,986	38,986	38,986	38,986	38,986	38,986	38,986	38,986	38,986	38,986	38,986
5	36,600	36,600	36,600	36,600	36,600	36,600	36,600	36,600	36,600	36,600	36,600
10	31,300	31,300	31,300	31,300	31,300	31,300	31,300	31,300	31,300	31,300	31,300
15	29,000	29,000	29,000	29,000	29,000	29,000	29,000	29,000	29,000	29,000	29,000
20	27,000	27,000	27,000	27,000	27,000	27,000	27,000	27,000	27,000	27,000	27,000
30	24,200	24,200	24,200	24,200	24,200	24,200	24,200	24,200	24,200	24,200	24,200
40	21,500	21,500	21,500	21,500	21,500	21,500	21,500	21,500	21,500	21,500	21,500
50	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900
60	18,280	18,280	18,280	18,280	18,280	18,280	18,280	18,280	18,280	18,280	18,280
70	16,300	16,300	16,300	16,300	16,300	16,300	16,300	16,300	16,300	16,300	16,300
80	14,600	14,600	14,600	14,600	14,600	14,600	14,600	14,600	14,600	14,600	14,600
85	13,500	13,500	13,500	13,500	13,500	13,500	13,500	13,500	13,500	13,500	13,500
90	12,200	12,200	12,200	12,200	12,200	12,200	12,200	12,200	12,200	12,200	12,200
95	10,700	10,700	10,700	10,700	10,700	10,700	10,700	10,700	10,700	10,700	10,700
98	10,100	10,100	10,100	10,100	10,100	10,100	10,100	10,100	10,100	10,100	10,100
99	9,700	9,700	9,700	9,700	9,700	9,700	9,700	9,700	9,700	9,700	9,700
99.5	9,354	9,354	9,354	9,354	9,354	9,354	9,354	9,354	9,354	9,354	9,354
99.8	8,200	8,200	8,200	8,200	8,200	8,200	8,200	8,200	8,200	8,200	8,200
99.9	7,036	7,036	7,036	7,036	7,036	7,036	7,036	7,036	7,036	7,036	7,036

4.2.2 Flow Analyses

This section contains the results of the flow analyses completed using the HEC-HMS model for each of the climate scenarios. The percent exceedance values listed in Table 4-4 and Table 4-5 show that the climate-adjusted inflows had a significant effect on the reservoir operations with both pool elevations and releases increasing for each climate scenario. The maximum pool elevation from the simulations was 1854.0 ft because the model was designed to limit the pool elevations at 1854.0 ft by allowing uncontrolled flow through the spillway once pool elevations exceeded 1854.0 ft. The effect of the climate change on pool elevations is noted at all exceedence frequencies, while effects on releases are larger for releases exceeded less than 10 percent of the time. Plots of the duration analyses shown in Table 4-4 and Table 4-5 are located in Appendix A – Duration and displayed in Figure 7-5 through Figure 7-8.

Table 4-4: Percent exceedance values for the HMS Flow pool-duration analyses.

Percent Exceedance	Future Baseline (ft)	Q1 10-39 (ft)	Q1 40-69 (ft)	Q2 10-39 (ft)	Q2 40-69 (ft)	Q3 10-39 (ft)	Q3 40-69 (ft)	Q4 10-39 (ft)	Q4 40-69 (ft)	Q5 10-39 (ft)	Q5 40-69 (ft)
0.1	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0
0.2	1853.4	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0
0.5	1851.9	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0
1	1850.5	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0
2	1849.3	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1853.9	1854.0	1854.0	1854.0
5	1848.1	1854.0	1854.0	1854.0	1854.0	1853.0	1854.0	1853.2	1853.5	1853.9	1854.0
10	1846.5	1853.8	1854.0	1853.6	1854.0	1851.4	1853.2	1851.6	1852.1	1852.9	1853.7
15	1844.9	1853.0	1853.4	1852.7	1853.5	1850.0	1852.2	1850.4	1850.9	1852.0	1852.9
20	1843.7	1852.1	1852.8	1851.7	1852.8	1848.8	1851.0	1849.2	1850.0	1850.8	1851.9
30	1841.3	1850.1	1851.3	1849.7	1851.3	1846.6	1848.8	1847.1	1847.8	1848.6	1849.8
40	1839.4	1848.6	1850.0	1847.6	1850.0	1844.2	1846.8	1844.7	1845.2	1846.4	1847.9
50	1837.4	1846.9	1848.7	1845.9	1848.7	1841.5	1844.4	1842.1	1842.4	1844.1	1846.2
60	1834.3	1845.4	1847.2	1844.1	1847.2	1838.4	1841.8	1838.9	1839.8	1841.7	1844.5
70	1828.4	1843.6	1845.8	1842.2	1845.9	1833.2	1839.4	1833.7	1836.4	1839.0	1842.7
80	1821.6	1841.8	1844.4	1840.0	1844.5	1829.7	1836.6	1830.2	1832.8	1835.7	1840.7
85	1818.9	1841.0	1843.4	1838.6	1843.4	1827.1	1834.7	1828.1	1829.9	1833.6	1839.5
90	1814.5	1840.1	1842.3	1837.5	1842.5	1820.2	1832.5	1821.5	1825.1	1831.2	1838.4
95	1809.8	1838.3	1841.2	1835.9	1841.2	1815.4	1829.7	1816.7	1820.8	1828.0	1837.0
98	1805.7	1835.6	1838.9	1833.0	1839.5	1813.3	1828.2	1814.7	1819.0	1826.4	1833.8
99	1805.0	1834.1	1835.3	1831.4	1835.3	1811.7	1826.0	1813.1	1817.3	1824.3	1832.5
99.5	1804.4	1832.1	1833.1	1830.3	1832.8	1810.6	1824.4	1812.1	1815.6	1822.8	1830.6
99.8	1804.0	1830.0	1830.3	1829.3	1830.1	1809.8	1824.2	1811.3	1815.1	1822.3	1829.3
99.9	1803.4	1829.2	1829.6	1829.1	1829.4	1809.0	1823.6	1810.5	1814.4	1821.7	1829.1

Table 4-5: Percent exceedance values for the HMS Flow release-duration analyses.

Percent Exceedance	Future Baseline (cfs)	Q1 10-39 (cfs)	Q1 40-69 (cfs)	Q2 10-39 (cfs)	Q2 40-69 (cfs)	Q3 10-39 (cfs)	Q3 40-69 (cfs)	Q4 10-39 (cfs)	Q4 40-69 (cfs)	Q5 10-39 (cfs)	Q5 40-69 (cfs)
0.1	65,100	106,221	107,269	105,046	108,893	95,431	101,969	97,824	97,968	101,357	105,104
0.2	65,000	99,161	99,669	98,454	101,698	88,772	95,794	88,771	91,056	94,201	97,357
0.5	50,147	80,013	83,478	78,731	85,820	65,100	75,793	65,047	69,003	75,717	78,421
1	49,500	68,648	72,774	65,100	75,339	50,433	65,000	50,100	57,000	62,399	66,632
2	38,986	57,006	60,318	54,279	63,158	41,977	51,008	41,311	46,100	50,000	55,110
5	36,600	39,585	44,626	38,700	45,848	36,800	38,200	36,900	37,100	37,900	39,000
10	31,300	34,600	36,000	33,700	36,100	31,500	32,900	31,600	31,900	32,500	34,000
15	29,000	30,300	31,000	30,000	31,100	29,200	29,800	29,200	29,400	29,700	30,076
20	27,000	28,200	28,900	28,100	28,900	27,200	27,800	27,300	27,400	27,700	28,100
30	24,200	25,100	25,400	25,000	25,400	24,300	24,700	24,300	24,400	24,600	25,100
40	21,500	22,500	22,900	22,400	22,900	21,700	22,100	21,700	21,800	22,000	22,400
50	19,900	20,200	20,400	20,150	20,400	19,900	20,100	19,900	20,000	20,000	20,200
60	18,280	18,800	19,000	18,600	19,000	18,300	18,488	18,300	18,300	18,400	18,700
70	16,300	17,000	17,200	17,000	17,200	16,400	16,800	16,400	16,500	16,700	17,000
80	14,600	15,000	15,000	14,900	15,000	14,700	14,800	14,700	14,800	14,800	15,000
85	13,500	13,800	13,800	13,800	13,800	13,600	13,700	13,600	13,600	13,700	13,800
90	12,200	12,500	12,500	12,500	12,500	12,300	12,400	12,300	12,300	12,300	12,500
95	10,700	10,900	10,900	10,900	11,000	10,700	10,800	10,700	10,800	10,800	10,900
98	10,100	10,200	10,200	10,200	10,200	10,100	10,100	10,100	10,100	10,100	10,200
99	9,700	9,900	9,900	9,900	9,900	9,800	9,800	9,800	9,800	9,800	9,900
99.5	9,354	9,600	9,600	9,600	9,600	9,354	9,354	9,354	9,354	9,354	9,600
99.8	8,200	8,400	8,400	8,400	8,400	8,200	8,200	8,200	8,200	8,200	8,400
99.9	7,036	8,100	8,100	8,100	8,100	7,036	7,036	7,036	7,036	7,036	8,100

4.2.3 Flow and Capacity Analyses

This section contains the results of the flow and capacity analyses completed using the HEC-HMS model for each of the climate scenarios. The percent exceedance values listed in Table 4-6 and Table 4-7 show that the combination of climate-adjusted elevation-storage relationships and inflows had a significant effect on the reservoir operations. Most of the effect is attributed to the climate-adjusted inflows. Plots of the duration analyses shown in Table 4-6 and Table 4-7 are located in Appendix A – Duration and displayed in Figure 7-23 through Figure 7-26.

Table 4-6: Percent exceedance values for the HMS Flow & Capacity pool-duration analyses.

Percent Exceedance	Future Baseline (ft)	Q1 10-39 (ft)	Q1 40-69 (ft)	Q2 10-39 (ft)	Q2 40-69 (ft)	Q3 10-39 (ft)	Q3 40-69 (ft)	Q4 10-39 (ft)	Q4 40-69 (ft)	Q5 10-39 (ft)	Q5 40-69 (ft)
0.1	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0
0.2	1853.4	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0
0.5	1851.9	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0
1	1850.5	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0
2	1849.3	1854.0	1854.0	1854.0	1854.0	1854.0	1854.0	1853.9	1854.0	1854.0	1854.0
5	1848.1	1854.0	1854.0	1854.0	1854.0	1853.0	1854.0	1853.1	1853.5	1853.9	1854.0
10	1846.5	1853.8	1854.0	1853.6	1854.0	1851.3	1853.2	1851.5	1852.1	1852.9	1853.7
15	1844.9	1853.0	1853.4	1852.7	1853.5	1849.9	1852.2	1850.4	1850.9	1852.0	1852.8
20	1843.7	1852.0	1852.8	1851.6	1852.7	1848.7	1850.9	1849.2	1849.9	1850.7	1851.8
30	1841.3	1850.0	1851.2	1849.6	1851.2	1846.5	1848.7	1847.0	1847.7	1848.5	1849.8
40	1839.4	1848.5	1849.9	1847.4	1849.9	1844.1	1846.7	1844.6	1845.1	1846.3	1847.8
50	1837.4	1846.8	1848.5	1845.8	1848.5	1841.4	1844.3	1842.0	1842.3	1844.0	1846.1
60	1834.3	1845.2	1847.1	1844.0	1847.1	1838.3	1841.7	1838.9	1839.7	1841.6	1844.4
70	1828.4	1843.5	1845.6	1842.1	1845.8	1833.1	1839.3	1833.6	1836.3	1838.9	1842.6
80	1821.6	1841.7	1844.2	1839.9	1844.3	1829.6	1836.5	1830.1	1832.7	1835.6	1840.6
85	1818.9	1840.9	1843.3	1838.5	1843.3	1826.9	1834.7	1827.9	1829.9	1833.5	1839.5
90	1814.5	1840.0	1842.2	1837.5	1842.4	1819.6	1832.4	1820.9	1824.8	1831.1	1838.4
95	1809.8	1838.2	1841.1	1835.9	1841.1	1814.6	1829.6	1816.0	1820.2	1827.8	1836.9
98	1805.7	1835.5	1838.8	1832.9	1839.4	1812.5	1828.1	1813.9	1818.3	1826.1	1833.7
99	1805.0	1834.0	1835.3	1831.3	1835.3	1810.7	1825.7	1812.2	1816.5	1823.9	1832.4
99.5	1804.4	1832.0	1833.1	1830.2	1832.8	1809.6	1824.0	1811.2	1814.8	1822.3	1830.5
99.8	1804.0	1830.0	1830.3	1829.2	1830.1	1808.8	1823.7	1810.3	1814.3	1821.8	1829.2
99.9	1803.4	1829.2	1829.5	1829.0	1829.3	1807.9	1823.1	1809.5	1813.5	1821.1	1829.0

Table 4-7: Percent exceedance values for the HMS Flow & Capacity release-duration analyses.

Percent Exceedance	Future Baseline (cfs)	Q1 10-39 (cfs)	Q1 40-69 (cfs)	Q2 10-39 (cfs)	Q2 40-69 (cfs)	Q3 10-39 (cfs)	Q3 40-69 (cfs)	Q4 10-39 (cfs)	Q4 40-69 (cfs)	Q5 10-39 (cfs)	Q5 40-69 (cfs)
0.1	65,100	106,501	109,464	105,442	110,727	95,694	102,381	97,060	97,630	101,409	105,876
0.2	65,000	99,430	101,938	99,318	102,561	90,480	95,009	89,061	91,496	95,342	99,119
0.5	50,147	79,794	83,490	78,685	85,413	65,100	76,096	65,100	68,876	75,644	78,396
1	49,500	67,723	72,622	65,100	75,012	50,199	64,997	50,100	56,915	63,666	66,199
2	38,986	57,241	60,726	53,664	62,789	42,226	51,768	41,634	46,100	50,000	55,023
5	36,600	39,500	44,657	38,700	45,803	36,800	38,300	36,900	37,065	37,900	39,000
10	31,300	34,600	36,000	33,730	36,024	31,500	32,900	31,600	31,900	32,500	34,000
15	29,000	30,300	31,075	30,000	31,200	29,200	29,800	29,200	29,400	29,700	30,100
20	27,000	28,200	28,800	28,100	28,900	27,300	27,800	27,300	27,400	27,700	28,100
30	24,200	25,100	25,400	25,000	25,400	24,300	24,700	24,300	24,400	24,600	25,100
40	21,500	22,500	22,900	22,400	22,900	21,700	22,100	21,700	21,800	22,000	22,400
50	19,900	20,200	20,400	20,200	20,400	19,900	20,100	19,900	20,000	20,000	20,200
60	18,280	18,800	19,000	18,600	18,939	18,300	18,488	18,300	18,300	18,400	18,700
70	16,300	17,005	17,200	17,000	17,200	16,400	16,800	16,400	16,500	16,700	17,000
80	14,600	15,000	15,000	14,900	15,000	14,700	14,800	14,700	14,800	14,800	15,000
85	13,500	13,800	13,800	13,800	13,800	13,600	13,700	13,600	13,600	13,700	13,800
90	12,200	12,500	12,500	12,500	12,500	12,300	12,400	12,300	12,300	12,300	12,500
95	10,700	10,900	10,900	10,900	10,998	10,700	10,800	10,700	10,800	10,800	10,900
98	10,100	10,200	10,200	10,200	10,200	10,100	10,100	10,100	10,100	10,100	10,200
99	9,700	9,900	9,900	9,900	9,900	9,800	9,800	9,800	9,800	9,800	9,900
99.5	9,354	9,600	9,600	9,600	9,600	9,354	9,354	9,354	9,354	9,354	9,600
99.8	8,200	8,400	8,400	8,400	8,400	8,200	8,200	8,200	8,200	8,200	8,400
99.9	7,036	8,100	8,100	8,100	8,100	7,036	7,036	7,036	7,036	7,036	8,100

4.3 DRM PERIOD OF RECORD ANALYSES

4.3.1 Capacity Analyses

This section contains the results of the capacity analyses completed using the DRM model for each of the climate scenarios. The percent exceedance values listed in Table 4-8 and Table 4-9 show that the climate-adjusted elevation-storage relationships had no significant effect on the reservoir operations; the percent exceedance values are similar for each of the simulations. Plots of the duration analyses shown in Table 4-8 and Table 4-9 are located in Appendix A – Duration and displayed in Figure 7-15 through Figure 7-18.

Table 4-8: Percent exceedance values for the DRM Capacity pool-duration analyses.

Percent Exceedance	Future Baseline (ft)	Q1 10-39 (ft)	Q1 40-69 (ft)	Q2 10-39 (ft)	Q2 40-69 (ft)	Q3 10-39 (ft)	Q3 40-69 (ft)	Q4 10-39 (ft)	Q4 40-69 (ft)	Q5 10-39 (ft)	Q5 40-69 (ft)
0.1	1854.5	1854.6	1854.6	1854.6	1854.6	1854.7	1854.6	1854.6	1854.6	1854.6	1854.6
0.2	1853.6	1853.6	1853.4	1853.6	1853.4	1853.6	1853.6	1853.6	1853.5	1853.5	1853.6
0.5	1851.9	1852.1	1852.1	1852.0	1852.1	1852.0	1851.9	1852.0	1851.9	1851.9	1852.0
1	1850.8	1850.8	1850.8	1850.7	1850.7	1850.8	1850.7	1850.7	1850.7	1850.7	1850.7
2	1849.9	1849.8	1849.7	1849.8	1849.8	1849.9	1849.8	1849.8	1850.0	1849.7	1849.7
5	1848.5	1848.4	1848.2	1848.5	1848.2	1848.6	1848.4	1848.5	1848.6	1848.4	1848.3
10	1846.1	1846.0	1846.0	1846.1	1846.0	1846.2	1846.1	1846.1	1846.2	1845.8	1846.0
15	1844.2	1844.1	1844.1	1844.1	1844.2	1844.2	1844.1	1844.2	1844.2	1844.1	1844.1
20	1842.8	1842.8	1842.8	1842.8	1842.8	1842.8	1842.8	1842.8	1842.9	1842.7	1842.8
30	1840.5	1840.4	1840.4	1840.4	1840.4	1840.5	1840.4	1840.5	1840.4	1840.4	1840.4
40	1838.2	1838.2	1838.2	1838.1	1838.2	1838.1	1838.1	1838.2	1838.2	1838.2	1838.1
50	1835.1	1835.2	1835.3	1835.2	1835.3	1835.0	1835.1	1835.0	1835.4	1835.4	1835.1
60	1829.5	1829.6	1829.6	1829.6	1829.6	1829.6	1829.6	1829.6	1829.5	1829.6	1829.6
70	1824.0	1824.3	1824.3	1824.4	1824.4	1824.0	1824.1	1824.0	1824.0	1824.1	1824.1
80	1817.3	1817.4	1817.4	1817.4	1817.5	1817.4	1817.4	1817.4	1817.4	1817.4	1817.4
85	1813.6	1813.7	1813.9	1813.8	1813.9	1813.8	1813.8	1813.7	1813.8	1814.0	1813.9
90	1809.9	1810.0	1810.1	1810.1	1810.2	1810.0	1810.0	1810.0	1810.0	1810.1	1810.1
95	1805.5	1805.7	1805.6	1805.6	1805.7	1805.5	1805.6	1805.6	1805.6	1805.4	1805.6
98	1803.5	1803.6	1803.4	1803.2	1803.4	1803.2	1803.6	1803.6	1803.3	1803.0	1803.3
99	1801.3	1801.4	1801.5	1801.3	1801.5	1801.3	1801.4	1801.3	1801.3	1801.1	1801.3
99.5	1800.5	1800.7	1800.7	1800.6	1800.7	1800.5	1800.7	1800.6	1800.5	1800.3	1800.6
99.8	1800.2	1800.4	1800.4	1800.2	1800.4	1800.2	1800.3	1800.3	1800.2	1800.0	1800.0
99.9	1800.0	1800.2	1800.2	1800.1	1800.2	1800.0	1800.2	1800.1	1800.0	1799.9	1799.9

Table 4-9: Percent exceedance values for the DRM Capacity release-duration analyses.

Percent Exceedance	Future Baseline (cfs)	Q1 10-39 (cfs)	Q1 40-69 (cfs)	Q2 10-39 (cfs)	Q2 40-69 (cfs)	Q3 10-39 (cfs)	Q3 40-69 (cfs)	Q4 10-39 (cfs)	Q4 40-69 (cfs)	Q5 10-39 (cfs)	Q5 40-69 (cfs)
0.1	60,000	66,465	65,000	65,000	65,000	66,465	65,000	66,465	65,000	65,000	65,000
0.2	55,000	55,000	55,000	55,000	55,000	55,000	55,000	55,000	55,000	55,000	55,000
0.5	47,304	50,000	47,533	50,865	50,567	47,360	49,327	47,199	50,000	48,266	47,432
1	42,190	42,239	42,210	42,230	42,239	42,209	42,220	42,220	42,229	42,190	42,200
2	41,559	41,630	41,519	41,569	41,580	41,529	41,539	41,510	41,559	41,480	41,529
5	38,000	38,000	38,000	38,000	38,000	38,000	38,000	38,000	38,000	38,000	38,000
10	32,410	32,390	32,400	32,400	32,380	32,380	32,390	32,393	32,490	32,430	32,300
15	29,590	29,530	29,530	29,700	29,330	29,410	29,629	29,547	29,700	29,450	29,580
20	27,570	27,440	27,650	27,490	27,680	27,640	27,480	27,540	27,650	27,500	27,450
30	22,870	22,800	22,800	22,990	22,800	22,860	23,000	22,800	22,800	23,170	22,830
40	19,300	19,350	19,510	19,410	19,920	19,370	19,430	19,300	19,250	19,390	19,640
50	18,000	18,000	18,000	18,000	18,000	18,000	18,000	18,000	18,000	18,000	18,000
60	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000
70	15,540	15,110	15,260	15,000	15,000	15,000	15,000	15,500	15,290	15,073	15,330
80	11,490	11,080	11,000	10,000	10,920	11,040	10,630	11,744	11,130	10,640	10,924
85	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
90	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
95	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
98	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
99	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
99.5	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
99.8	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
99.9	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000

4.3.2 Flow Analyses

This section contains the results of the flow analyses completed using the DRM model for each of the climate scenarios. The percent exceedance values listed in Table 4-10 and Table 4-11, show that the climate-adjusted elevation-storage relationships had a significant effect on the reservoir operations.

The climate scenarios with more precipitation (Q1 and Q2) caused the pool elevation to increase so it was assumed that the climate scenarios with less precipitation would cause the pool elevation and releases to decrease; however, the Q3_40-69 climate scenario (lower precipitation and lower temperature) does not follow this trend. Even though Q3_40-69 climate-scenario had less precipitation, the releases and pool elevations still increased and resembled a climate scenario with more precipitation. The Q3_40-69 VIC factors in March and April for both Williston (Garrison Dam) and Wolf Point (Fort Peck) resemble the VIC factors of a climate scenario with more precipitation. During the period of record, the incremental flow for Garrison in May through July is generally higher than the incremental flow in March and April; however, some of the largest floods occurred in the early spring months of March and April, which corresponded to large VIC factors for the Q3_40-69 climate scenario. It is because of these large events coinciding with the large Q3_40-69 VIC factors that the pool elevations and releases, for the percent exceedance values less than two percent, resemble a climate scenario with more precipitation. An example of a large flood coinciding with a large Q3_40-69 VIC factor is shown in Figure 4-4. Plots of the duration analyses shown in Table 4-10 and Table 4-11 are located in Appendix A – Duration and displayed in Figure 7-19 through Figure 7-22.

Table 4-10: Percent exceedance values for the DRM Flow pool-duration analyses.

Percent Exceedance	Future Baseline (ft)	Q1 10-39 (ft)	Q1 40-69 (ft)	Q2 10-39 (ft)	Q2 40-69 (ft)	Q3 10-39 (ft)	Q3 40-69 (ft)	Q4 10-39 (ft)	Q4 40-69 (ft)	Q5 10-39 (ft)	Q5 40-69 (ft)
0.1	1854.5	1856.0	1856.1	1855.6	1855.7	1854.4	1855.7	1854.4	1854.3	1854.8	1855.7
0.2	1853.6	1855.3	1855.8	1855.2	1855.4	1853.6	1855.0	1853.5	1854.1	1854.5	1855.3
0.5	1851.9	1853.9	1855.2	1854.3	1854.5	1851.9	1853.6	1852.3	1853.1	1853.5	1854.2
1	1850.8	1852.5	1853.9	1852.1	1853.8	1850.9	1851.7	1851.0	1851.0	1851.7	1852.4
2	1849.9	1851.2	1852.6	1850.7	1852.5	1850.0	1850.7	1850.1	1850.3	1850.7	1851.0
5	1848.5	1850.0	1850.7	1849.9	1850.6	1848.9	1849.8	1848.9	1849.2	1849.6	1849.9
10	1846.1	1847.9	1848.9	1847.8	1848.7	1846.4	1847.5	1846.8	1847.0	1847.2	1847.8
15	1844.2	1846.1	1846.9	1845.7	1846.7	1844.2	1845.5	1844.5	1844.6	1845.2	1845.9
20	1842.8	1844.4	1845.3	1844.1	1845.1	1843.0	1843.8	1843.1	1843.2	1843.7	1844.2
30	1840.5	1842.0	1842.7	1841.9	1842.4	1840.6	1841.6	1840.8	1841.0	1841.3	1842.1
40	1838.2	1839.8	1840.4	1839.4	1840.3	1838.2	1839.0	1838.4	1838.6	1839.0	1839.6
50	1835.1	1837.6	1838.2	1837.4	1838.3	1835.2	1836.7	1835.2	1835.8	1837.0	1837.6
60	1829.5	1834.6	1836.2	1833.9	1836.0	1830.0	1832.2	1830.1	1831.0	1832.0	1834.1
70	1824.0	1829.9	1831.2	1828.9	1830.8	1824.2	1827.6	1824.5	1825.9	1826.4	1829.3
80	1817.3	1823.3	1826.5	1821.9	1826.1	1817.8	1821.3	1817.8	1818.8	1819.8	1822.8
85	1813.6	1821.1	1824.5	1819.9	1824.3	1814.7	1819.2	1814.9	1816.1	1817.2	1820.7
90	1809.9	1818.7	1821.7	1817.3	1821.2	1811.0	1815.9	1811.2	1812.5	1814.1	1818.1
95	1805.5	1814.6	1818.2	1813.2	1817.0	1806.9	1811.9	1807.0	1808.7	1809.9	1813.9
98	1803.5	1812.5	1816.5	1810.8	1815.1	1805.0	1809.6	1805.0	1806.6	1807.7	1811.4
99	1801.3	1811.7	1815.7	1809.9	1814.4	1803.4	1808.7	1803.4	1805.6	1806.7	1810.8
99.5	1800.5	1810.8	1814.7	1809.3	1813.3	1802.6	1808.0	1802.6	1804.6	1805.8	1810.0
99.8	1800.2	1810.0	1814.0	1807.9	1812.8	1802.0	1806.8	1802.0	1804.0	1804.9	1809.0
99.9	1800.0	1809.8	1813.6	1807.7	1812.3	1801.9	1806.6	1801.8	1803.8	1804.7	1808.8

Table 4-11: Percent exceedance values for the DRM Flow release-duration analyses.

Percent Exceedance	Future Baseline (cfs)	Q1 10-39 (cfs)	Q1 40-69 (cfs)	Q2 10-39 (cfs)	Q2 40-69 (cfs)	Q3 10-39 (cfs)	Q3 40-69 (cfs)	Q4 10-39 (cfs)	Q4 40-69 (cfs)	Q5 10-39 (cfs)	Q5 40-69 (cfs)
0.1	60,000	90,000	90,000	85,000	90,000	60,000	88,910	55,000	56,465	65,000	86,800
0.2	55,000	82,801	84,565	72,930	85,000	55,000	72,291	55,000	55,000	55,000	75,000
0.5	47,304	55,000	55,000	55,000	55,000	55,000	55,000	55,000	55,000	55,000	55,000
1	42,190	55,000	55,000	55,000	55,000	51,800	55,000	51,499	51,870	54,998	55,000
2	41,559	52,010	55,000	51,910	55,000	42,180	51,850	42,180	42,380	45,619	52,069
5	38,000	41,750	42,490	41,560	42,420	39,860	41,387	39,780	40,240	41,230	41,580
10	32,410	38,000	39,729	38,000	40,270	33,772	37,190	33,640	35,850	37,280	38,000
15	29,590	33,610	37,150	33,290	37,668	30,669	32,270	30,190	31,120	32,640	33,310
20	27,570	31,100	33,296	30,000	33,030	28,000	30,000	28,000	28,360	30,000	30,710
30	22,870	27,190	28,000	26,500	28,000	23,250	26,210	23,080	24,300	25,000	26,980
40	19,300	22,800	24,300	22,800	24,300	21,000	22,800	20,450	21,690	22,056	22,800
50	18,000	19,555	21,150	19,000	21,120	18,000	19,000	18,000	19,000	19,000	19,120
60	16,000	17,850	18,770	16,838	18,592	16,000	16,000	16,000	16,000	16,000	16,730
70	15,540	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000
80	11,490	15,000	15,000	15,000	15,000	14,650	15,000	15,000	15,000	14,720	15,000
85	10,000	12,260	14,900	10,730	15,000	10,000	10,000	10,000	10,000	10,000	11,481
90	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
95	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
98	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
99	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
99.5	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
99.8	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
99.9	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000

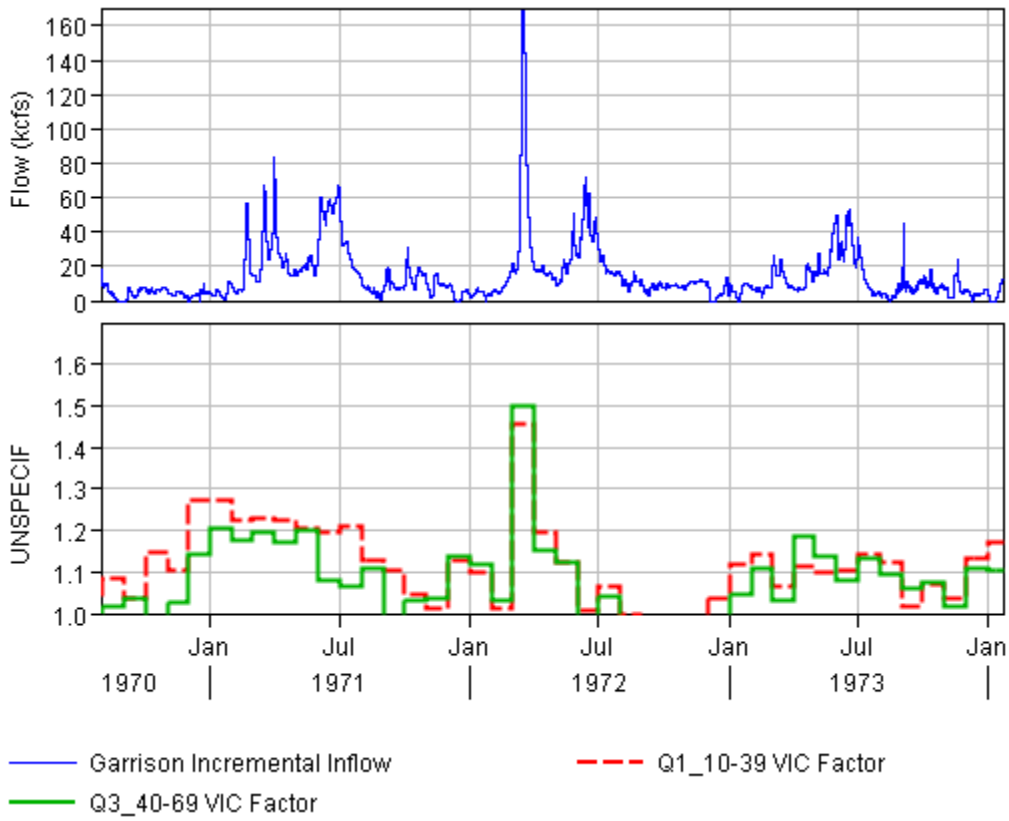


Figure 4-4: Example of a large Q3_40-69 VIC factor coinciding with a large flood.

4.3.3 Flow and Capacity Analyses

This section contains the results of the flow and capacity analyses completed using the DRM model for each of the climate scenarios. The percent exceedance values listed in Table 4-12 and Table 4-13 show that the climate-adjusted elevation-storage relationships had a significant effect on the reservoir operations and follow the same trends as the flow analyses. Plots of the duration analyses shown in Table 4-12 and Table 4-13 are located in Appendix A – Duration and displayed in Figure 7-23 through Figure 7-26.

Table 4-12: Percent exceedance values for the DRM Flow & Capacity pool-duration analyses.

Percent Exceedance	Future Baseline (ft)	Q1 10-39 (ft)	Q1 40-69 (ft)	Q2 10-39 (ft)	Q2 40-69 (ft)	Q3 10-39 (ft)	Q3 40-69 (ft)	Q4 10-39 (ft)	Q4 40-69 (ft)	Q5 10-39 (ft)	Q5 40-69 (ft)
0.1	1854.5	1855.8	1856.3	1855.5	1856.1	1854.7	1855.5	1854.6	1854.7	1855.0	1855.8
0.2	1853.6	1855.4	1856.0	1855.0	1855.8	1853.8	1854.9	1854.2	1854.0	1854.6	1855.3
0.5	1851.9	1854.2	1855.3	1854.1	1855.1	1853.1	1853.6	1853.2	1853.2	1853.5	1854.3
1	1850.8	1852.9	1854.0	1852.3	1854.1	1851.4	1852.1	1851.4	1851.5	1852.0	1852.5
2	1849.9	1851.7	1852.8	1851.3	1852.8	1850.3	1851.0	1850.4	1850.4	1850.7	1851.5
5	1848.5	1850.0	1851.1	1850.0	1851.1	1849.2	1849.9	1849.2	1849.4	1849.7	1850.0
10	1846.1	1848.4	1849.4	1847.9	1849.2	1846.7	1847.9	1846.8	1847.2	1847.5	1848.1
15	1844.2	1846.5	1847.2	1846.1	1847.3	1844.5	1845.7	1844.7	1844.9	1845.4	1846.3
20	1842.8	1844.9	1845.5	1844.5	1845.6	1843.2	1844.2	1843.1	1843.5	1844.0	1844.7
30	1840.5	1842.4	1842.8	1842.0	1842.7	1840.9	1841.7	1840.9	1841.2	1841.5	1842.3
40	1838.2	1840.0	1840.6	1839.6	1840.6	1838.5	1839.3	1838.5	1839.0	1839.0	1839.8
50	1835.1	1837.9	1838.5	1837.7	1838.5	1835.9	1837.2	1835.9	1837.0	1836.9	1837.7
60	1829.5	1835.1	1836.5	1834.2	1836.3	1830.4	1832.7	1830.6	1831.6	1831.8	1834.7
70	1824.0	1830.5	1832.3	1830.0	1831.9	1824.9	1828.5	1825.1	1826.7	1827.3	1830.1
80	1817.3	1824.5	1828.1	1822.9	1827.4	1818.4	1822.6	1818.5	1820.0	1820.6	1824.0
85	1813.6	1822.1	1825.8	1820.9	1825.5	1815.3	1820.3	1815.6	1817.2	1818.1	1821.7
90	1809.9	1819.8	1823.1	1818.4	1822.2	1811.6	1817.2	1811.9	1813.6	1815.0	1819.2
95	1805.5	1815.9	1819.6	1814.3	1818.3	1807.8	1813.0	1808.0	1809.8	1811.0	1815.0
98	1803.5	1813.7	1818.0	1811.8	1816.4	1805.6	1810.8	1805.9	1807.6	1808.7	1812.6
99	1801.3	1812.9	1817.1	1811.0	1815.8	1804.4	1809.7	1804.3	1806.6	1807.7	1812.0
99.5	1800.5	1812.2	1816.0	1810.4	1814.6	1803.6	1809.1	1803.4	1805.5	1806.8	1811.4
99.8	1800.2	1811.1	1815.5	1809.1	1814.1	1803.1	1807.9	1802.8	1805.0	1805.9	1810.0
99.9	1800.0	1810.8	1815.0	1808.9	1813.6	1802.9	1807.7	1802.7	1804.8	1805.7	1809.8

Table 4-13: Percent exceedance values for the DRM Flow & Capacity release-duration analyses.

Percent Exceedance	Future Baseline (cfs)	Q1 10-39 (cfs)	Q1 40-69 (cfs)	Q2 10-39 (cfs)	Q2 40-69 (cfs)	Q3 10-39 (cfs)	Q3 40-69 (cfs)	Q4 10-39 (cfs)	Q4 40-69 (cfs)	Q5 10-39 (cfs)	Q5 40-69 (cfs)
0.1	60,000	82,936	92,820	85,627	95,000	71,465	83,600	71,465	75,000	76,465	84,100
0.2	55,000	71,629	86,624	70,000	90,000	55,000	65,000	55,000	55,000	55,000	72,033
0.5	47,304	55,000	55,000	55,000	55,000	55,000	55,000	55,000	55,000	55,000	55,000
1	42,190	55,000	55,000	55,000	55,000	51,840	55,000	47,670	51,900	55,000	55,000
2	41,559	52,150	55,000	51,839	55,000	42,349	51,909	42,229	42,419	46,979	51,910
5	38,000	42,040	42,640	41,580	42,500	40,280	41,490	40,220	40,580	41,306	41,606
10	32,410	38,410	40,119	38,000	40,689	33,666	37,430	33,880	35,156	36,512	38,000
15	29,590	33,820	37,110	33,320	38,000	30,910	32,560	30,920	31,259	32,360	33,580
20	27,570	31,460	33,130	31,000	33,310	28,000	30,000	28,000	29,050	29,700	31,360
30	22,870	27,369	28,000	26,500	28,000	23,340	26,200	23,668	24,300	25,000	26,819
40	19,300	22,800	24,040	22,800	24,300	20,434	22,800	20,000	21,822	22,000	22,800
50	18,000	19,320	21,200	19,000	21,520	18,000	19,000	18,000	18,420	18,740	19,000
60	16,000	17,100	18,468	16,100	18,120	16,000	16,000	16,000	16,000	16,000	16,050
70	15,540	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000	16,000
80	11,490	15,000	15,000	15,000	15,000	12,240	15,000	12,500	13,534	14,990	15,000
85	10,000	10,962	13,210	10,000	13,005	10,000	10,000	10,000	10,000	10,000	10,010
90	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
95	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
98	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
99	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
99.5	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
99.8	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
99.9	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000

5 CONCLUSION AND SUMMARY

5.1 METHODOLOGY

The VIC model had difficulty matching observed runoff values even after the model had been calibrated to observed runoff. To alleviate this problem, a bias-correction method was implemented to force the VIC runoff to match observed runoff. A comparison between the original VIC runoff, bias-corrected VIC runoff, and the VIC climate-change runoff showed that the bias-correction resulted in a larger change in runoff than the climate change.

5.2 SPILLWAY DESIGN FLOOD ANALYSES

Results from the early spring flood analysis indicated that the future, climate-adjusted sediment loads would not affect dam safety at Garrison. Lake Sakakawea has a very large storage capacity (~ 23 million acre-ft) and a large spillway capacity (827,000 cfs), so the changes in sediment loading caused by climate change would not significantly decrease the available storage and affect the reservoirs ability to safely pass the spillway design flood given that the spillway design flood does not increase for future climates.

5.3 HEC-HMS PERIOD OF RECORD ANALYSES

Results of the HEC-HMS period of record analyses showed that climate change had a significant effect on the reservoir operations for all climate-change scenarios. As with the spillway design flood analysis, the climate-adjusted sedimentation did not significantly change the reservoir operations; however, the HEC-HMS period of record analyses also incorporated climate-adjusted inflows, which significantly affected the reservoir operations. The pool-duration analysis showed that the percent of time Lake Sakakawea's pool elevations reached or exceeded the top of the spillway gates (1854.0 ft) increased from 0.1% (observed pool elevations) to 1% for all climate scenarios; one climate scenario resulted in an increase to 10%. However, these results are not realistic because the HEC-HMS model on simulated the Garrison Dam. All six of the main stem dams need to modeled as a system in order to achieve realistic results.

Based on the pool duration plots shown in Appendix A – Duration Plots, precipitation was the more critical parameter. When only precipitation was considered (Q1 climate scenario minus Q4 climate scenario), the average change in pool elevation was 5.6 ft (based on the fifty percent exceedance pool elevation for both periods). However, when only temperature was considered (Q1 climate scenario minus Q2 climate scenario), the average change in pool elevation is 0.5 ft (based on the fifty percent exceedance pool elevation for both periods).

5.4 DRM PERIOD OF RECORD ANALYSES

The results of the DRM period of record analyses showed that climate change had an effect on the reservoir operations. As with the HEC-HMS analyses, the climate-adjusted inflows had a larger influence on reservoir operations than the climate-adjusted sedimentation although the effect was less pronounced than with the HEC-HMS analyses. The six Missouri River dams are

operated as a system, so the effect of the increased incremental inflow at one dam can be spread throughout the system. If incremental inflows to Garrison Dam are forecasted to increase, storage availability can be increased by increasing the releases at Garrison Dam and decreasing the releases at Fort Peck; therefore, the DRM provided more realistic results than the HEC-HMS model.

The DRM and HEC-HMS results showed that even though precipitation is the more critical parameter for climate change, timing also plays an important role in climate change. The climate scenarios with more precipitation (Q1 and Q2) caused the pool elevation to increase so it was assumed that the climate scenarios with less precipitation would cause the pool elevation and releases to decrease; however, the Q3_40-69 climate scenario (lower precipitation and higher temperature) does not follow this trend. Even though Q3_40-69 climate-scenario had less precipitation, the releases and pool elevations still increased and resembled a climate scenario with more precipitation. The Q3_40-69 VIC factors in March and April for both Williston (Garrison Dam) and Wolf Point (Fort Peck) resemble the VIC factors of a climate scenario with more precipitation. During the period of record, the incremental flow for Garrison in May through July is generally higher than the incremental flow in March and April; however, some of the largest floods occurred in the early spring months of March and April, which corresponded to large VIC factors for the Q3_40-69 climate scenario. It is because of these large events coinciding with the large Q3_40-69 VIC factors that the pool elevations and releases, for the percent exceedance values less than two percent, resemble a climate scenario with more precipitation.

5.5 LESSONED LEARNED

1. Changes in flow due to bias corrections are greater than changes due to future climates
2. All climate-change scenarios resulted in an increase in sediment loading and inflows
3. Climate-adjusted sediment rates have no impact on dam safety as long as the spillway design flood does not increase
4. Climate-adjusted sediment rates have little impact on pool elevations and releases for any climate scenario, but this may change for smaller reservoirs
5. Climate-adjusted flows have a large impact on pool elevations and releases for all climate scenarios
6. The Missouri River main stem dams need to be modeled as a system
7. Precipitation is the driving factor, but the timing plays an important role. The climate scenarios with less precipitation can result in increased inflows due to timing changes in runoff,which can increase spring runoff

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7 APPENDIX A – DURATION PLOTS

This appendix contains the duration plots for the HMS and DRM simulations. Duration plots were created for each of the different analysis: capacity, flow, flow and capacity. The climate-adjusted inflows for Garrison are also displayed in this appendix.

7.1 HMS Capacity Simulations 7-1

7.2 HMS Flow Simulations 7-3

7.3 HMS Flow & Capacity Simulations 7-5

7.4 Spreadsheet Period of Record Analyses 7-7

7.5 DRM Capacity Simulations 7-8

7.6 DRM Flow Simulations 7-10

7.7 DRM Flow & Capacity Simulations 7-12

7.8 Climate-Adjusted Inflows 7-14

7.1 HMS CAPACITY SIMULATIONS

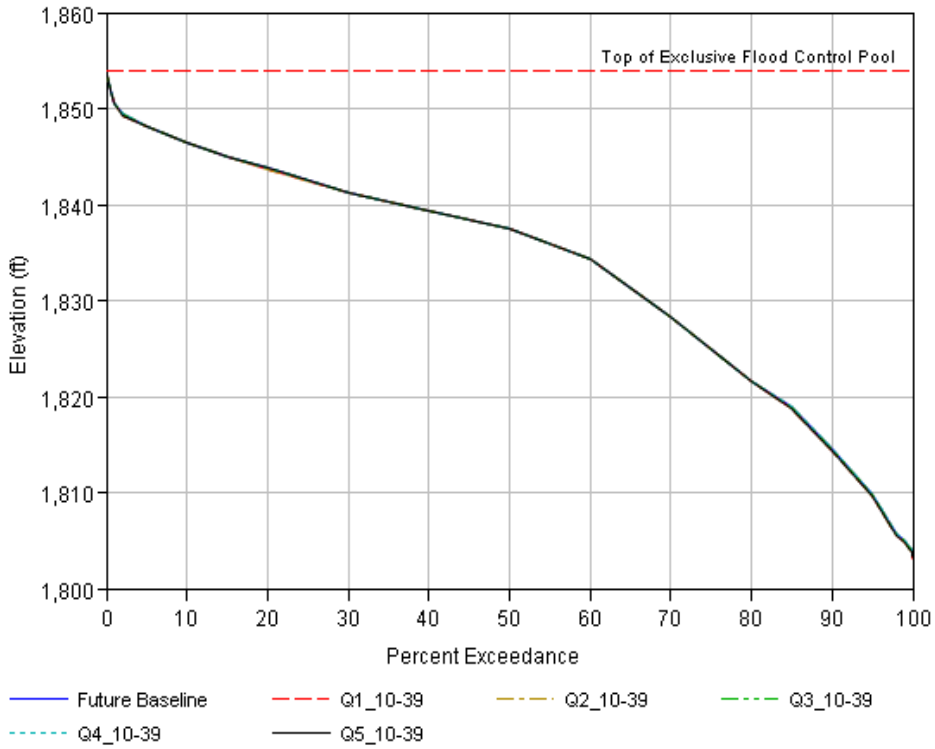

Figure 7-1: HMS Capacity pool-duration curves for the period of 2010-2039.

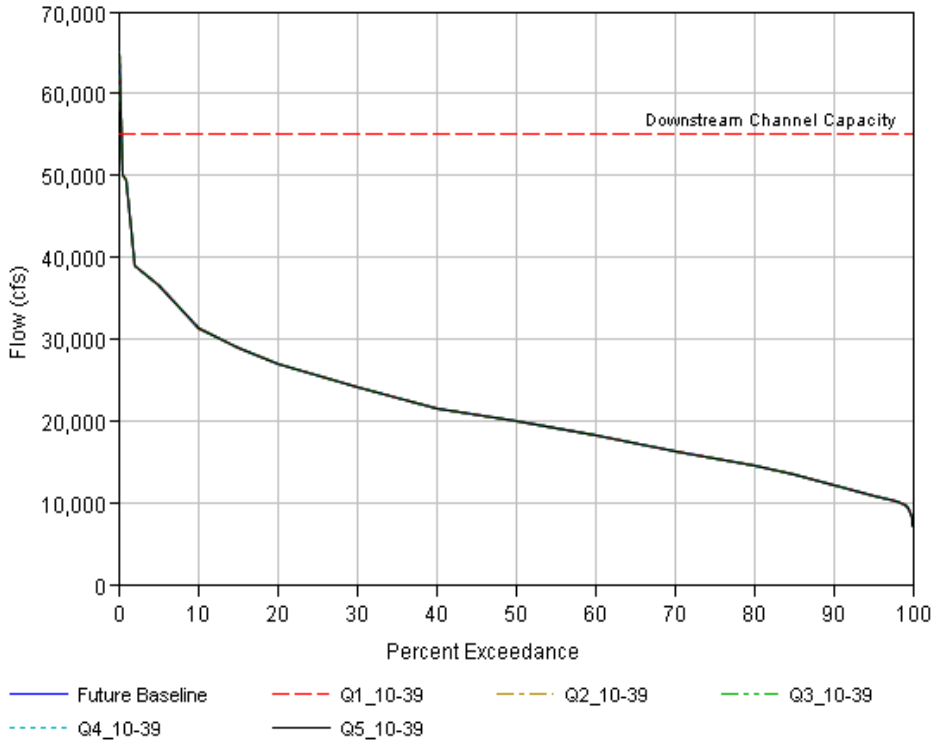

Figure 7-2: HMS Capacity release-duration curves for the period of 2010-2039.

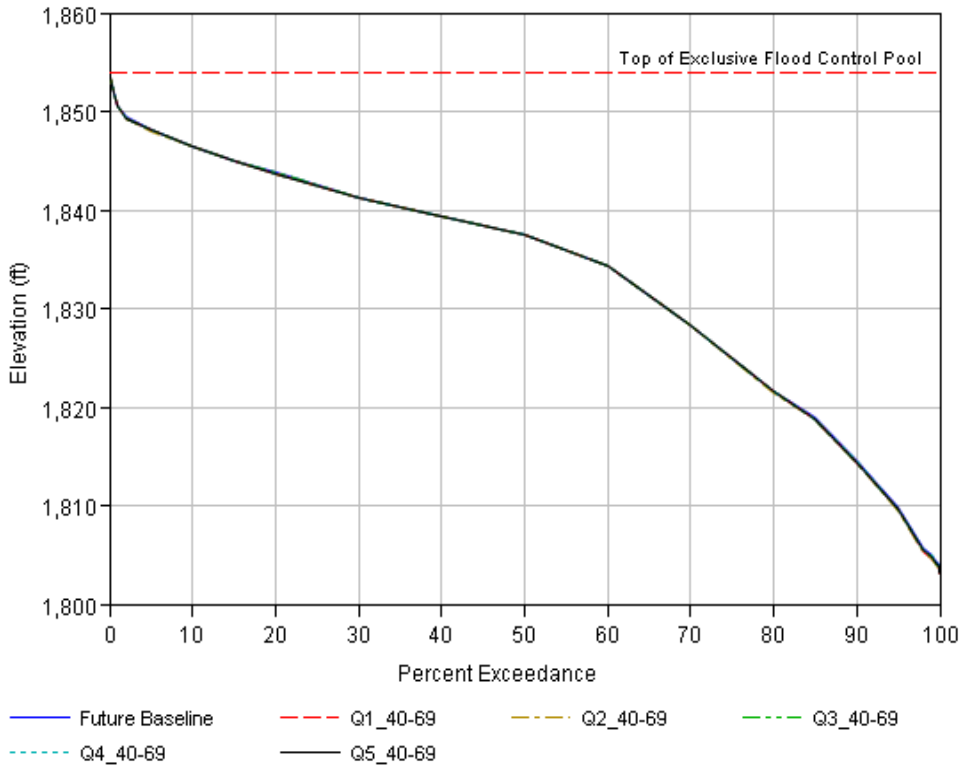

Figure 7-3: HMS Capacity pool-duration curves for the period of 2040-2069.

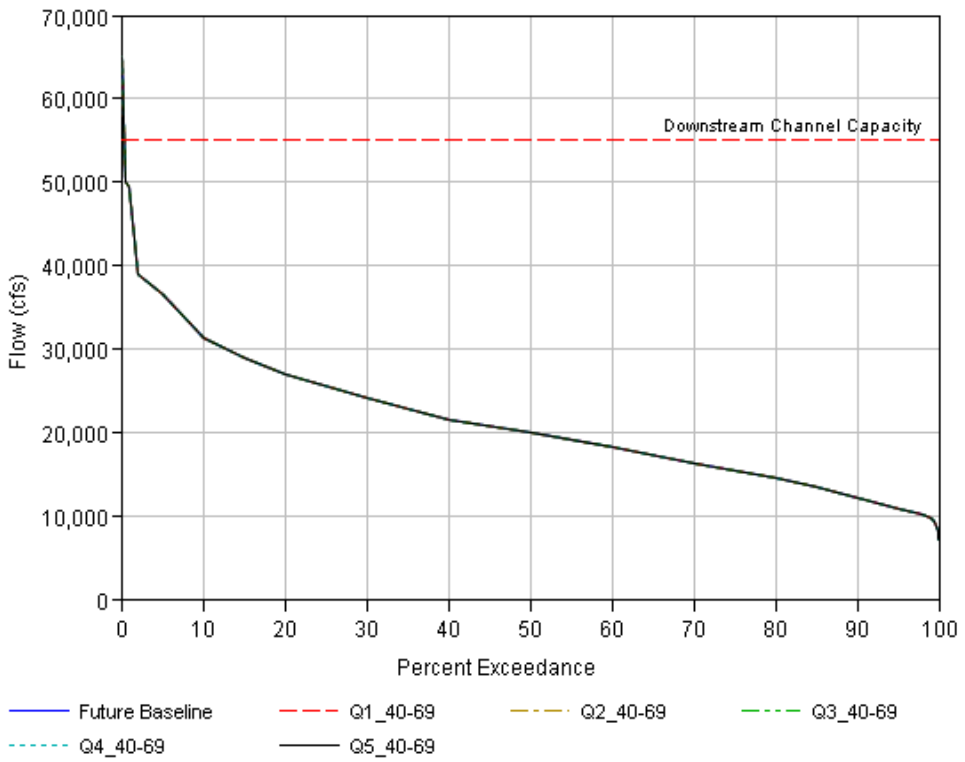

Figure 7-4: HMS Capacity release-duration curves for the period of 2040-2069.

7.2 HMS FLOW SIMULATIONS

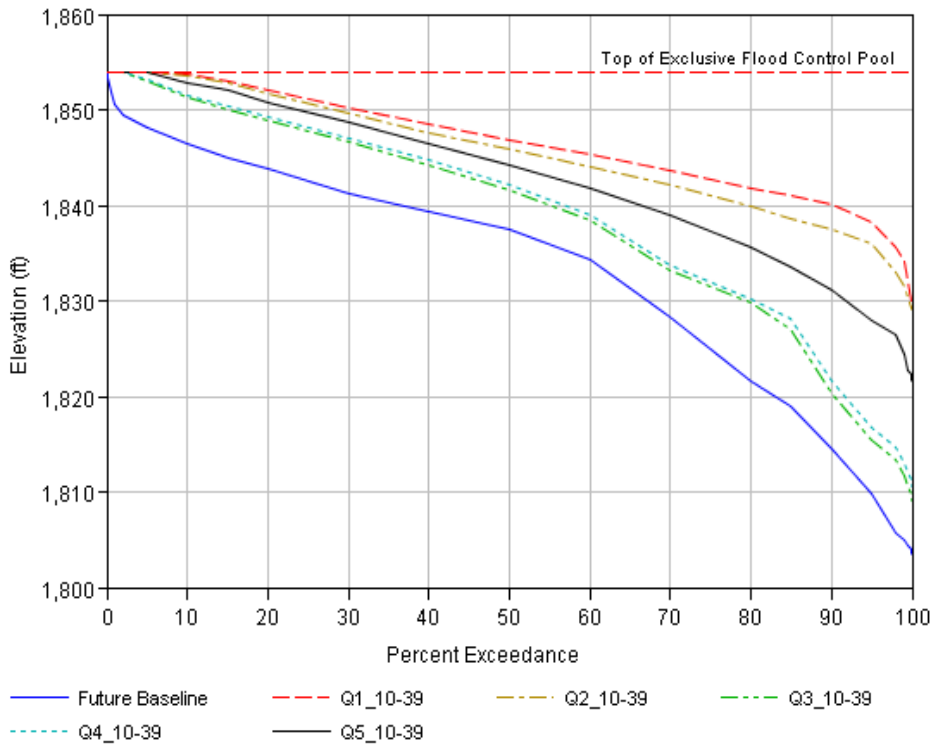

Figure 7-5: HMS Flow pool-duration curves for the period of 2010-2039.

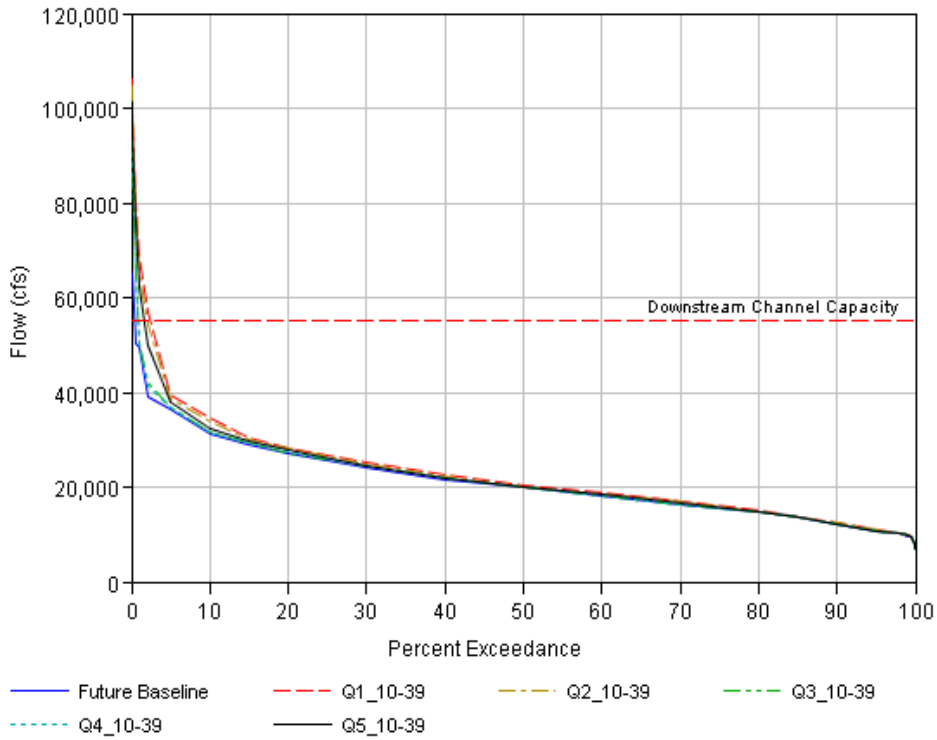

Figure 7-6: HMS Flow release-duration curves for the period of 2010-2039.

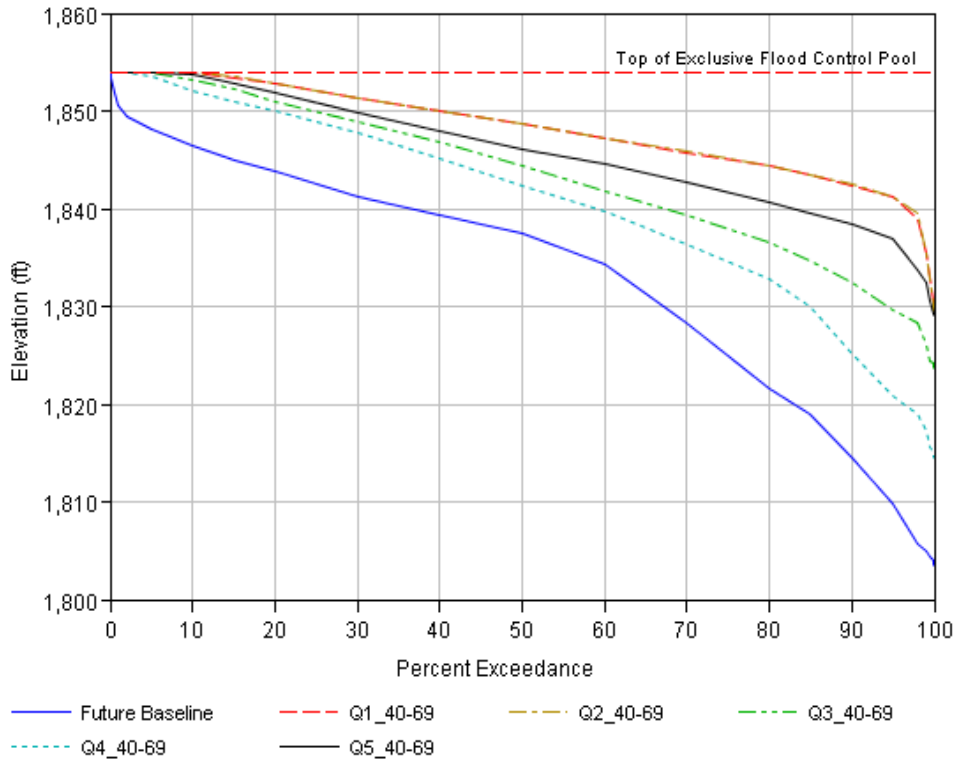

Figure 7-7: HMS Flow pool-duration curves for the period of 2040-2069.

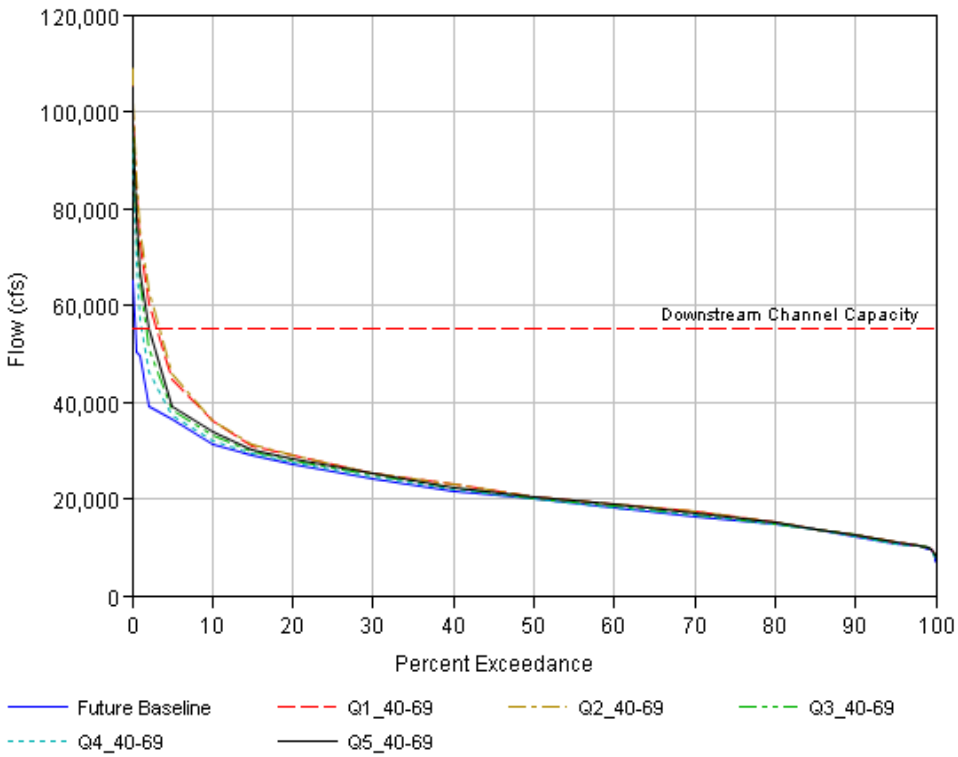

Figure 7-8: HMS Flow release-duration curves for the period of 2040-2069.

7.3 HMS FLOW & CAPACITY SIMULATIONS

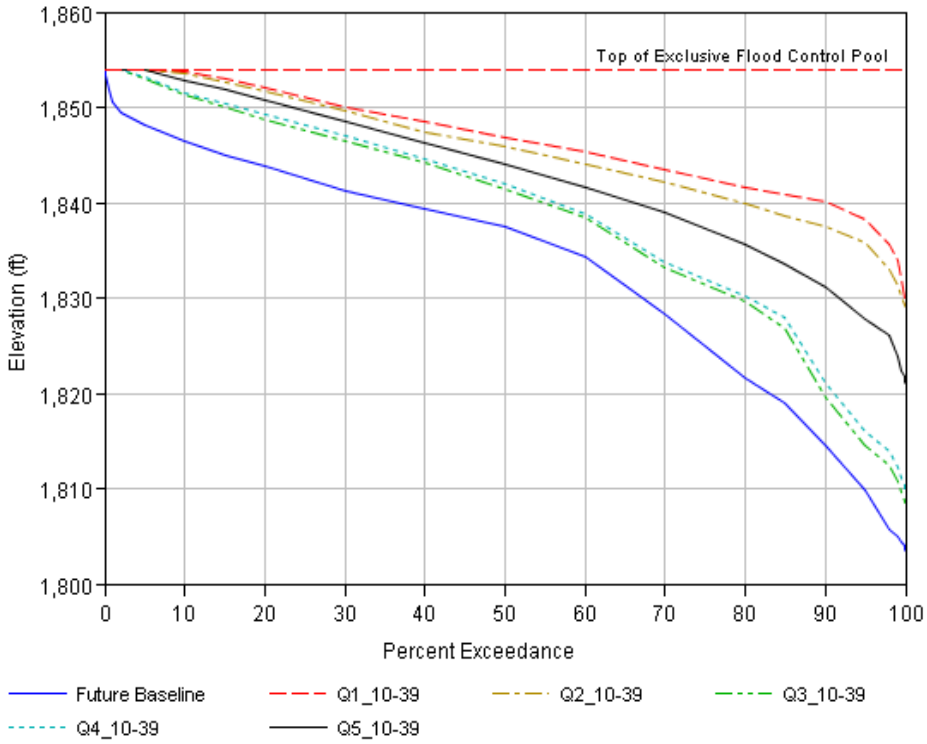

Figure 7-9: HMS Flow & Capacity pool-duration curves for the period of 2010-2039.

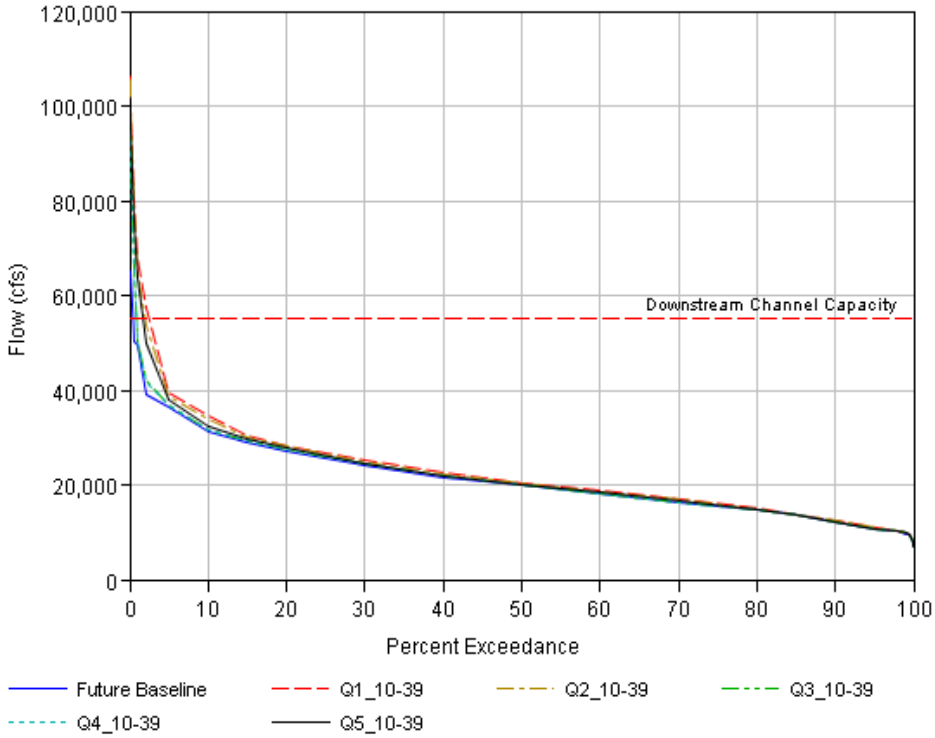

Figure 7-10: HMS Flow & Capacity release-duration curves for the period of 2010-2039.

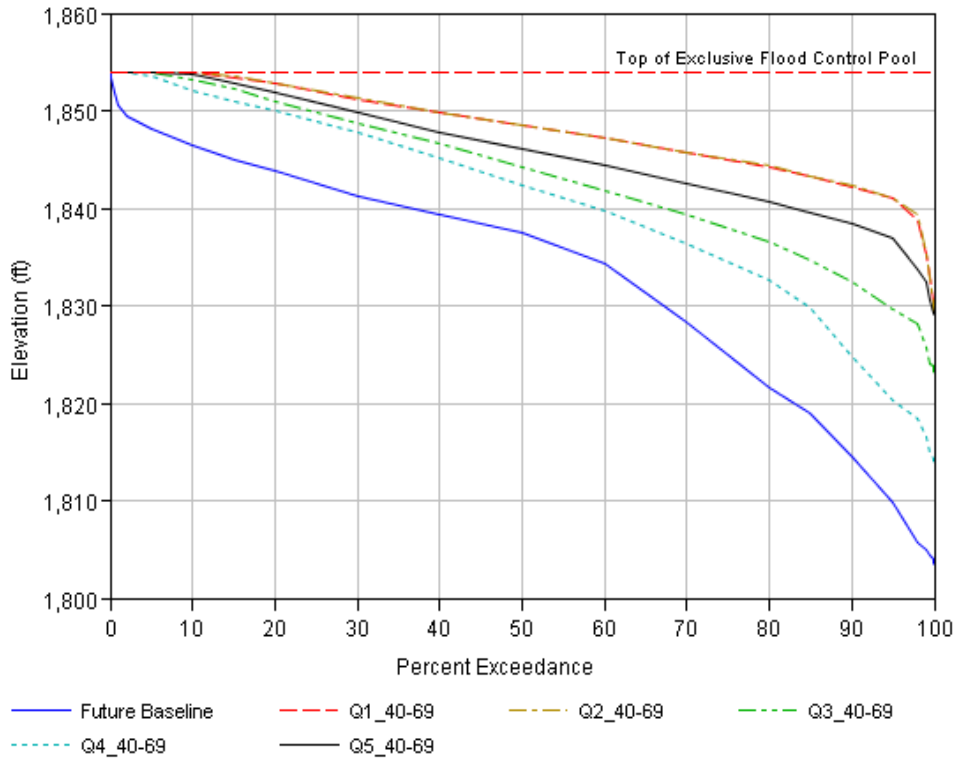

Figure 7-11: HMS Flow & Capacity pool-duration curves for the period of 2040-2069.

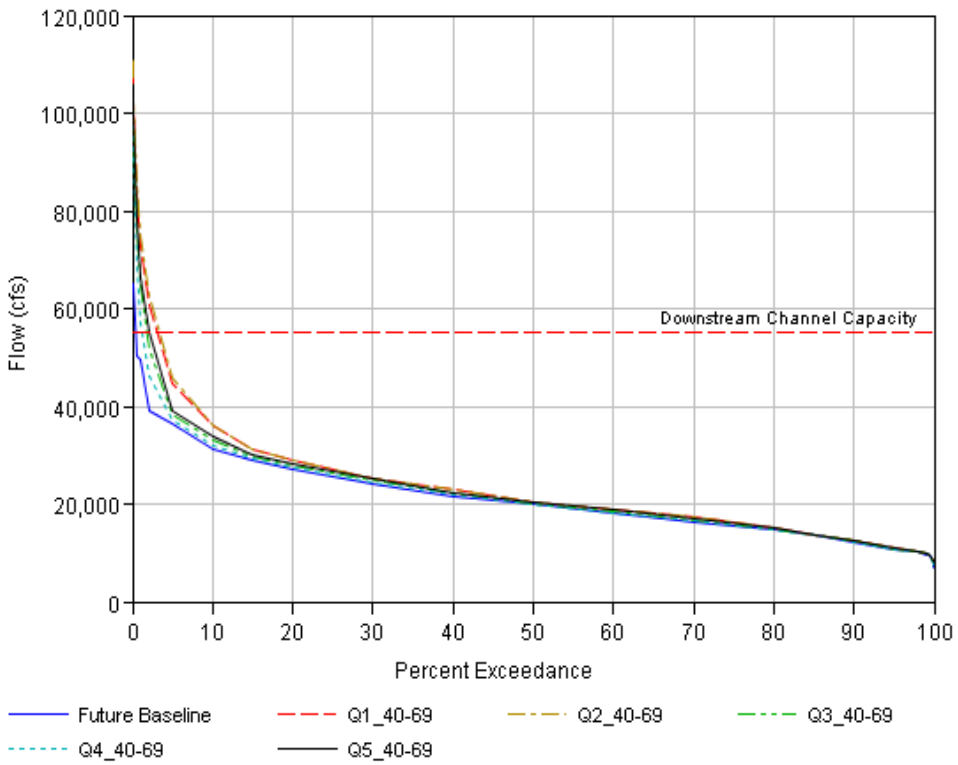

Figure 7-12: HMS Flow & Capacity release-duration curves for the period of 2040-2069.

7.4 SPREADSHEET PERIOD OF RECORD ANALYSES

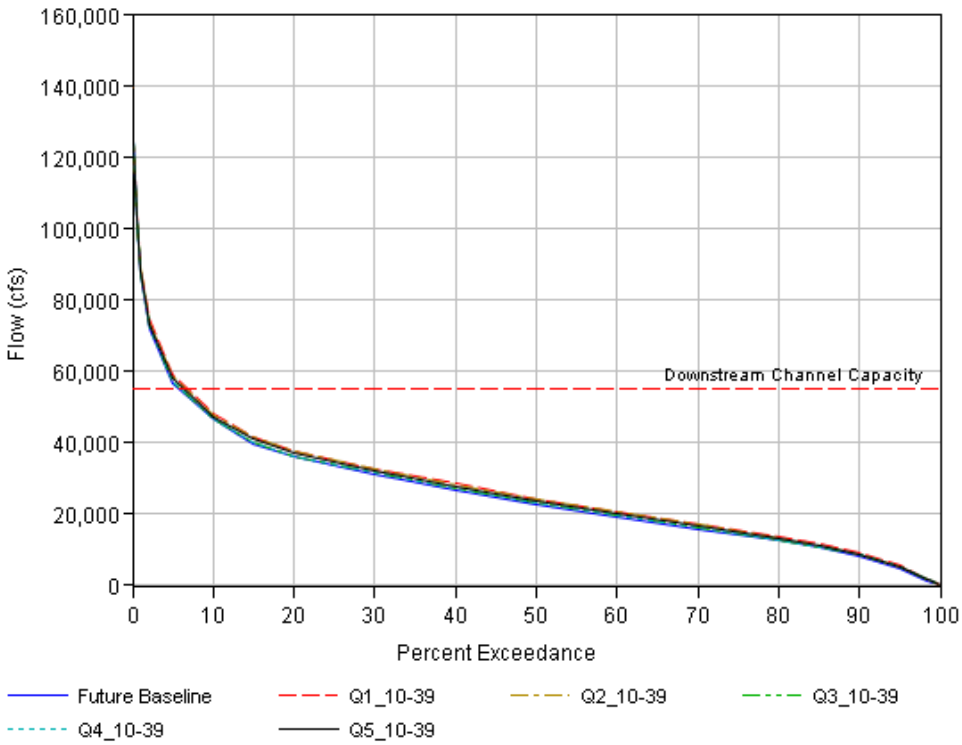

Figure 7-13: Spreadsheet release duration curves for the period 2010-2039.

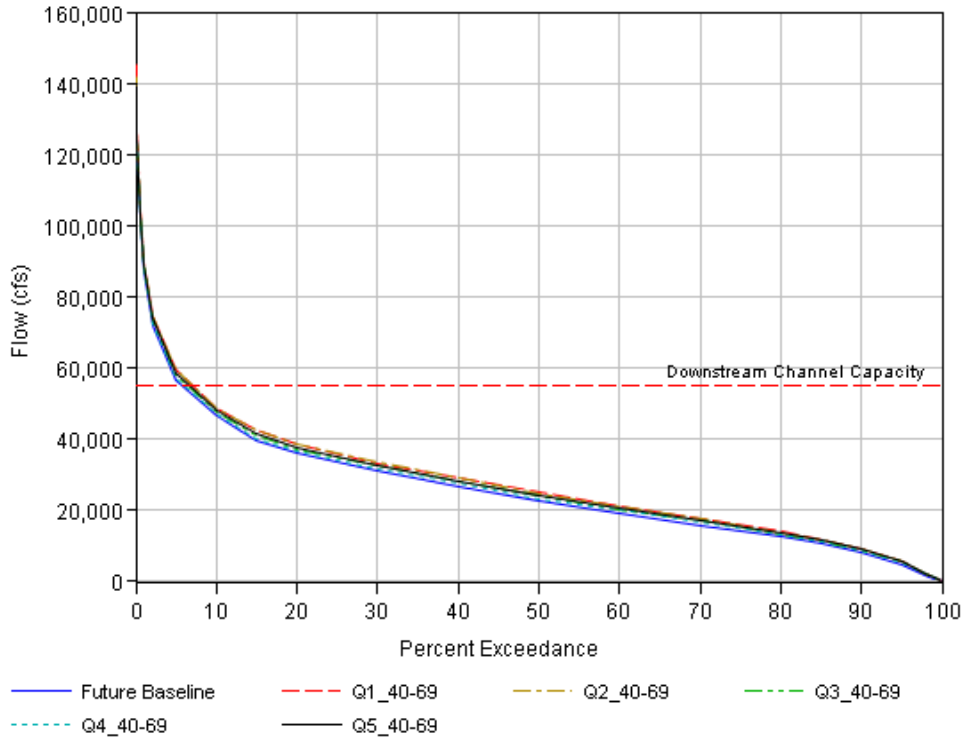

Figure 7-14: Spreadsheet release duration curves for the period 2040-2069.

7.5 DRM CAPACITY SIMULATIONS

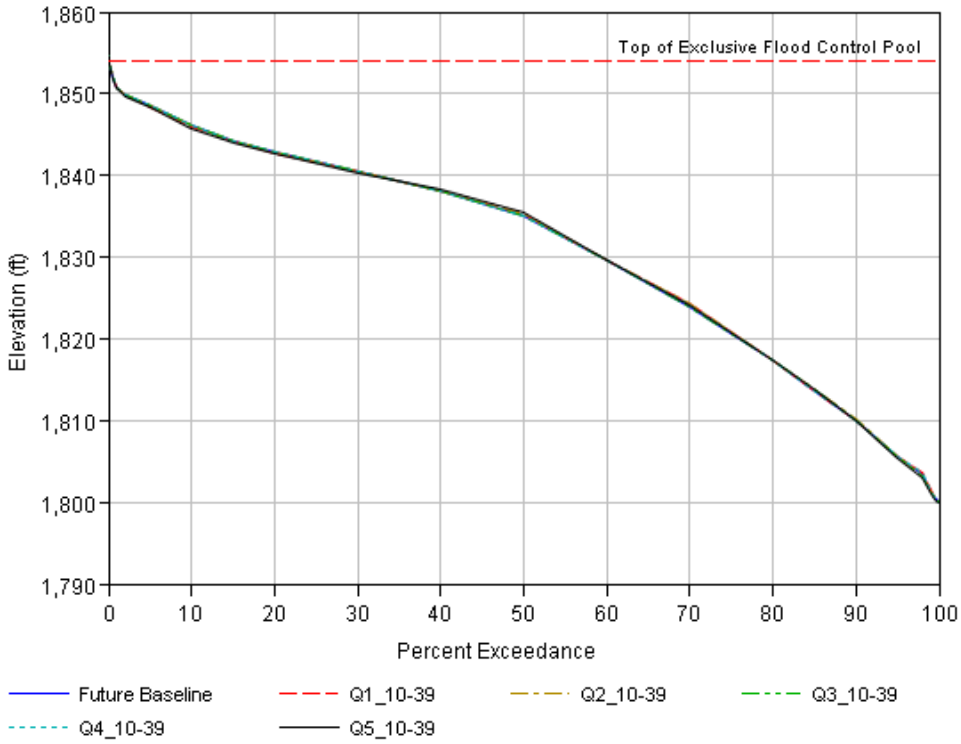

Figure 7-15: DRM Capacity pool-duration curves for the period of 2010-2039.

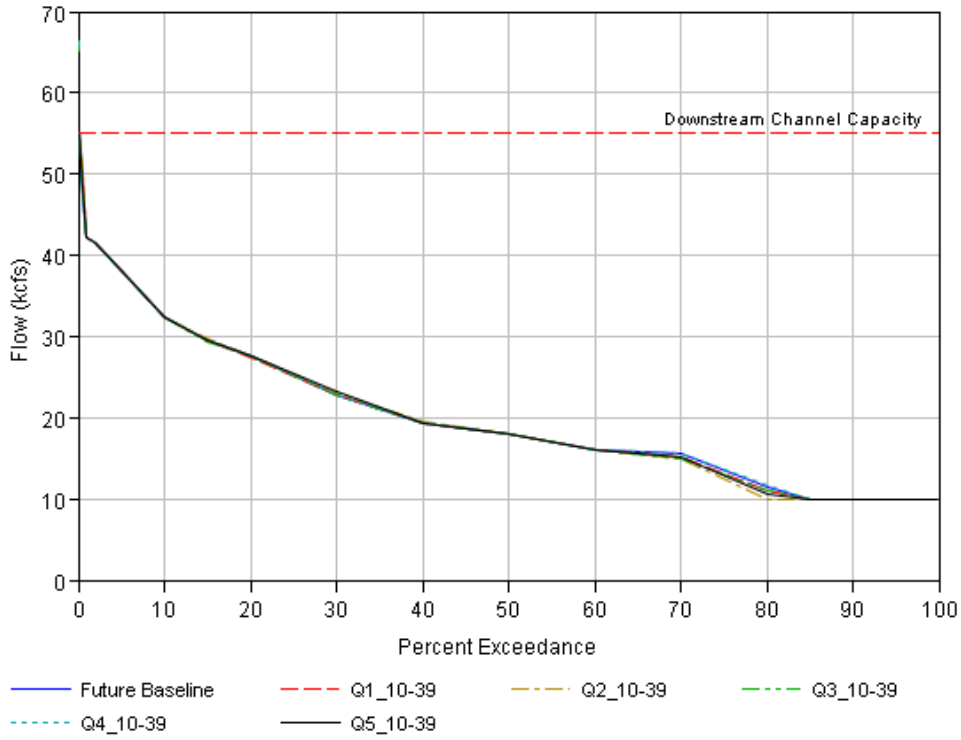

Figure 7-16: DRM Capacity release-duration curves for the period of 2010-2039.

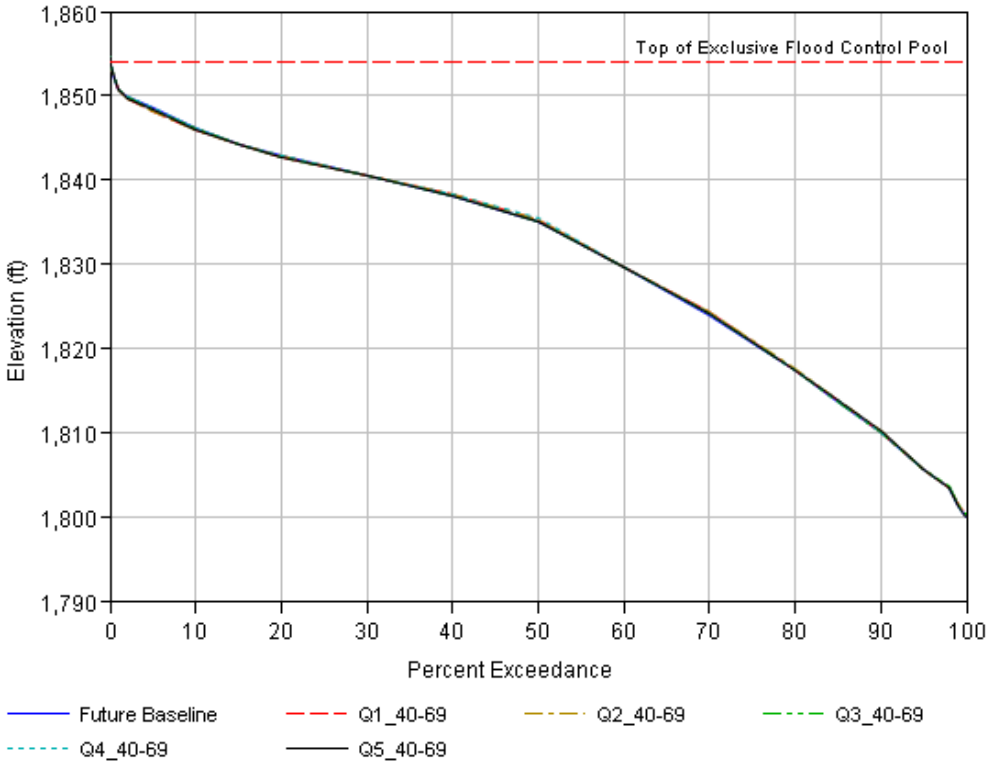

Figure 7-17: DRM Capacity pool-duration curves for the period of 2040-2069.

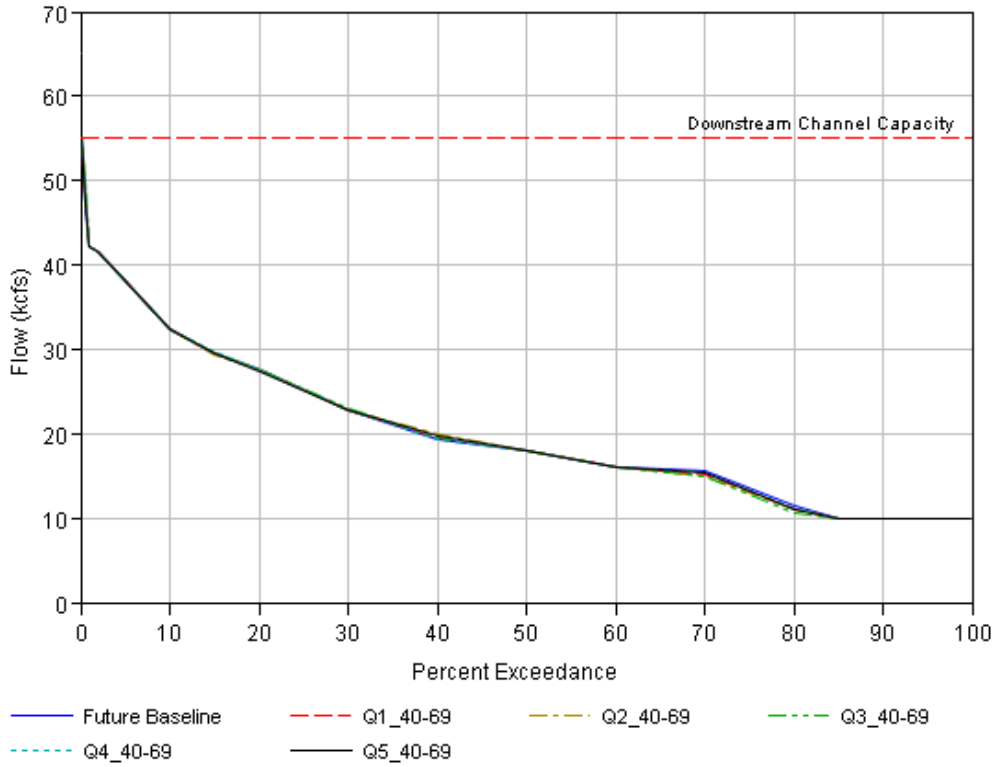

Figure 7-18: DRM Capacity release-duration curves for the period of 2040-2069.

7.6 DRM FLOW SIMULATIONS

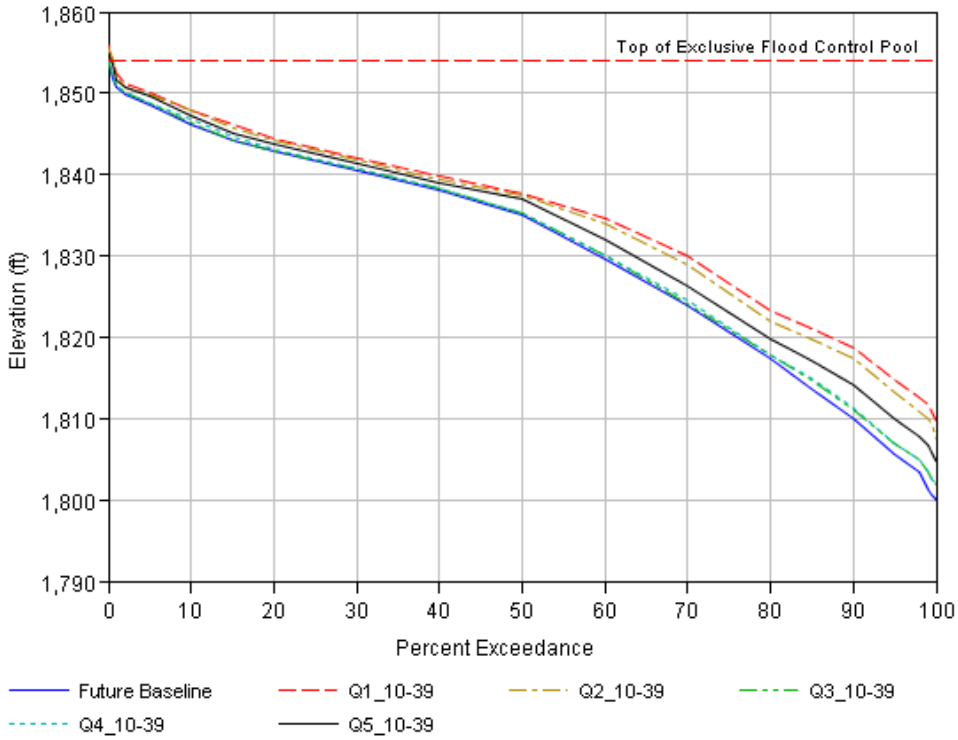

Figure 7-19: DRM Flow pool-duration curves for the period of 2010-2039.

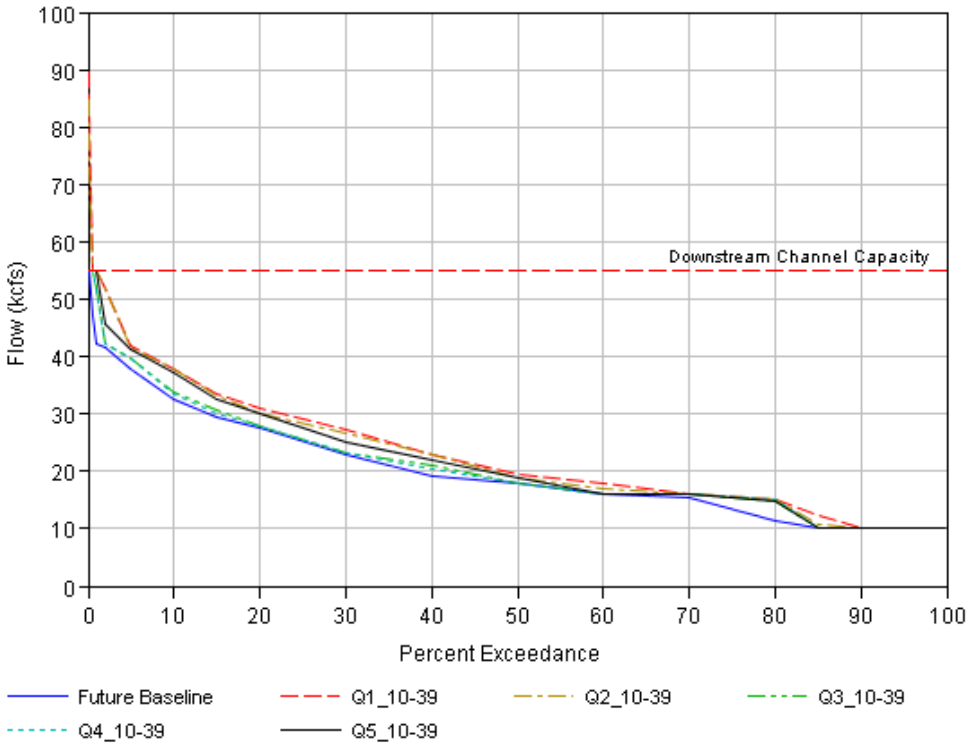

Figure 7-20: DRM Flow release-duration curves for the period of 2010-2039.

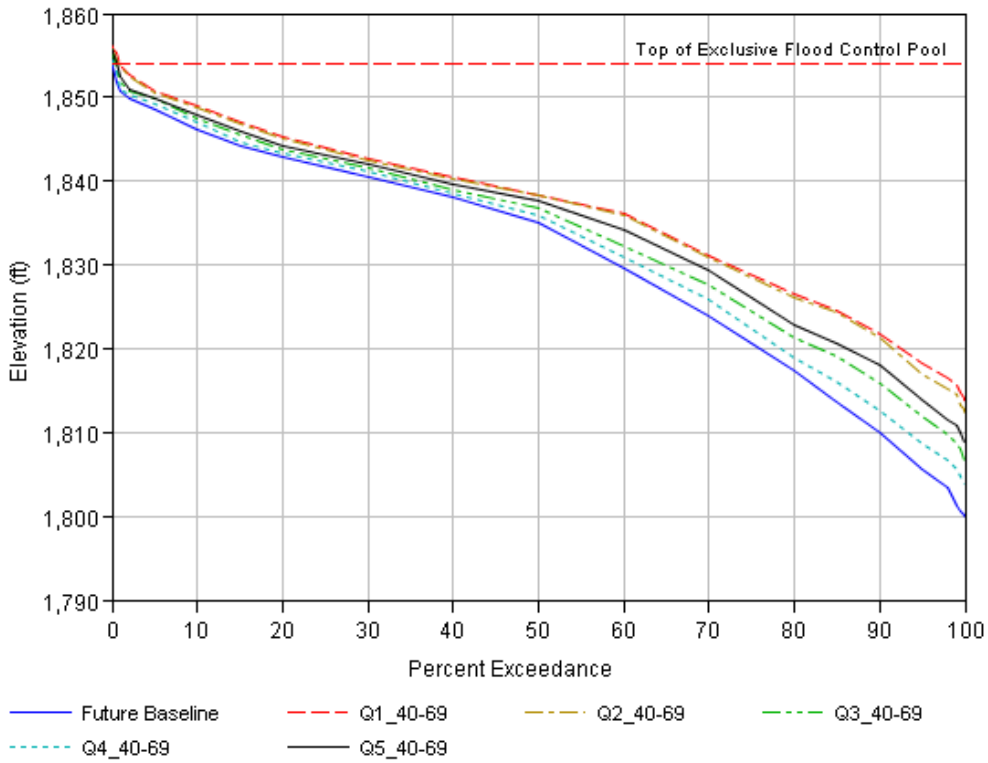

Figure 7-21: DRM Flow pool-duration curves for the period of 2040-2069.

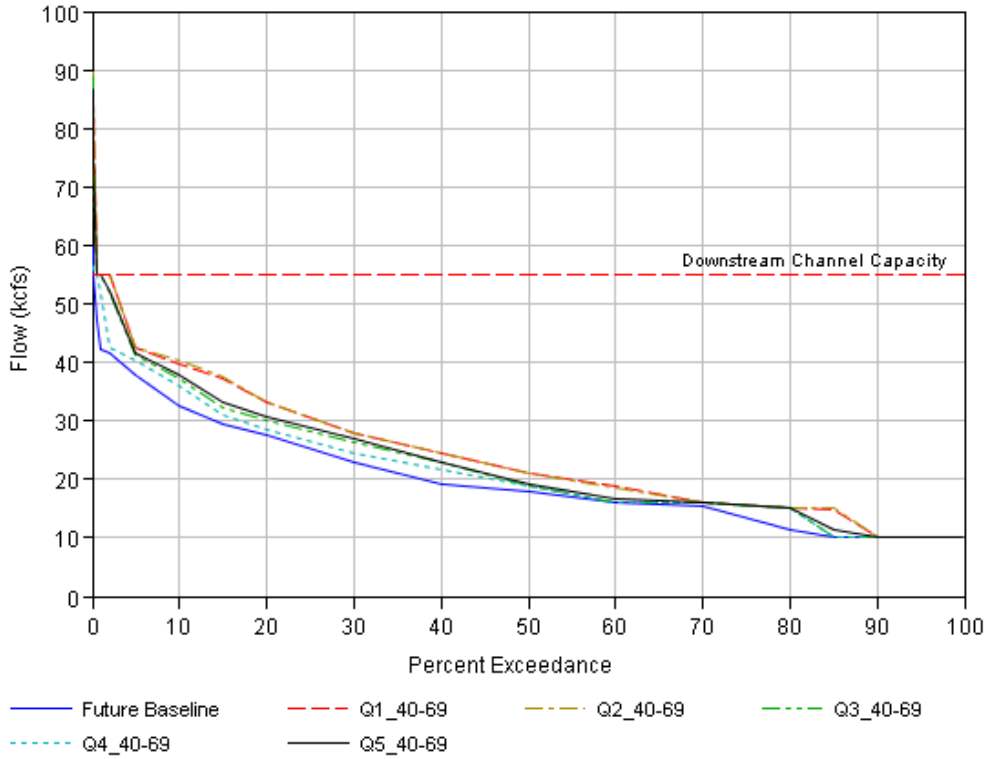

Figure 7-22: DRM Flow release-duration curves for the period of 2040-2069.

7.7 DRM FLOW & CAPACITY SIMULATIONS

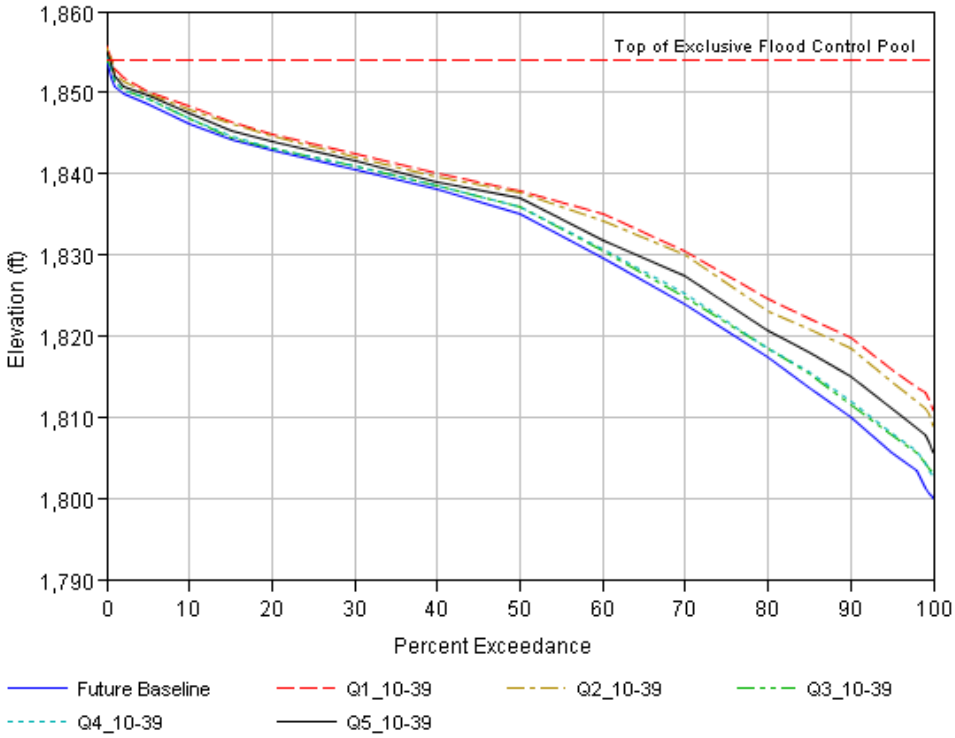

Figure 7-23: DRM Flow & Capacity pool-duration curves for the period of 2010-2039.

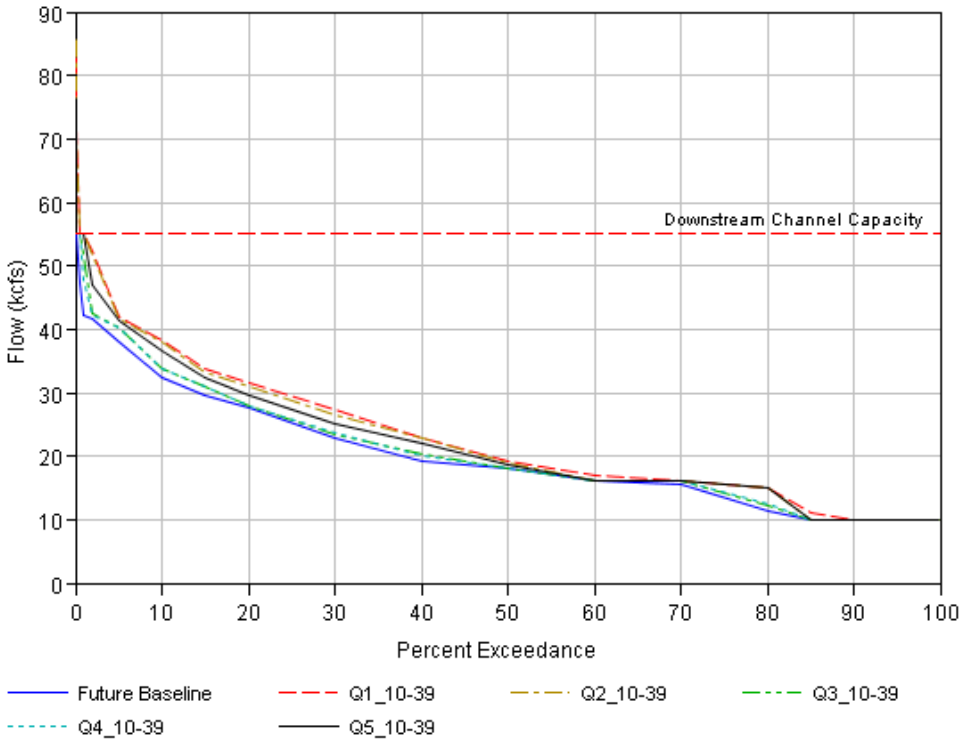

Figure 7-24: DRM Flow & Capacity release-duration curves for the period of 2010-2039.

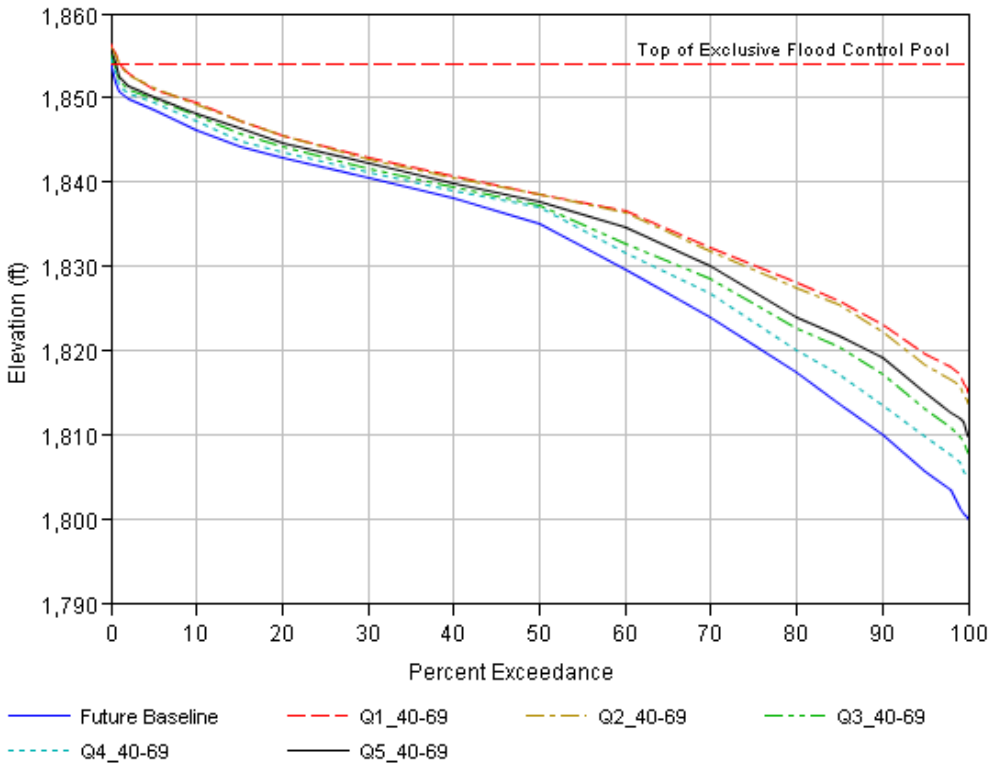

Figure 7-25: DRM Flow & Capacity pool-duration curves for the period of 2040-2069.

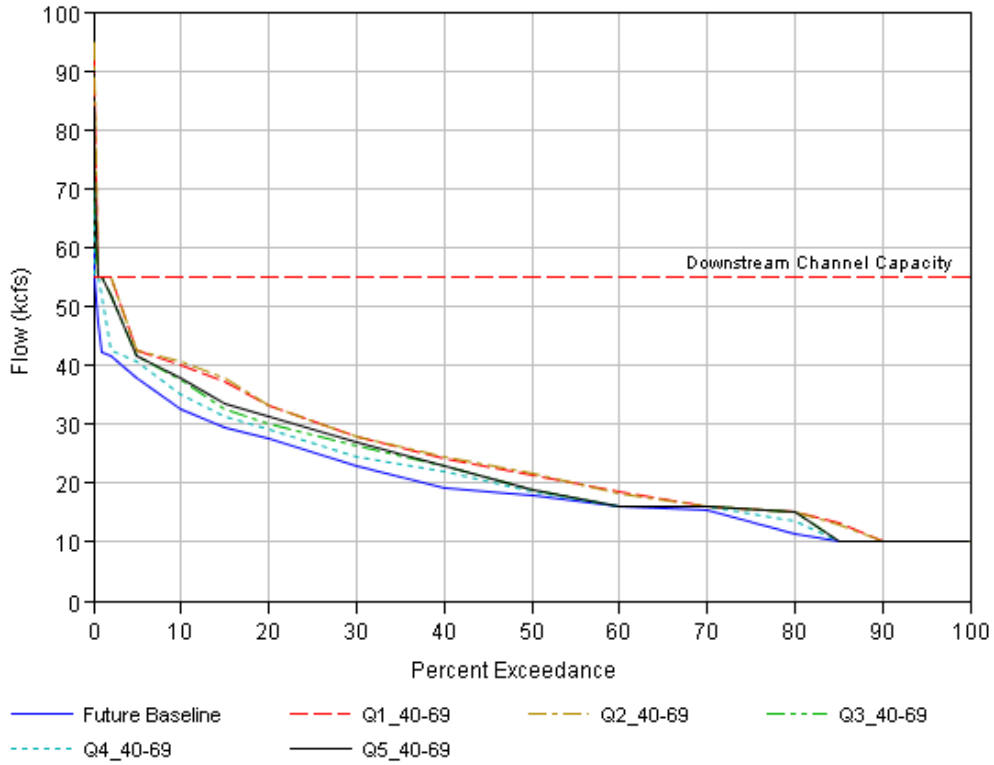

Figure 7-26: DRM Flow & Capacity release-duration curves for the period of 2040-2069.

7.8 CLIMATE-ADJUSTED INFLOWS

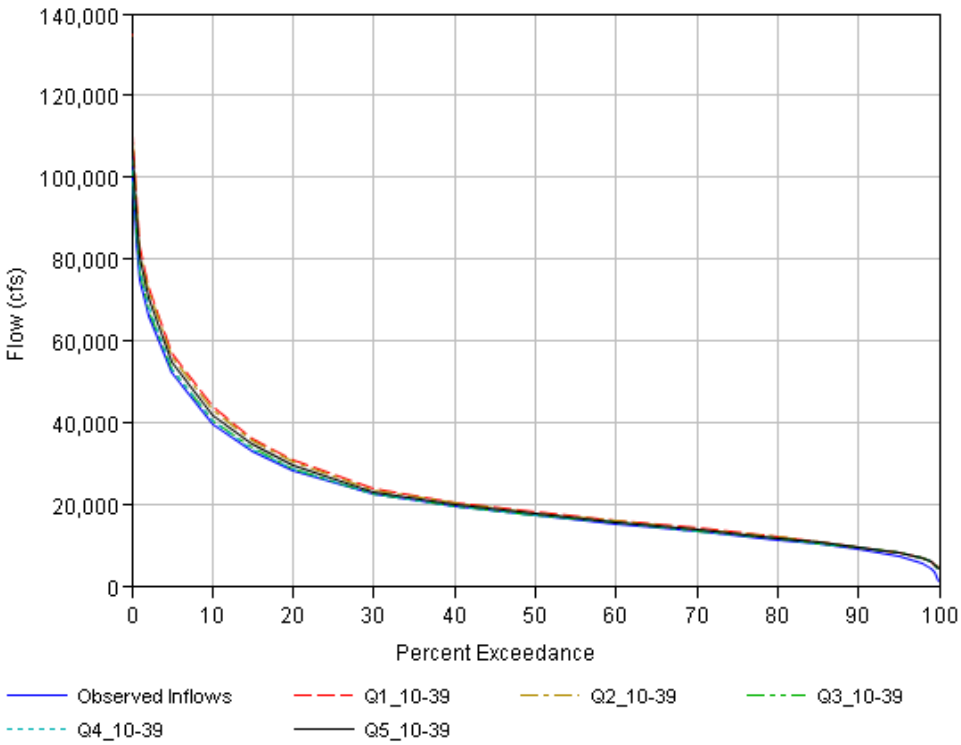

Figure 7-27: Inflow duration curves for the period 2010-2039.

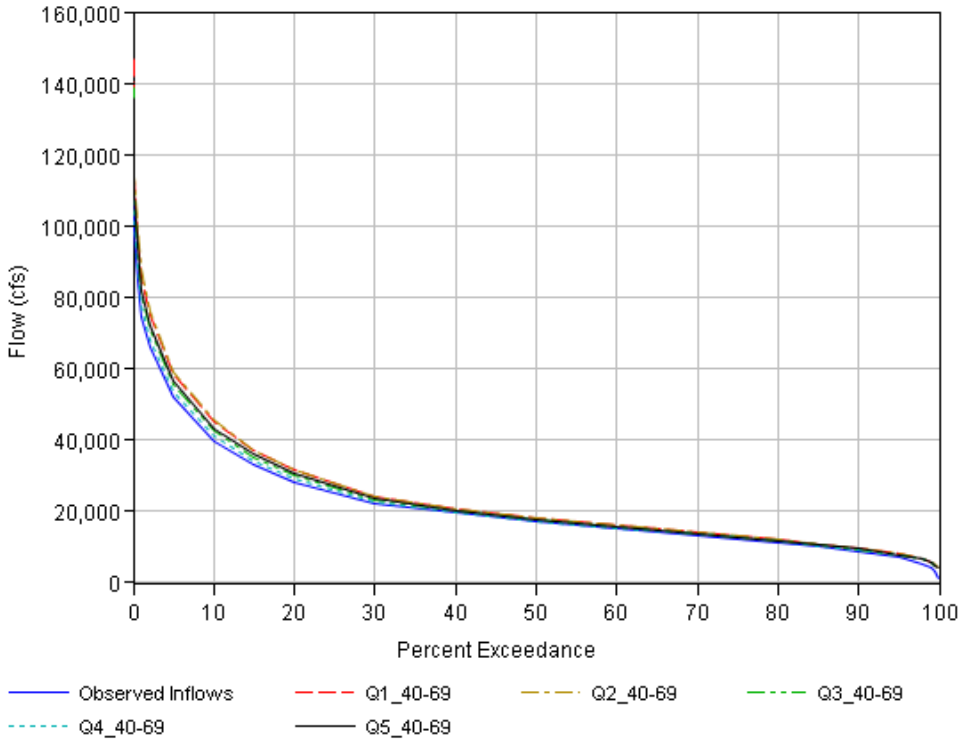

Figure 7-28: Inflow duration curves for the period 2040-2069.