Interagency Flood Risk Management (InFRM)

Watershed Hydrology Assessment for the Nueces River Basin

Appendix E:
Reservoir Analyses

March 2025

INTERAGENCY FLOOD RISK MANAGEMENT

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1 Reservoir Analyses for the Nueces River Basin Dams

1.1 Introduction

This section of the report describes the methods used to produce the pool frequency curves for the Nueces River Basin reservoir projects. The reservoir projects that have been analyzed for this section are Choke Canyon Reservoir and Lake Corpus Christi. More details about who owns and operates these projects are listed in section 8.1.3. The frequency curves were developed to represent the current reservoir control plan and watershed conditions (as of 2019). A frequency analysis is a statistical method of prediction that consists of studying past events that are characteristic of a particular hydrology process in order to determine the probabilities of occurrence of these events in the future. A stage-frequency curve estimates the annual chance of exceedance (ACE) for reservoir pool elevations. For example, if a reservoir pool at the spillway crest has an ACE of 1/50 (1 in 50 years on average), then the reservoir has a 2% chance of the reservoir pool elevation equaling or exceeding the spillway crest elevation in any given year. The stage-frequency curve can be determined using empirical (observed or measured) data; however, the reservoir pool elevations associated with 1% ACE (100-year) or 0.2% (500-year) occurrence are typically beyond the observed reservoir pool elevation period of record (POR). Models serve the purpose of extrapolating reservoir pool elevation frequencies beyond the observed record.

For the presented study, the pool frequency curves presenting current conditions were developed to evaluate the Nueces River Basin projects' pool elevations resulting from the 50% ACE (2-year) to 0.2% (500-year) events. This study incorporates available reservoir daily inflow (historical peaks through 2019) and daily pool data (historical peaks through 2019) into statistical software and applies statistical methods to estimate the critical inflow duration and simulate inflow and elevation period of record for each project. The historical peaks, if available, may be observed and recorded by local residents or seen as water marks on bridge piers or tree trunks; those water elevation marks can be translated into peak inflow or release discharge values via the use of models or by extrapolating rating curves or extrapolation of observed data points. For each project, the Hydrologic Engineering Center-Statistical Software Package (HEC-SSP)[1] was used to compute volume duration frequency curves from the annual maximum peak reservoir inflows. An empirical pool frequency curve was developed from the available reservoir pool Annual Maximum Series (AMS). An event based stochastic Monte Carlo simulation model (Risk Management Center- Reservoir Frequency Analysis RMC-RFA)[2] was used to extrapolate the pool frequency curve beyond the limits of empirical pool frequency curve. RiverWare[3] was used to develop a current condition POR for reservoir inflows and elevations. The AMS results derived from RiverWare was used to create the empirical pool frequency curve. The empirical stage-frequency curve was used to validate RFA model simulation results. The results showed adequate validation to the upper tail end of the empirical pool frequency curves and is believed to be a reasonable extrapolation for frequency of rare pool events.

No previous records or pool frequency elevation estimates were made to compare to the results documented in this chapter for the Nueces River Basin Lakes. In this chapter, main emphases were put to accurately capture the 1% ACE (100-year) and 0.2% (500-year) events by utilizing the RMC-RFA program throughout Water Year (WY) 2019 for each project.

1.2 Watershed Description

The Nueces River Basin[7] is located in south-central Texas and is the seventh largest river basin in Texas, with a drainage area totaling 16,675 square miles (Figure E.1). The watershed spans and drains all or parts of 24 counties. The basin is approximately 315 miles long, with a maximum width near its center of approximately 90 miles and includes about 6 percent of the total land area of Texas. There are no USACE Reservoirs in the Nueces River Basin, however, the Three Rivers Local Protection Project is located downstream of Choke Canyon Dam on the Frio River. The Nueces River is located in the arid valley of South Texas and empties into the Gulf of Mexico in Corpus Christi, Texas, and lies only within the Galveston District boundary. The Balcones Fault runs East-West through the Northern part of the basin and is responsible for streamflow loss resulting in the groundwater recharge in Edwards Aquifer and the Carizo-Wilcox Aquifer. Water supply in the Nueces basin relies primarily on groundwater except for the two major lakes in the Southern part of the basin. Both Choke Canyon Reservoir and Lake Corpus Christi provide water supply. The total contributing drainage area to Choke Canyon Reservoir is 5,490 square miles and Lake Corpus Christi is 16,502 square miles.

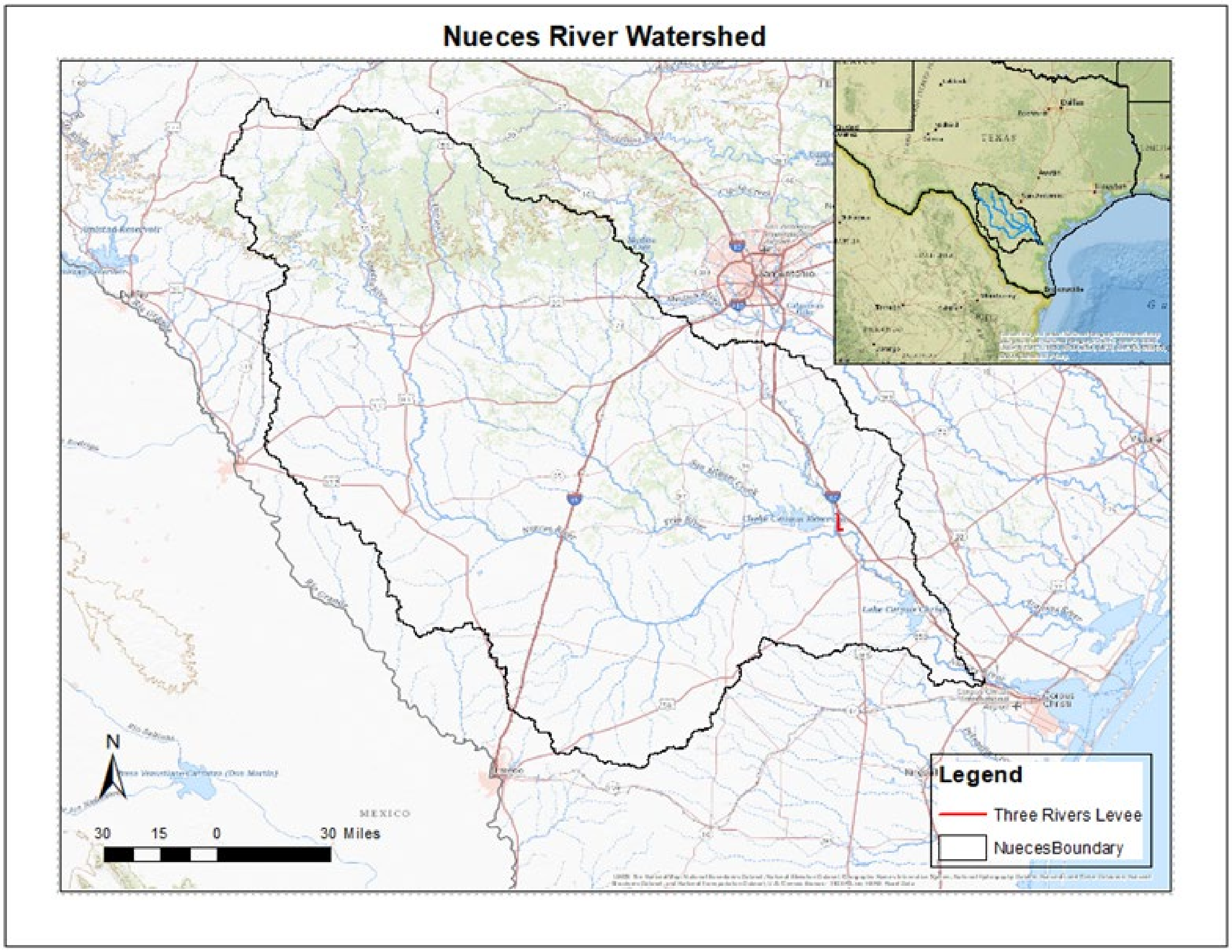

Figure E.1: Map of the Nueces River Watershed

1.2.1 **Nueces River Watershed Gages**

Figure E.2 and Table E.1 show the corresponding reservoir projects and the USGS gages used to develop the Nueces River Basin inflow and release discharges. In many instances, project inflows are estimated from the nearest USGS gage upstream of the dam, especially if the project drainage area does not vary significantly from the nearest USGS gage. The nearest USGS gage rating curve can also be used to estimate the historical inflow and release peak discharges for the projects. Detailed analyses for hydrology development using RiverWare can be found in Appendix D of this report. The POR for Nueces River Basin Lakes' inflows were obtained from RiverWare.

Figure E.2: Selected USGS Gage Locations in the Nueces River Basin

Table: E.1 USGS and USACE-SWD Data

Location	Data Type (Units)	Source
San Miguel nr Tilden, Tex.	Discharge (cubic feet per second)	USGS 08206700
Frio River at Tilden, Tex.	Discharge (cubic feet per second)	USGS 08206600
Nueces Choke Canyon Res nr Three Rivers, Tex.	Discharge (Release) (cubic feet per second)	USGS 08206910
Frio Rv at Calliham, Tex.	Discharge (Inflow) (cubic feet per second)	USGS 08207000
Atascosa Rv at Whitsett, Tex.	Discharge (cubic feet per second)	USGS 08208000
Nueces Rv nr Tilden, Tex.	Discharge (cubic feet per second)	USGS 08194500
Nueces River nr Three Rivers, Tex.	Discharge (cubic feet per second)	USGS 08210000
Nueces River nr Mathis, Tex.	Discharge (Release) (cubic feet per second)	USGS 08211000
Nueces River nr Bluntzer, Tex.	Discharge (cubic feet per second)	USGS 08211200
Nueces River at Calallen, Tex.	Discharge (cubic feet per second)	USGS 08211500
Choke Canyon Pool	Elevation (NGVD-29 feet)	City of Corpus Christi database
Corpus Christi Pool	Elevation (NGVD-29 feet)	City of Corpus Christi database

1.3 Climate

Climatological conditions[7,10] over the watershed are generally mild and vary from subtropical along the Gulf Coast to semiarid in the upper headwater regions. The rainfall decreases rather uniformly from the Gulf of Mexico to the headwaters. Most of the rainfall in the study area typically occurs in the form of intense, isolated storms during the spring, early summer, and fall. Mean annual rainfall measured in or near the study area ranged from 21.0 to 32.2 inches. About 92 percent of the rainfall in the region evapotranspires each year. The average annual temperatures over the Basin are generally moderate, with the highest at the Gulf and decreasing gradually with the increase in latitude and elevation. Winter months are generally mild, but occasional cold periods of short duration result from the rapid movement of cold high-pressure air masses from the northwest. Snowfall and subfreezing temperatures are rare in the lower portion of the Basin near the Gulf. Summer temperatures are high throughout the Basin. Near the lakes, the average high in January is 65°F and low 45°F. The record low was 11°F and the record high was 109°F.

1.4 Runoff

The Nueces River[10] Basin is subject to three general types of flood-producing rainfall: thunderstorms, frontal rainfall, and tropical cyclones. Thunderstorms in the watershed are sometimes accompanied by excessive rainfall for periods of up to 8 hours, but rarely produce excessive rainfall over an extensive area. Thunderstorms cause flash flooding in streams and are especially damaging to crops, because they frequently occur during the growing season. The frontal storms result from warm moisture-laden air masses rising from the western Gulf of Mexico and converging with a tropical or polar air mass. These storms may occur in the late summer months and tend to last for several days. The cyclonic storms originate in the Mid-Atlantic Ocean, the Gulf of Mexico, and the Pacific Ocean. When tropical air masses, brought ashore by hurricanes, converge with a cold air mass, torrential rains occur. June through November is considered to be Atlantic hurricane season.

1.5 Methods

1.5.1 Empirical Stage-Frequency

For the evaluation of a simulated reservoir pool frequency curve predictive capability, an empirical reservoir pool frequency curve is created. An empirical reservoir stage-frequency curve is constructed by ranking the observed/simulated peak annual reservoir stages, assigning the data a plotting position, and then plotting the data on probability paper using a plotting position formula. Many plotting position formulas can be used for the orientation of an empirical reservoir pool frequency curve, but a plotting position formula that is flexible and makes the fewest assumptions is preferred[6,5]. The Weibull plotting position formula was selected. This formula is an unbiased estimator of expected exceedance probability for all distributions and is used to plot the series of peak annual reservoir stages. The formula for Weibull is:

$$P_i = i / (n + 1)$$

Where, i is the rank of the event, n is the sample size in years, and P_i is the exceedance probability for an event with rank i pool frequency

1.5.2 Risk Management Center - Reservoir Frequency Analysis (RMC-RFA)

RMC-RFA software was developed by the USACE Risk Management Center for use in dam safety risk assessments. It can produce a stage-frequency curve with confidence bounds using a stochastic model with the volume-sampling approach. The model functions best in situations where dam operations are relatively simple, especially when the spillway is not regulated using gates. A simplification of the operational rules is assumed through the use of an elevation-discharge (release) table which is based on a combination of dam discharge structures and calibration to historical releases. Development of model inputs is aided by tools within the program that allow the user to estimate inputs, such as flood seasonality or pool duration curves, in a consistent and automated manner. Other inputs, such as the volume frequency curve or reservoir operations, are developed by the user independently.

1.5.3 Volume-Sampling Approach

A common method[6] for estimating a pool frequency curve for a dam is by volume-based sampling. In this method, a large number of flood events is generated using random sampling of flood volumes, the associated flood hydrographs are routed through the reservoir, and the peak reservoir elevation for each event is recorded.

The general workflow for a volume-based pool frequency analysis is as follows:

1. Choose a stage for the reservoir to begin the flood event
2. Choose an inflow flood hydrograph to scale
3. Sample a flood volume from the reservoir inflow frequency curve
4. Scale the selected flood hydrograph to match the sampled flood volume
5. Route the scaled flood hydrograph through the reservoir using an operations model
6. Record the peak stage that occurred during the event

For the stochastic model, RMC-RFA, choices made in steps 1-3 are made using random selection from a probability distribution. The choice is random in the sense that it occurs without pattern, but the relative frequency of the outcomes in the long term is defined by a probability distribution. Reservoir stages for starting the simulation come from a *pool duration curve*, which is a probability distribution for the elevation of the reservoir pool. They may be seasonally based, in which case first the season of the flood event occurrence is selected at random, and then a starting stage is selected at random from the pool duration curve for that particular season. Sampled flood volumes come from the flow frequency curve produced by fitting an analytical probability distribution to an AMS inflow of N-day river discharges. In the volume-based approach, instead of analyzing instantaneous peak discharge (as is typically the case in a Bulletin 17B/C-type analysis[8]), the analysis is performed on a longer-duration volume (*e.g.,* 15-day average inflow discharge.)

When steps 1-6 are performed a large number of times (for example, 10,000 *samples*), the resulting peak stages are ranked and plotted, producing a stage-frequency curve for the reservoir. However, substantial uncertainty exists in several of the inputs to the model, especially the inflow frequency curve. To account for these uncertainties, steps 1-6 are performed a large number of times with different parameters for the inputs. The input parameters are varied across *realizations*, and for each realization, steps 1-6 are repeated over a large number of *samples.* Thus, the full simulation with uncertainty will contain a number of events equal to the number of realizations times the number of samples. By varying parameters across realizations, the uncertainty in the probability of an event, for example reaching spillway crest elevation, can be better assessed. Each realization will produce an estimate of the probability of reaching this elevation based on the parameters used to drive the realization. Percentiles (for example the 5th and 95th percentiles) of these probabilities produce a confidence interval for the probability of reaching the spillway. If the mean probability of exceeding any stage is taken, then the result is the *expected frequency curve*, which is the single best estimate for the probability of exceeding a particular stage.

1.6 Data Analysis and Model Input

1.6.1 Inflow Hydrograph and Pool Stage

Estimate of daily average inflow discharges and pool elevations for the Nueces River Basin projects were retrieved from the City of Corpus Christi water management database system for WY 1943 through WY 2019. Records prior to project construction were simulated using RiverWare. The Nueces River Basin projects impoundment dates are shown in Table E.2. RiverWare software mimics a watershed by modeling its features as linked objects, including storage or power reservoir objects, stream reach objects, groundwater storage objects, or diversion objects. In a simple model, these objects simulate basic hydrologic processes through mass balance calculations and can be linked to one another through inflow-outflow calculations. More advanced modeling is achieved by selecting object-specific methods that further define the hydrologic processes associated with each object. Additionally, RiverWare may operate under a rule-based simulation, which creates logic-based interdependency of objects through user-defined rules. These rules may look forwards and backwards in time and given priorities in one rule may supersede others depending on the importance defined by the user. These detailed yet simple modeling techniques allow RiverWare to simulate reservoirs' pool elevations and inflow efficiently. The lakes hourly inflow hydrographs are shown in Figures E.3 and E.4. Figures E.5 and E.6 display selected data of observed and simulated daily average inflow and pool elevations for Lakes Choke Canyon and Corpus Christi.

Table E.2: Nueces River Basin Dams Deliberate Impoundment Dates

Project	Deliberate Impoundment Date
Choke Canyon Reservoir	October 1984
Lake Corpus Christi	September 1948

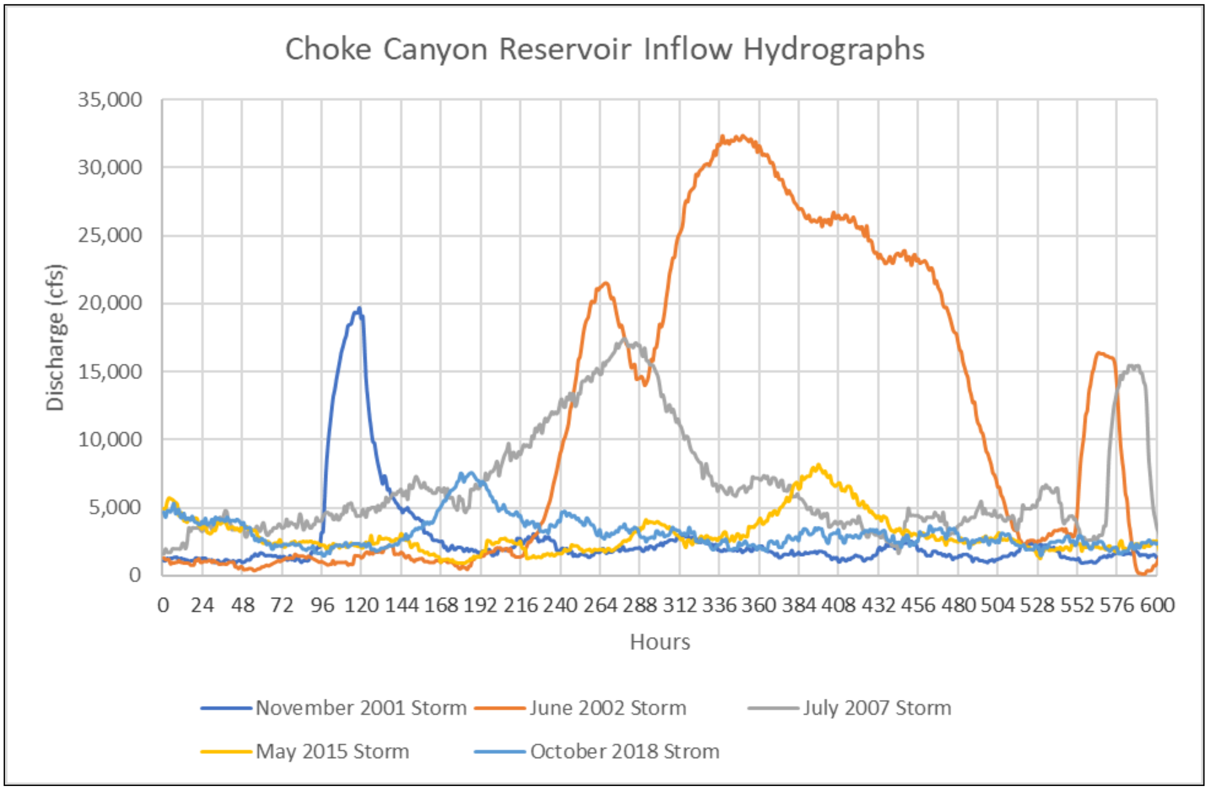

Figure E.3: Choke Canyon Reservoir Inflow Hydrographs

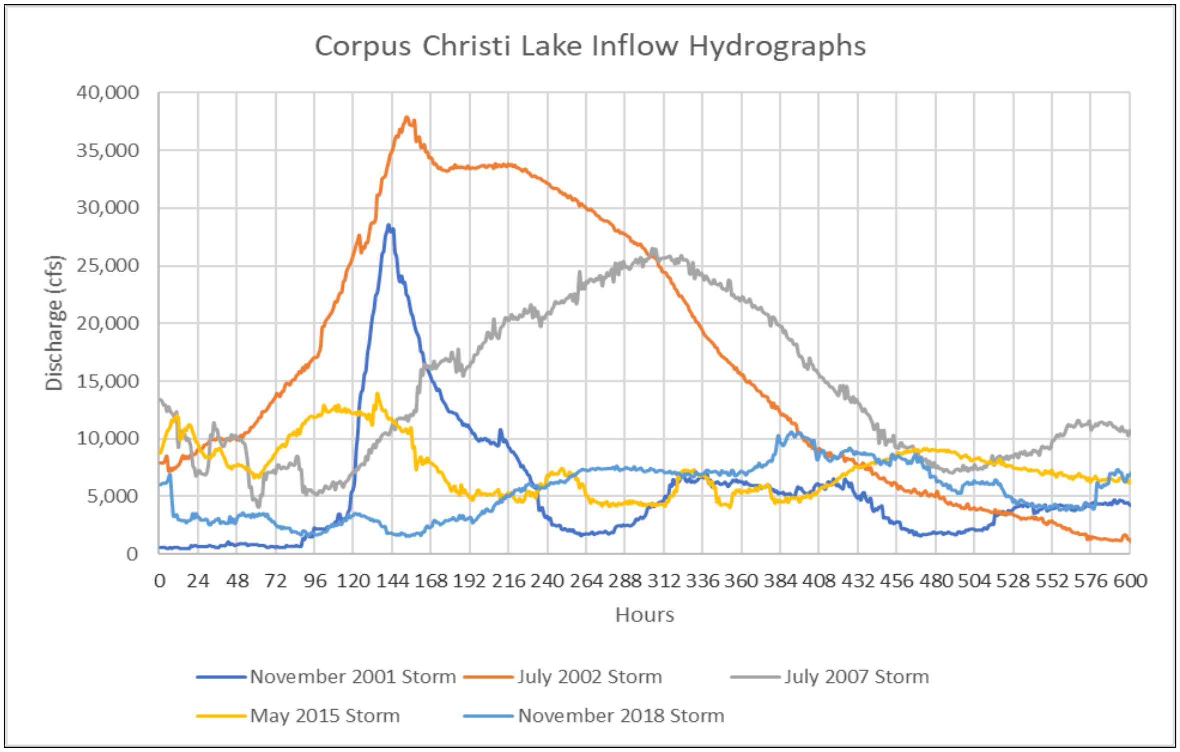

Figure E.4: Lake Corpus Christi Inflow Hydrographs

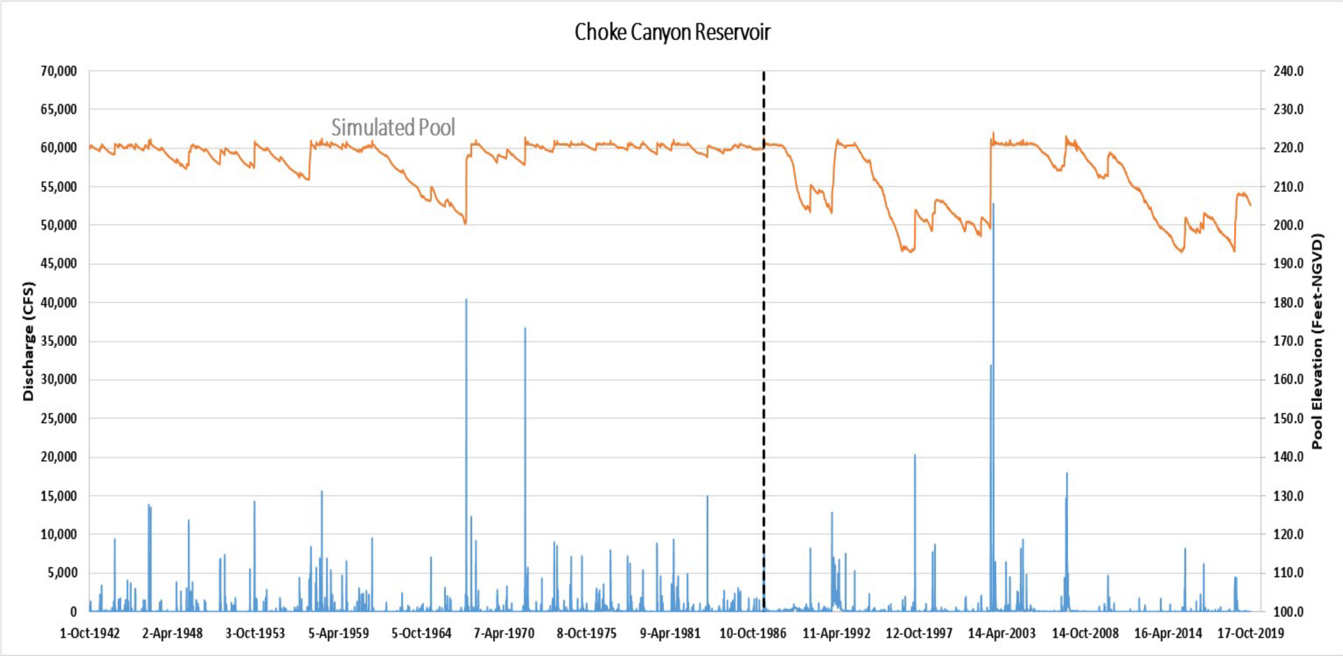

Figure E.5: Choke Canyon Reservoir Daily Average Inflow and Pool Elevation

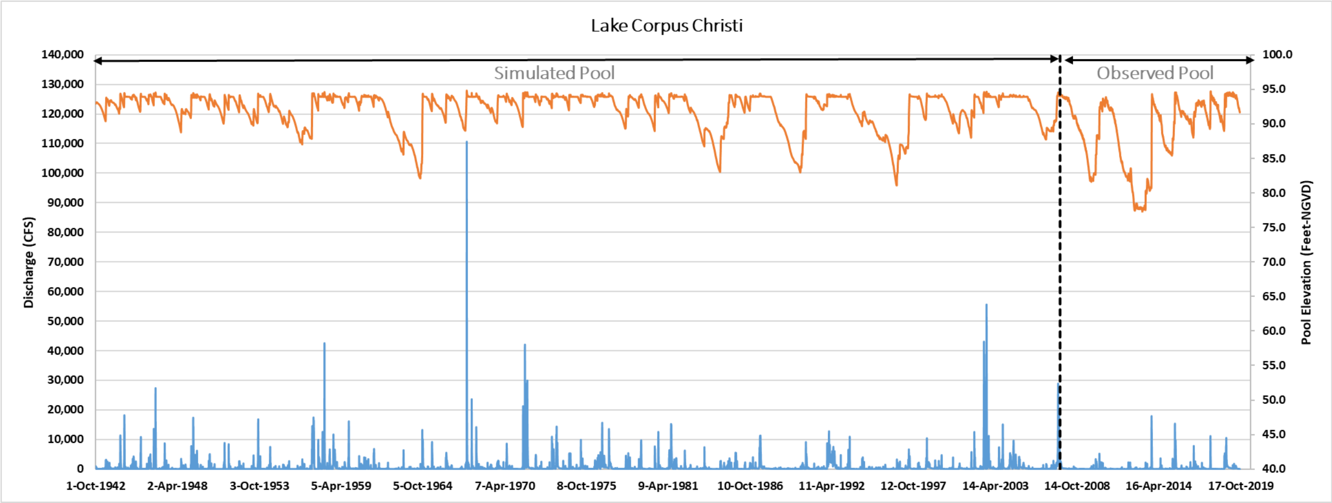

Figure E.6: Lake Corpus Christi Daily Average Inflow and Pool Elevation

1.6.2 **Historical Discharge Peak Estimates**

The lake inflow systematic record contains observed (recorded) post-dam construction inflow discharges and pre-dam construction synthetic inflow discharge years generated using RiverWare. Choke Canyon Reservoir inflow discharge peaks are annual maximum peaks for the POR 01 October 1915 through 30 September 2019. There were no historical inflow discharge peaks recorded prior to this period. Inflows to Lake Corpus Christi utilized the simulated inflow annual maximum discharge peaks for the POR 01 October 1942 through 30 September 2019. There were no additional independent inflow Historical discharge peaks recorded for the lake. For the simulated record, the largest inflow daily average maximum discharge peaks that stood out for both projects were the September (1967 and 2002) of 40,085cfs and 51,600cfs for Choke Canyon Reservoir; 109,550cfs and 55,140cfs, respectively, for Lake Corpus Christi.

1.6.3 **Daily Average AMS Estimates**

An extract of the n-day inflow discharge average maximum annual peak for each project was made available for the analysis. Choke Canyon Reservoir inflow AMS consists of discharge peaks extracted from USGS 08207000 Frio Rv at Calliham, Tex., USGS 08206700 San Miguel nr Tilden and USGS 08206600 Frio River at Tilden, Tex., combined, whereas Corpus Christi's AMS inflow is RiverWare simulation extract. Inflows to each lake were processed in HEC-DSS Vue to produce the 15-day AMS. The critical duration best estimate in days is shown in section 9.7.

1.7 Critical Inflow Duration Analysis

The critical inflow duration[11] can be defined as the inflow duration that tends to produce most consistently the highest water surface elevation for the reservoir. The critical inflow duration accounts for the most significant storm events, which are normally selected based on a screening criterion that capture project inflow hydrographs with a minimum threshold peak determined on a case-by-case basis (*i.e.,* Choke Canyon critical inflow duration minimum threshold peak is 8,000 cfs less than Corpus Christi's). The studied lakes are in the lower portion of the Nueces River Basin, where weather patterns and climate are similar. Rivers flowing to the lakes have flat slopes and wide floodplains, which allow for longer critical durations. The storm duration can also impact critical durations; longer storms result in longer critical durations. To determine critical inflow duration of the observed rainfall-runoff events, extreme rainfall runoff (inflow) events are examined. All large inflow events are independent, meaning that different year hydrographs can be presented in one figure to determine the proper critical duration. The duration peak inflow was used to determine a reasonable value for critical inflow duration. Although this method was found accurate to produce good estimates, the critical duration can be adjusted later during the analysis to reflect the most appropriate frequency curve. Best engineering judgment remains necessary in the final selection of the most appropriate value. For each project, a set of historical inflow events (hydrographs) with daily peak inflows greater than a certain threshold were extracted from USGS gages or RiverWare simulated daily average inflow period of record (*i.e*., examine the top 20% largest independent inflow events for each project inflow). The best-estimate inflow duration for the reservoir is estimated in two ways. First, by taking the average hydrograph of the major events specified. Figures E.7 and E.8 illustrate the lakes inflow critical durations best estimates excluding baseflow. Second, Identify the most extreme historical peak reservoir events as seen in Table E.3. Then, locate the reservoir inflow, stage, and discharge hydrographs corresponding to each peak stage event. Select events that are consistent with the types of events likely to be the driver of extreme peak stages. Reservoir peak stage occurs when the reservoir outflow equals the inflow on the receding limb of the inflow hydrograph. Figure E.9 is an example of one selected event, which illustrates the visual procedure of the second method. Best estimates of the n-day critical durations for the projects are listed in Table E.3. These results were finalized after making several sensitivity analyses while running the RMC-RFA program. The best critical duration estimate produced the most conservative elevation frequency in the lake. The purpose of this analysis is to have a better understanding of the runoff response from large single rain events that helps establish what inflow volume discharge frequency curves need to be examined.

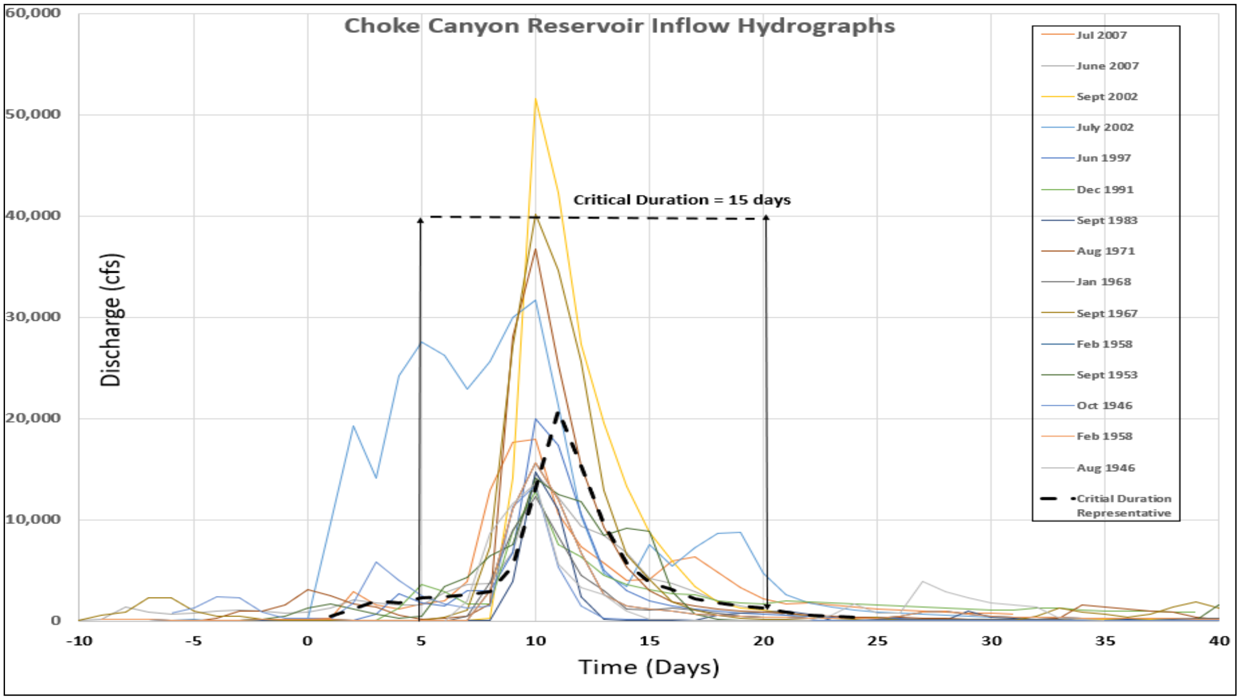

Figure E.7: Choke Canyon Reservoir Critical Duration Inflow Analysis

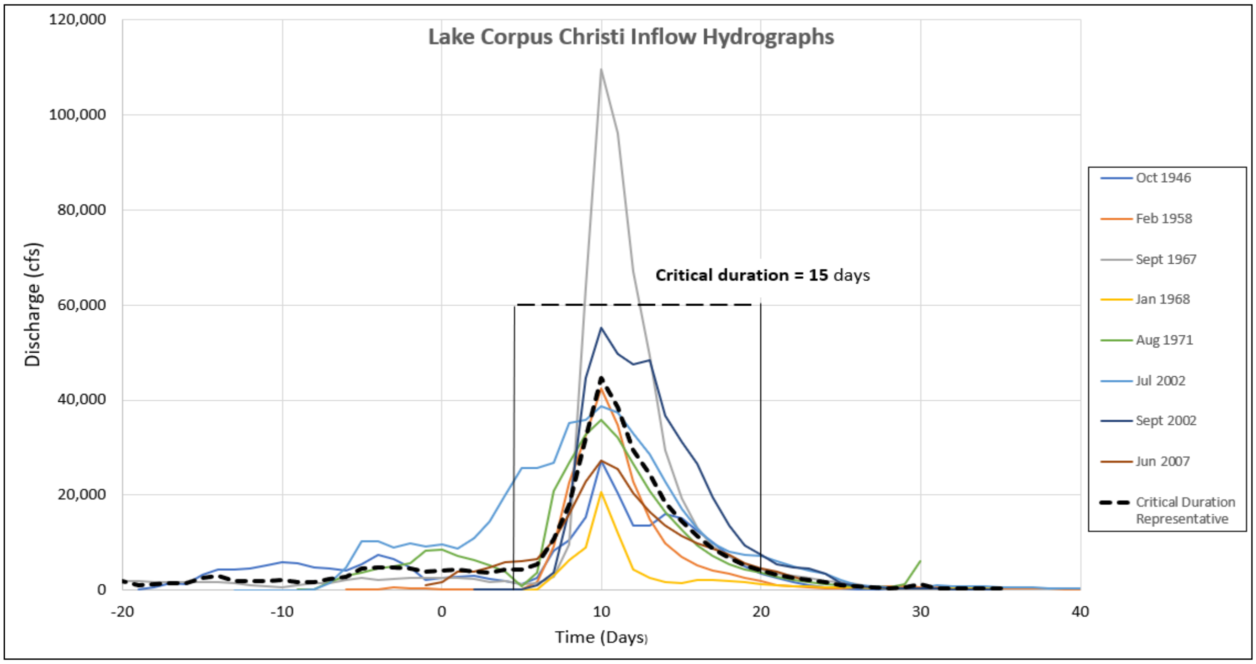

Figure E.8: Lake Corpus Christi Critical Duration Inflow Analysis

Table E.3: Nueces River Basin Inflow Duration Analysis

Project	Inflow Duration Method		
	Minimum Threshold Peak (CFS)	Number of Analyzed Inflow Events	Critical Duration (Days)
Choke Canyon Reservoir	12,000	15	15
Lake Corpus Christi	20,000	8	15
Project	**Inflow-Outflow Coincidental Hydrograph Method**		
	Event Date	**Number of Analyzed Inflow Events**	**Critical Duration (Best Estimate, Days)**
Choke Canyon Reservoir	Oct46, Sep53, Feb58, Sep67, Jan68, Aug71, Oct83, Dec91, Jun97, Jul02, Sep02, Jul07, Sep07	13	15
Lake Corpus Christi	Feb58, Sep67, Jan68, Aug71, Jul02, Sep02, Jun07	7	15

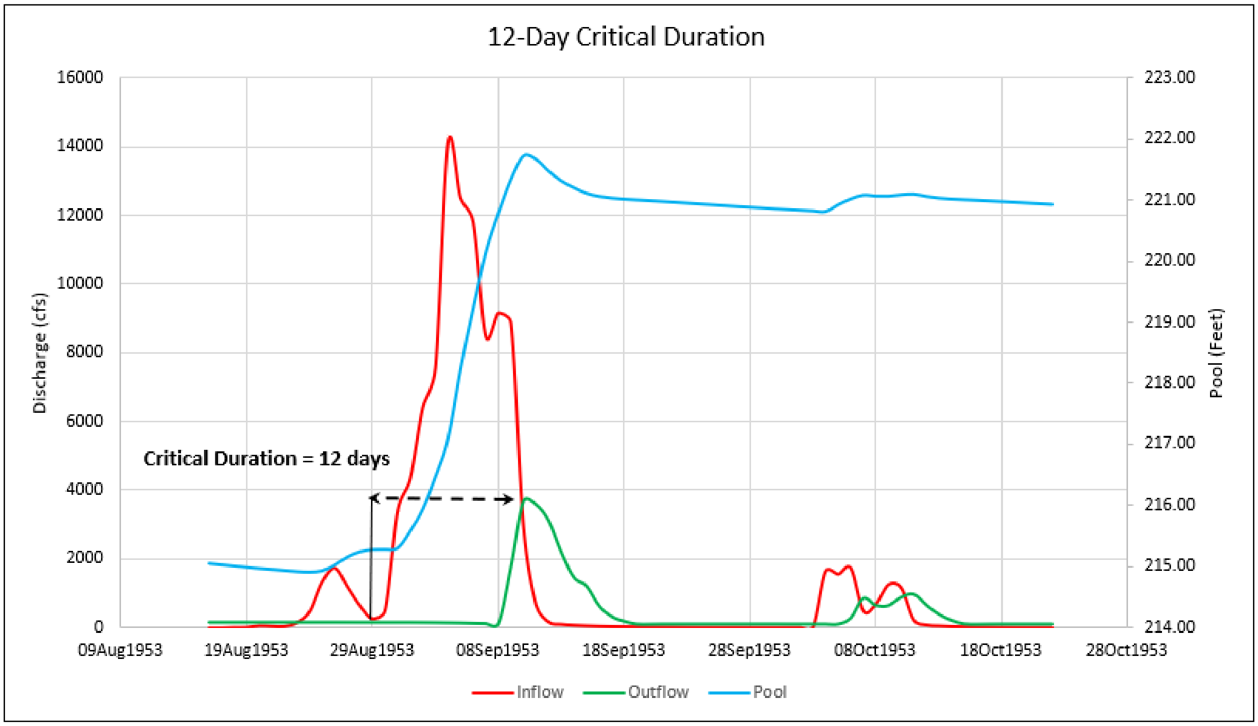

Figure E.9- September 1953 Flood Event for Choke Canyon Reservoir

1.7.1 Volume/Flow Frequency Statistical Analysis

The volume/flow frequency analyses for the Nueces River Basin Lakes were estimated by following Bulletin 17C guidelines and procedures (statistical techniques) to determine exceedance probabilities associated with specific flow rates utilizing HEC-SSP 2.2. The observed and simulated daily average annual maximum peaks were used to establish a relationship between flow magnitude and frequency. In this chapter, the term volume/flow frequency refers to the frequency with which a flow over a given duration, such as 15-Day expected to be equaled or exceeded. The duration selection was based on inspecting the shape of the hydrographs such as those shown in Figures E.7, E.8, and E.9. The critical durations best estimate are listed in Table E.3. To adequately assess the risk associated with the Nueces River Basin Dams' structures in question, the 15-Day critical duration was used to construct hypothetical inflow frequency events for Choke Canyon Reservoir and Lake Corpus Christi. The events were routed through the projects to estimate reservoirs' stage-frequency curves.

1.7.2 **Bulletin 17B/C**

The use of bulletin 17C guidance allows for computations of the annual exceedance probability of the instantaneous and daily average inflow discharge peaks, using the Expected Moments Algorithm (EMA). It estimates distribution parameters based on sample moment in a more integrated manner that incorporates non-standard, censored, or historical data at once, rather than as a series of adjustment procedures[4]. It should be noted that Bulletin 17B procedures and guidelines would produce similar results if Bulletin 17C procedures were followed since historical interval peaks were not available. In this chapter, Bulletin 17C procedures were followed for the analysis.

1.7.3 **HEC-SSP Computations**

A series of n-day volume duration frequency curves was developed for each of the Nueces River Basin projects. The volume duration frequency results from this analysis were developed using HEC-SSP. The Multiple Grubbs-Beck algorithm was used to perform sensitivity analysis for the low outlier test. Plotting position of the data follow the Log-Pearson III plotting position algorithm distribution. The station skew option was used for the analysis for the projects using the systematic records. For consistency, each developed frequency curve went the same analysis techniques before adoption. Table E.4 contains skews and record lengths for each project analyzed using HEC-SSP.

Table E.4: Summary of HEC-SSP Input Parameters

Project	Systematic Record (years)	Station Skew (Critical Duration)
Choke Canyon Reservoir	104	-0.347
Lake Corpus Christi	77	+0.109

Note: The actual systematic record length is less than the systematic record length shown in the Table. The actual systematic record length was extended utilizing USGS and RiverWare.

The Nueces River Basin Lakes computed frequency flows from HEC-SSP are listed in Table E.5. The statistical parameters generated based on applying the Bulletin17C method, station skews, and low outlier tests for Multiple Grubbs-Beck are listed in Table E.6. Only pertinent critical durations were listed for each project.

Table E.5: Nueces River Basin Lakes Bulletin 17C Computed Median Inflows

N	ACE	Bulletin 17C AMS Computed Average (Median) Peaks (CFS)	
Years	%	Choke Canyon Reservoir	Lake Corpus Christi
		15-Day	15-Day
500	0.2	25,850	74,830
200	0.5	20,260	55,040
100	1	16,435	42,820
50	2	12,970	32,620
20	5	8,935	21,800
10	10	6,310	15,310
5	20	4,050	10,040
2	50	1,615	4,560

Table E.6: Nueces River Basin Lakes Bulletin 17C Computed Median Inflow Statistics

Statistics	Computed Statistics	
	Choke Canyon Reservoir	Lake Corpus Christi
	15-Day	15-Day
Mean	3.180	3.666
Standard Deviation	0.501	0.401
Station Skew	-0.347	+0.109
Historical Events	None	None
Low Outlier	18	17
Missing Flow	0	0
Systematic Events	104	77
Effective Record Length	86	60

1.8 RMC-RFA Data Input

1.8.1 Inflow Hydrographs

Several inflow hydrographs were selected to route through RMC-RFA. The particular years of which reservoir inflow hydrographs were routed are:

Choke Canyon Reservoir and Lake Corpus Christi:
Available hourly inflow hydrographs for November 2001, June 2002, July 2007, May 2015, and October 2018.

The selected hydrographs' characteristics represent different hydrograph shapes (from peaky to large volume events) seen at the Nueces River Basin Lakes. However, the selection of particular hourly hydrographs was determined by using the hydrographs that influence the best pool frequency curve estimate through RMC-RFA. The selected hourly hydrographs for both lakes are shown in Figure E.10.

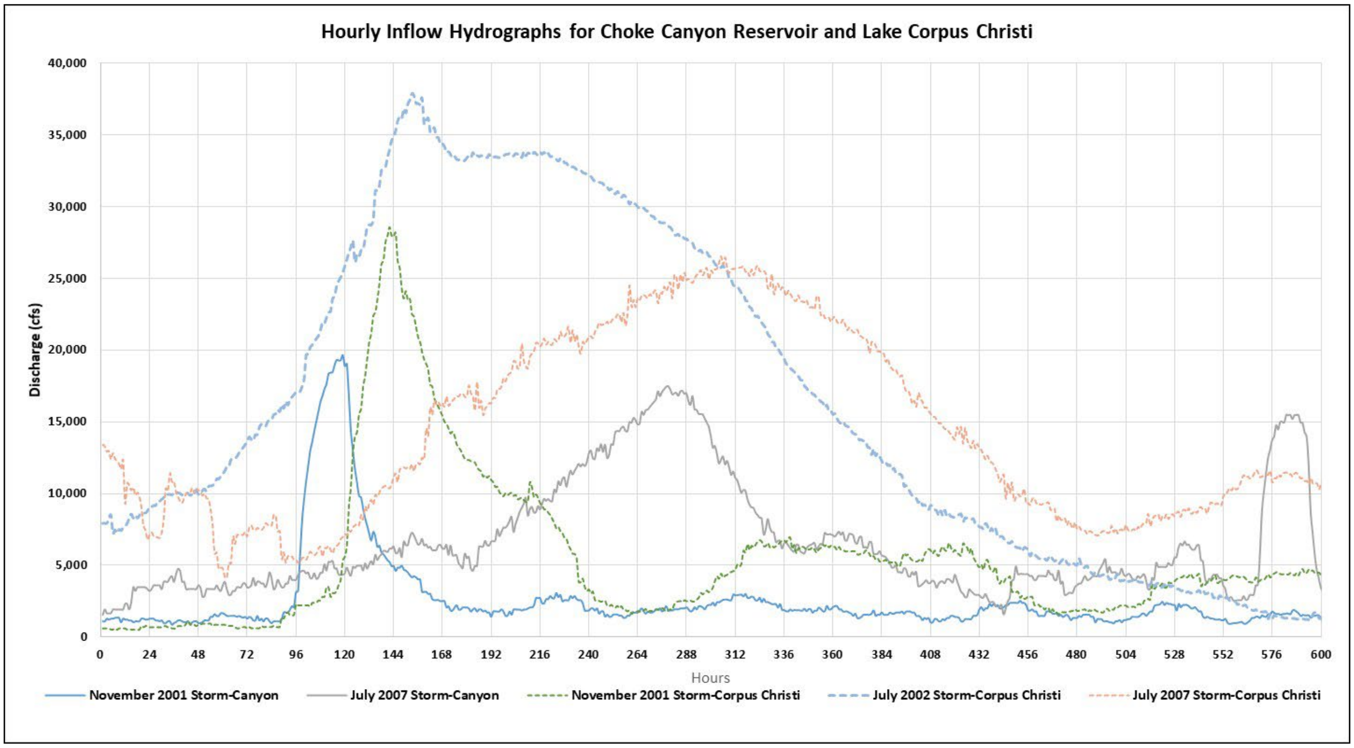

Figure E.10: Choke Canyon and Lake Corpus Christi Inflow Hydrographs

1.8.2 **Volume Frequency Curve Computation**

The computed volume frequency statistical parameters shown in Table E.6 were fed into the RMC-RFA program to produce the n-day duration inflows for all projects. As stated in the HEC-SSP computations section, Bulletin 17C procedures and guidelines were followed to produce the inflow volume discharge frequencies. Plots of the 15-Day inflow discharge frequency curves for the Nueces River Basin Lakes are shown in Figures E.11 and E.12.

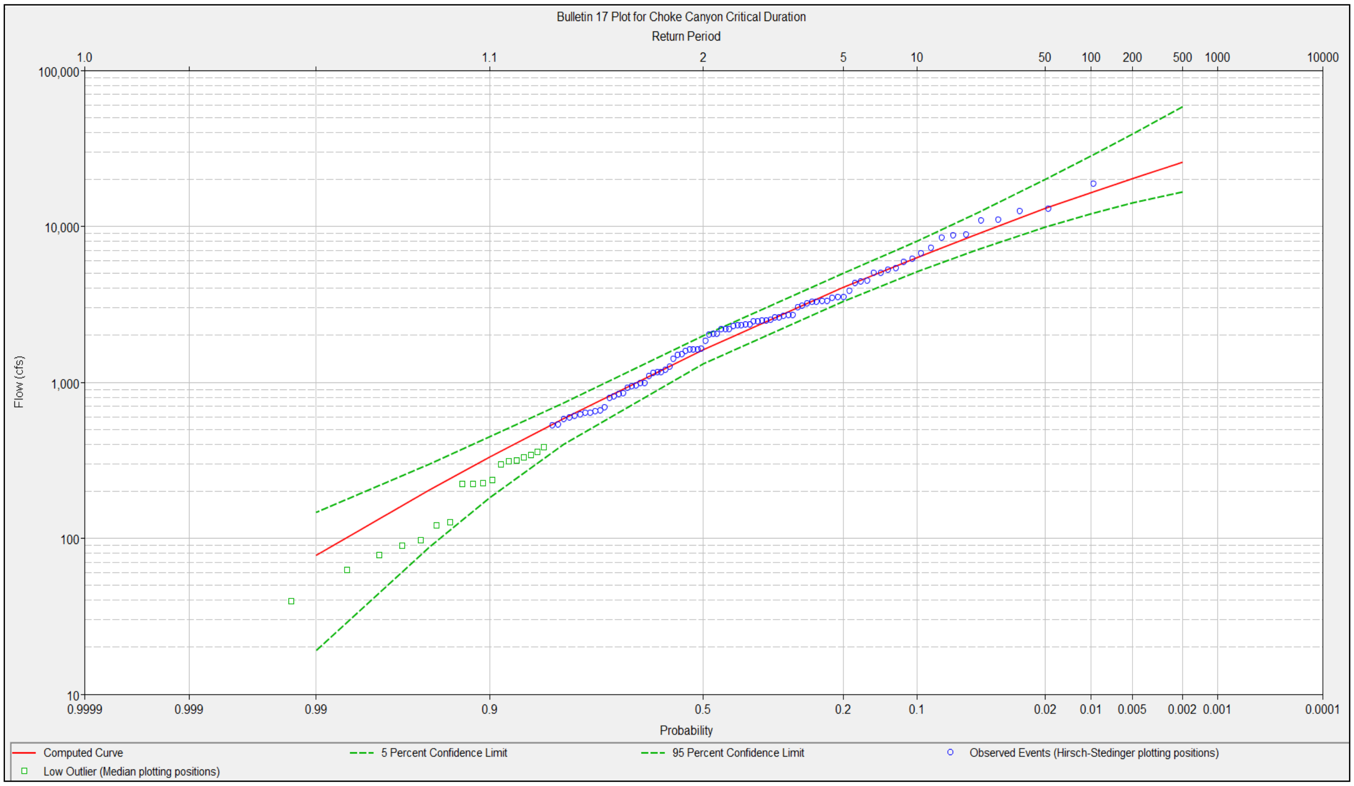

Figure E.11: Choke Canyon Reservoir Computed 15-Day Volume Frequency Curve

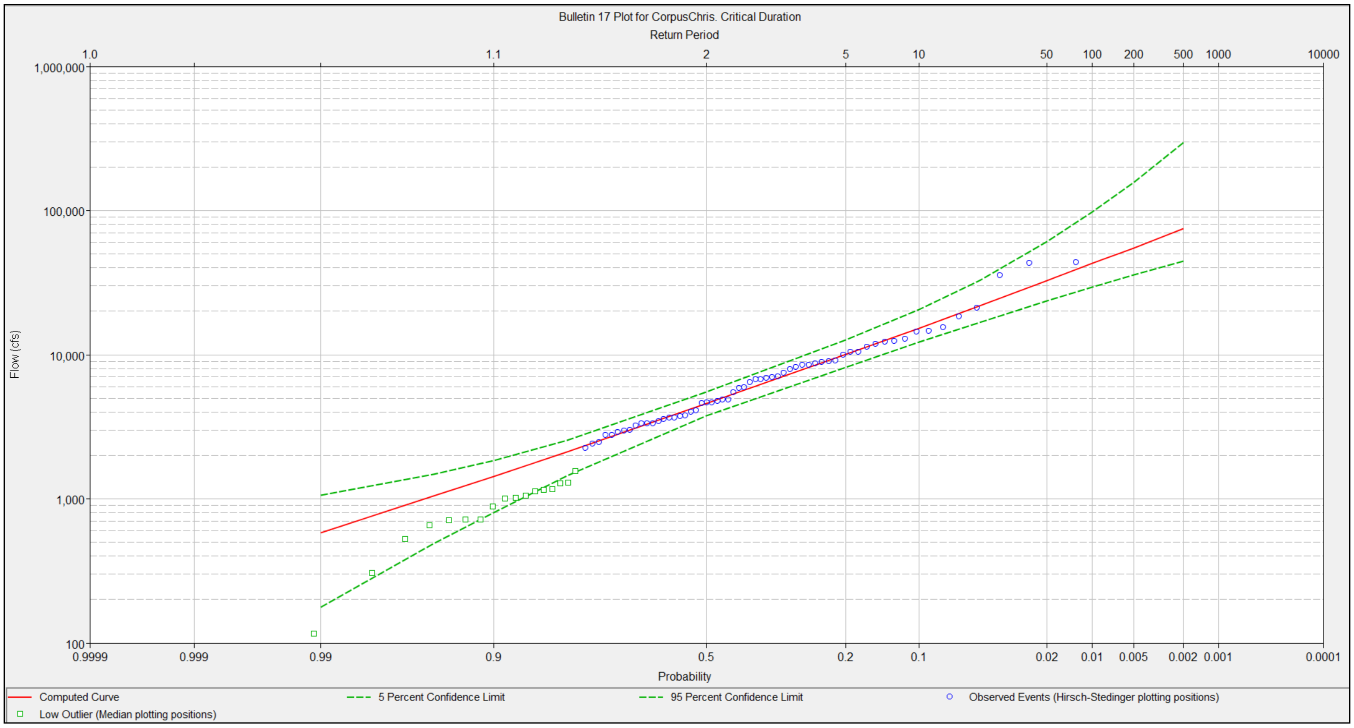

Figure E.12: Lake Corpus Christi Computed 15-Day Volume Frequency Curve

1.9 RMC-RFA Analyses

1.9.1 Flood Seasonality

Many reservoirs have operations (pool level) that vary by season in response to the cyclical changes in meteorology and hydrology throughout the year. The inflow pattern at the Nueces River Basin Lakes have three general types of flood-producing rainfall: thunderstorms, frontal rainfall, and tropical cyclones. Generally, the highest 24-hour and monthly precipitation periods have occurred during tropical cyclones. However, there are some instances of heavy precipitation resulting from local thunder storms. It should be noted that thunderstorms can occur at any time of the year and tropical storms can happen between June and November. Due to meteorological and hydrologic conditions, most significant floods occur during late spring, summer, and fall months.

The term *flood seasonality* is intended to describe the frequency of occurrence of rare floods on a seasonal basis, where a rare flood is defined as any event where the flow exceeds some user specified threshold for a specified flow duration. In the RMC-RFA model operation, a month of flood occurrence is first selected at random according to the relative frequency. Once the month of flood occurrence is specified, a starting pool elevation for the event can be determined from the reservoir stage-duration curve for that particular month. This approach ensures that seasonal variation in reservoir operations is a part of the peak-stage simulation.

The flood seasonality analysis is performed two (2) ways: 1) Assign critical n-day flood seasonality, threshold flow, maximum events per year, and minimum days between events. With these criteria, a total number of events can be calculated. It should be noted that the critical duration used could be different from the volume frequency curve adopted critical duration. 2) Screen out annual maximum peak reservoir pool elevations for the period of record. Peak reservoir pool elevations are the result of significant inflow events and variation of reservoir pool operations. A sensitivity analysis can be done to determine which method applies best when running the RMC-RFA; this is done to obtain the best starting pool answer corresponding to the most frequent events for each month. Projects of which the flood seasonality input parameters were applied (method 1) are listed in Table E.7. A list of results obtained by method 1 were also included in Table E.8. The relative frequencies shown in Table E.8 can be presented in a plot format (Figures E.13 and E.14).

Table E.7: Flood Seasonality Parameters Input Method

Project	Critical Duration (Days	Threshold Flow (CFS)	Minimum Days Between Events	Maximum Number of Events
Choke Canyon Reservoir	15	2,000	4	6
Lake Corpus Christi	15	4,000	6	7

Table E.8: Reservoir Stage AMS Peak Analysis and Parameter Input Method Results

Month	Relative Frequency by Stage (Method 1)			
	Choke Canyon Reservoir		Lake Corpus Christi	
	Freq.	Relative Frequency	Freq.	Relative Frequency
January	2	0.027	2	0.021
February	3	0.041	3	0.031
March	3	0.041	2	0.021
April	0	0.000	0	0.000
May	9	0.123	7	0.073
June	8	0.110	16	0.167
July	21	0.288	16	0.167
August	4	0.055	7	0.073
September	10	0.137	10	0.104
October	10	0.137	21	0.219
November	3	0.041	11	0.115
December	0	0.000	1	0.010

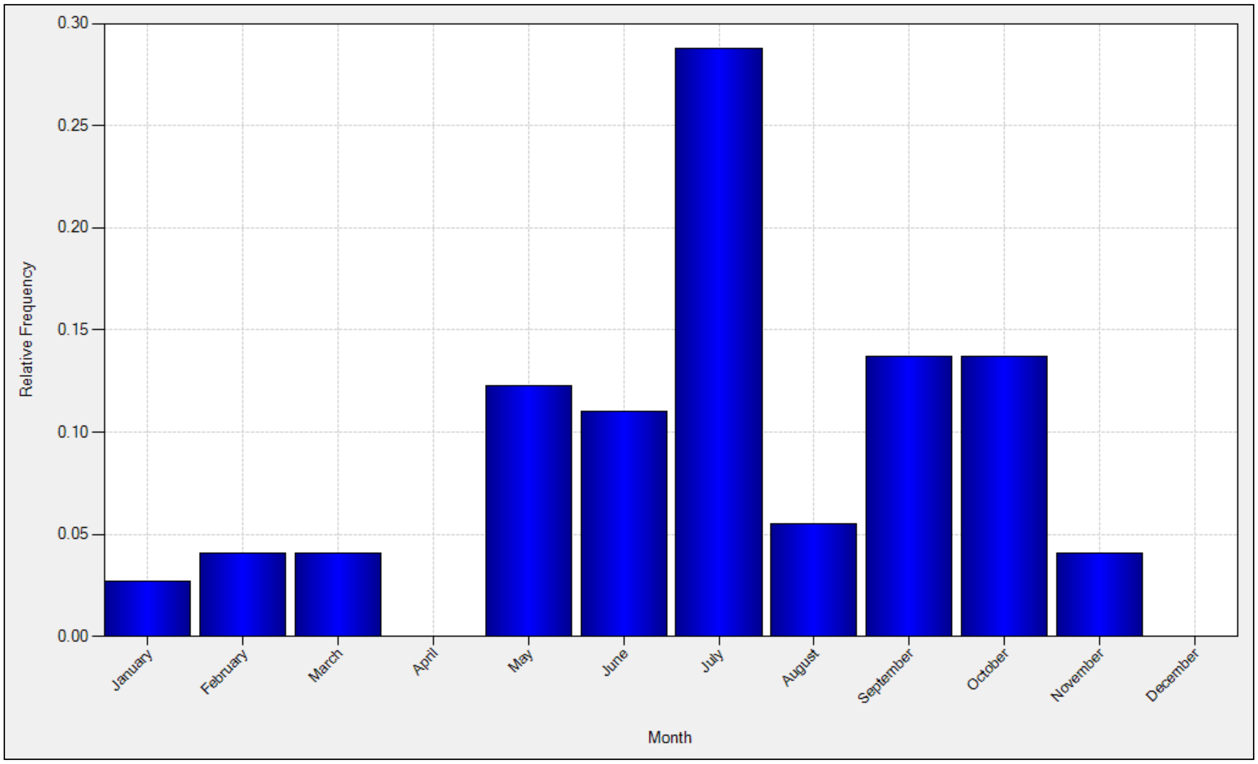

Figure E.13: Choke Canyon Reservoir Histogram of RMC-RFA Relative Frequency Output

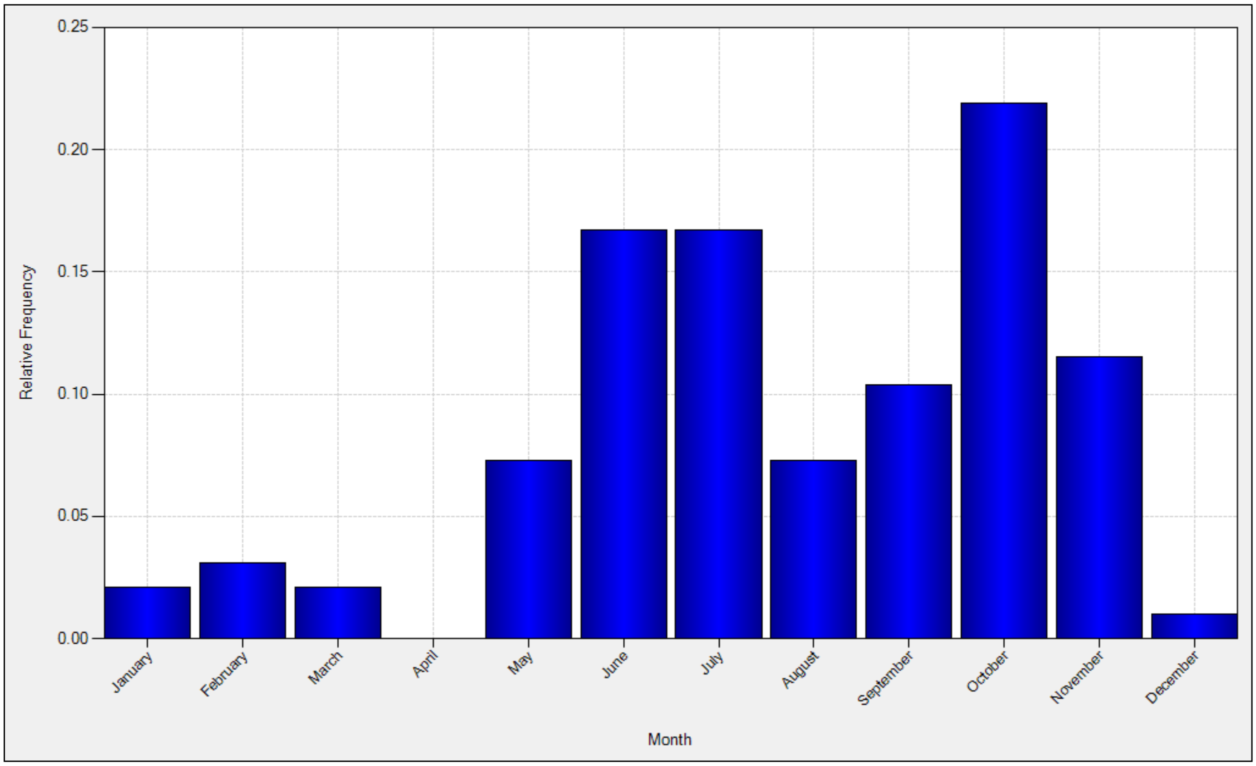

Figure E.14: Lake Corpu Christi Histogram of RMC-RFA Relative Frequency Output

1.9.2 Reservoir Starting Stage

Reservoir starting pool duration curves represent the percent of time during which particular reservoir pools are exceeded. Reservoirs starting stage were estimated by analyzing pool elevations by first filtering observed daily average pools, so that they only represent typical starting pools based on a pool change threshold. Then, the filtered data set is stored by month or season. Because RMC-RFA chooses a starting pool elevation for its simulations based on historic data, the historic data must be filtered so that it is not influenced by flooding events. Starting pool elevations should form the basis for flooding events, not be the result of said events. Therefore, historic pool elevations were filtered with pool change thresholds and typical high (flood) pool durations that are reservoirs dependent (Table E.9). This filtered stage data now forms the basis for the starting pool elevation for the RMC-RFA reservoir simulation. A sensitivity analysis was performed, and the model's produced starting stage was not impacted by varying the pool change threshold and typical high pool values. The reservoirs final starting stage duration curves for the lakes are shown in Figures E.15 and E.16.

Table E.9: Nueces River Basin Reservoir Starting Stage Duration Input

Project	Average Pool Change Threshold (Feet)	Typical high Pool duration (Days)
Choke Canyon Reservoir	14	6
Lake Corpus Christi	12	7

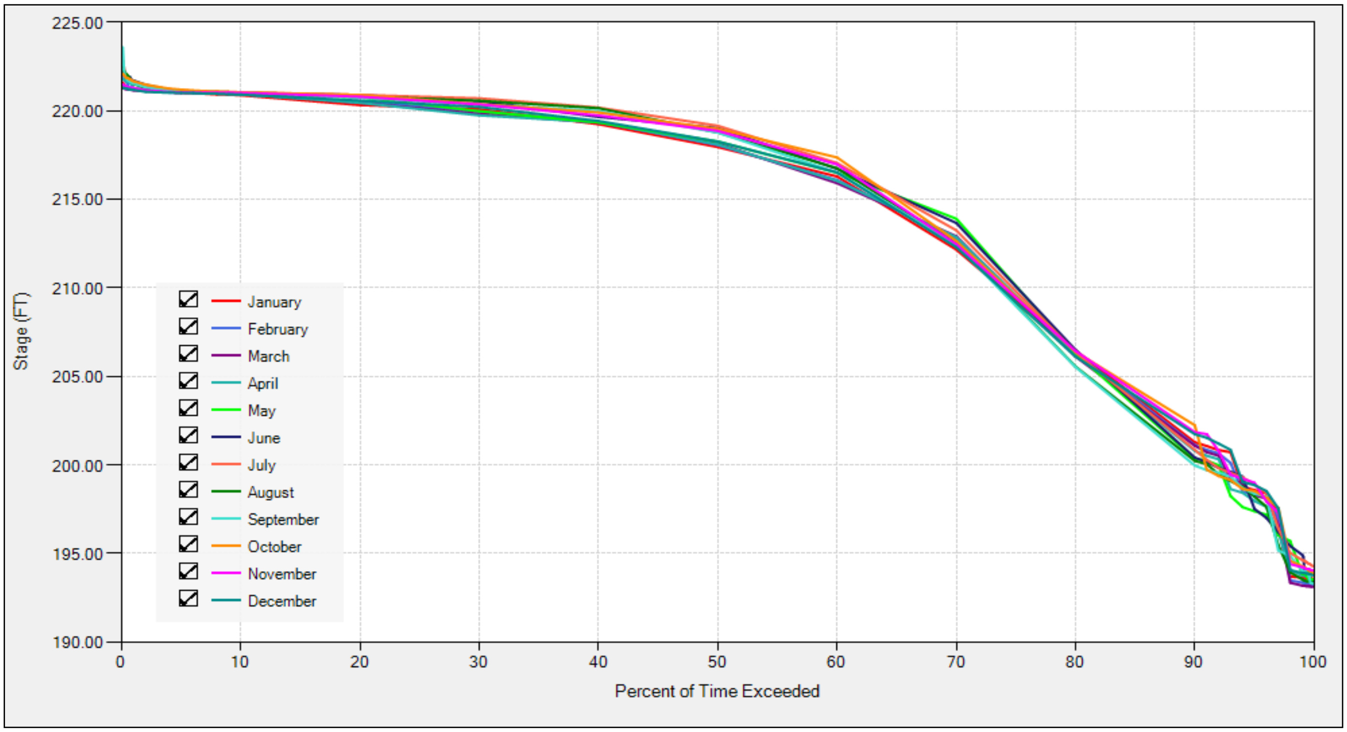

Figure E.15: Choke Canyon Reservoir Starting Stage Durations

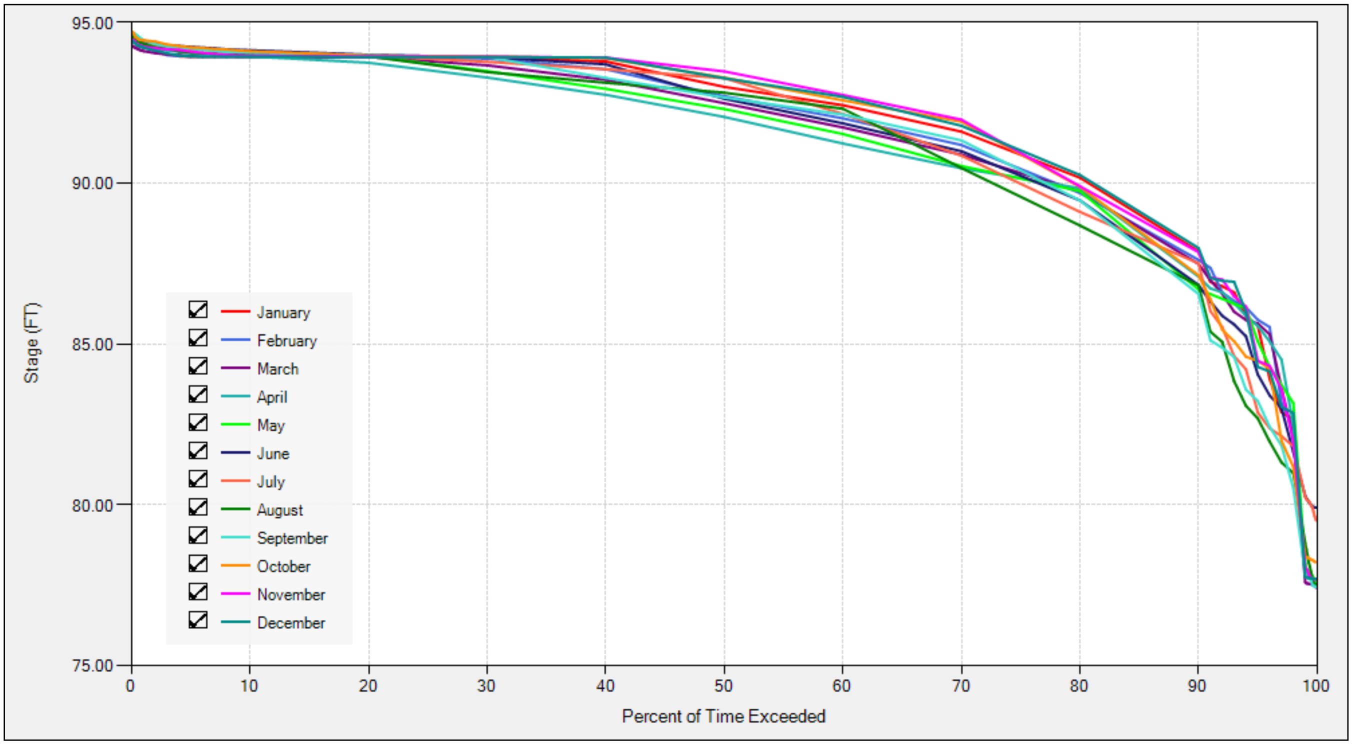

Figure E.16: Lake Corpus Christi Starting Stage Durations

1.9.3 Empirical Frequency Curve

For the evaluation of hydrologic hazards of each project, an extreme-value series of annual maximum stage was generated from the n-year systematic (RiverWare + Observed) period of record. The RiverWare simulated pool elevation peaks were used either prior to dam impoundment dates when the observed pool elevation peaks were not available, or if occurred due to irregular operations (e.g., emergency drawdown), for an intent of extending pool record. Each POR annual maximum series was extracted, the AMS was ranked, and it was plotted on log probability paper using the Weibull plotting position formula shown in Section 9.5.1. Figures E.17 and E.18 are Lakes Choke Canyon and Corpus Christi empirical pool frequency relationship, when applying the Weibull plotting positions. The systematic frequency peaks for the projects were plotted against the RMC-RFA expected pool frequency data points, see Section 10.0 plots. The plotting position of the highest and lowest points are the most uncertain due to having insufficient record lengths necessary to inform accurate plotting positions at the extremes. For each project, a duration frequency plot comparison between annual maximum pool elevations for: Observed, simulated (RiverWare), and combined (RiverWare + Observed), were made using the Weibull plotting position formula. Figures E.19 and E.20 are illustrations of the distribution comparison for the lakes. In general, longer observed pool record tends to show good distribution and match well when plotted against the extended pool record. Shorter observed pool record increases uncertainty and shifts the distribution from being more representative for rarer frequencies. An example of pool with short record (35 years of observed pool data) is Choke Canyon Reservoir (Figure E.19). Notice the distribution shifts to the right side and coarser data point plotting position. Selections of pool peaks are based on normal operations to ensure homogeneity. For Lake Corpus Christi, the observed pool for the period of WY2007 through WY2019 will be selected over simulated to perform statistical analysis, but simulated pool peaks will be analyzed for periods prior to WY2007. This approach ensures that the analyzed data is homogenous and valid for statistical analysis. This is also because of changes to reservoir operations were due to structural instability.

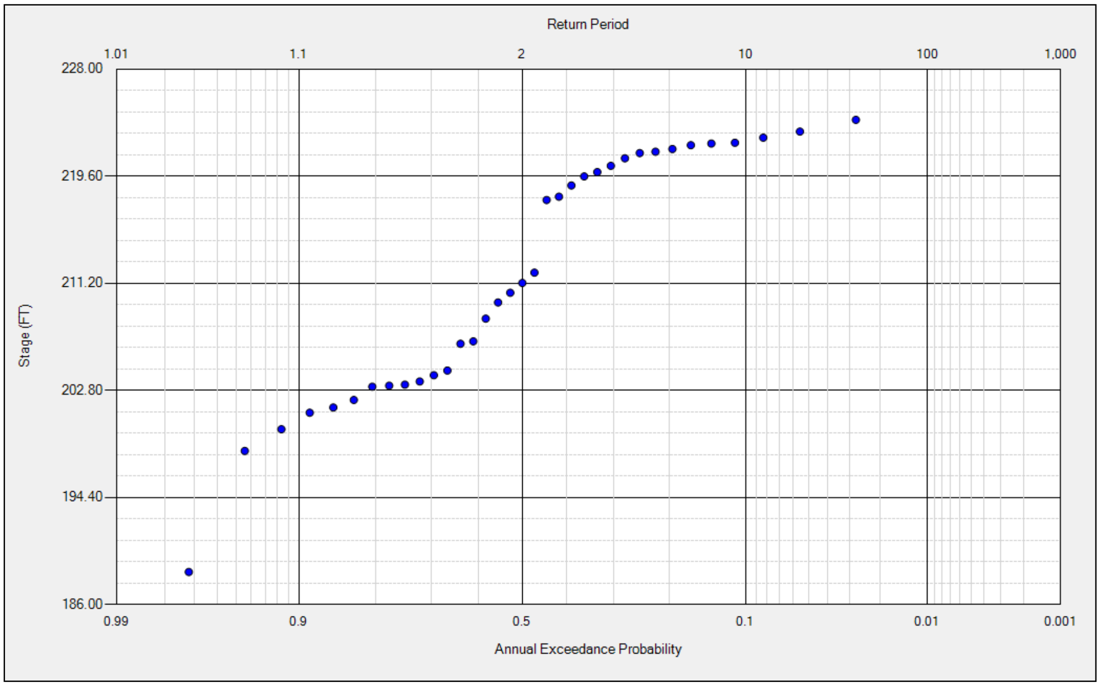

Figure E.17: Stage Duration Frequency for Choke Canyon Reservoir

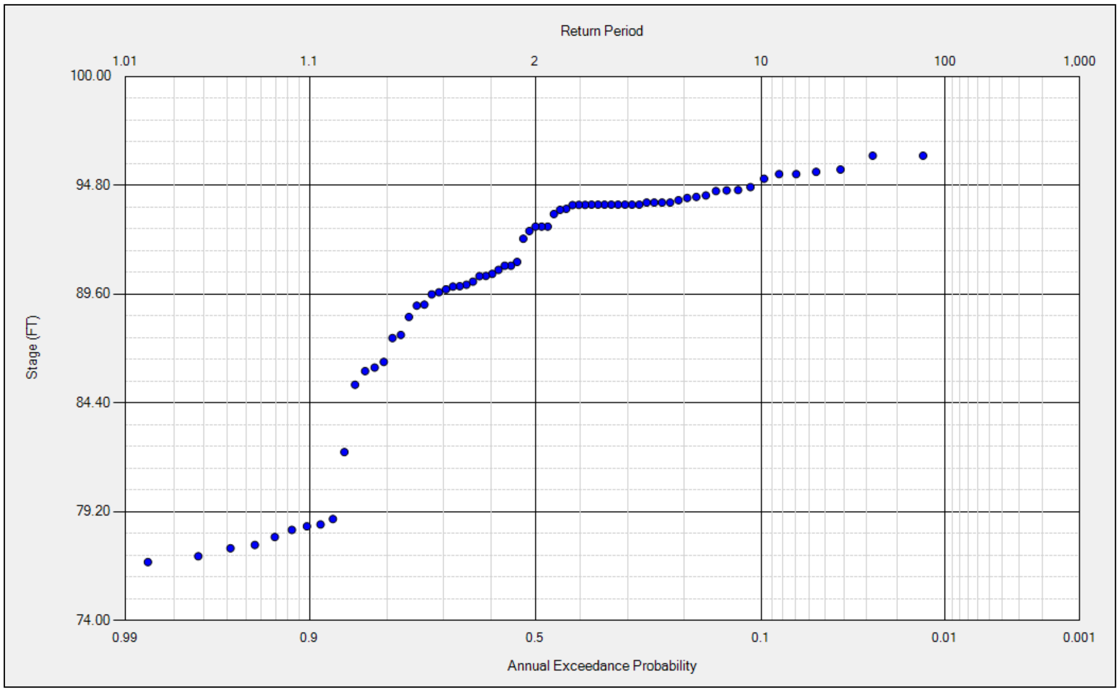

Figure E.18: Stage Duration Frequency for Lake Corpus Christi

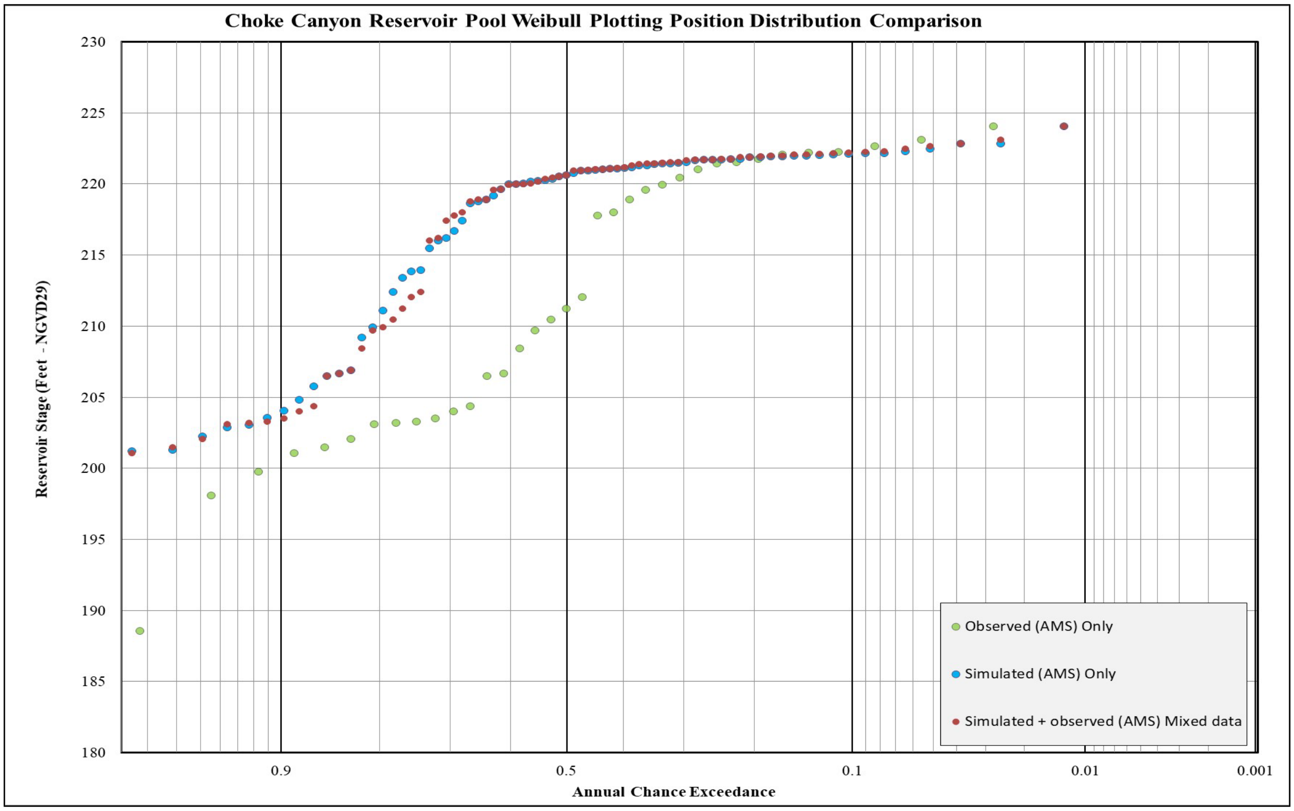

Figure E.19: Illustration of Choke Canyon Reservoir AMS Pool Weibull Plotting Position Distributions

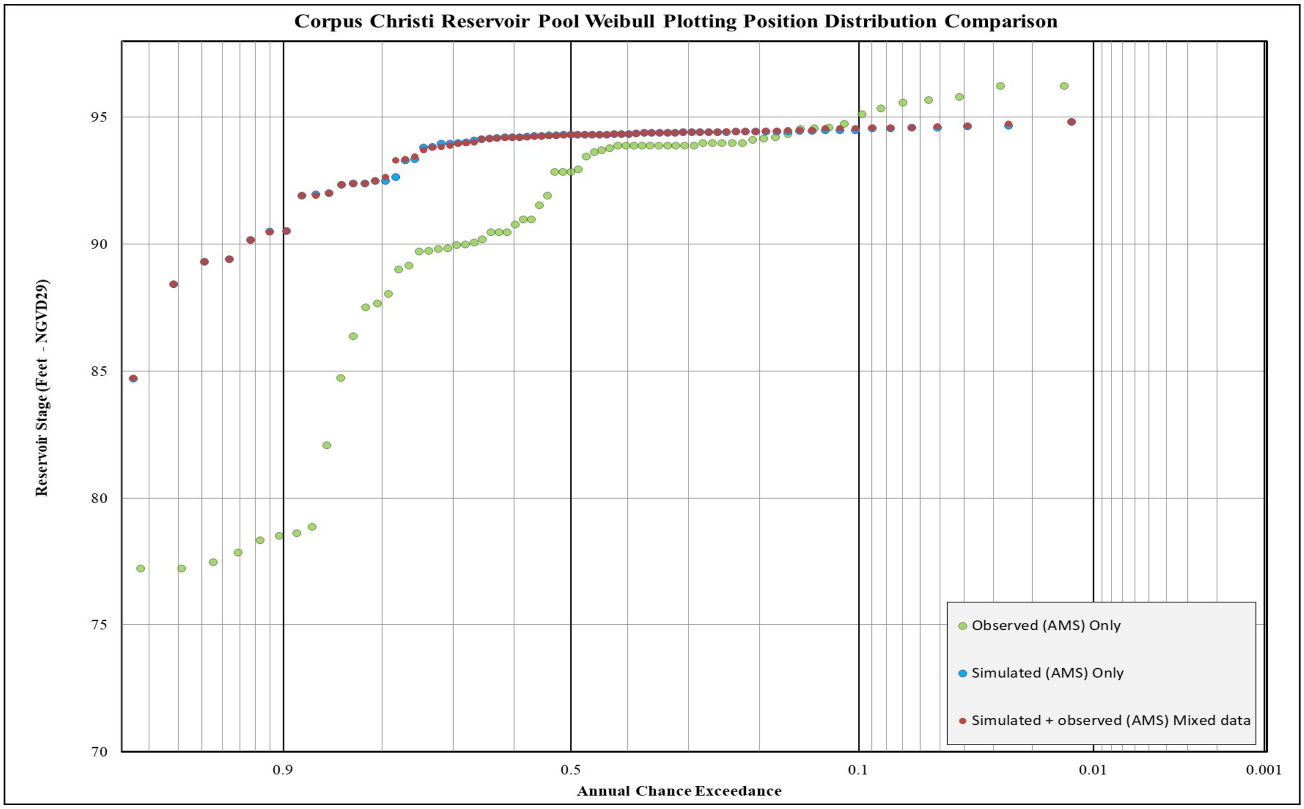

Figure E.20: Illustration of Lake Corpus Christi AMS Pool Weibull Plotting Position Distributions

1.9.4 Reservoir Model

The reservoir details such as top of dam and spillway elevations were obtained from the water data for Texas digital library. Volumetric surveys of both reservoirs were accomplished to update storage information. This was done using current GPS, acoustical depth sounder, and GIS technology. Data was then gathered and processed to generate the stage-storage curves for the reservoirs. The information is needed in order for the simulation to run. The volumetric and sedimentation survey (mostly up to conservation) of the lakes were completed in 2013 for Choke Canyon Reservoir and 2016 for Lake Corpus Christi. The Texas Water Development Board digital library was used to retrieve capacity data for elevation below 220ft-NGVD for Choke Canyon Reservoir, and elevation below 94 ft-NGVD for Lake Corpus Christi. Elevation above 220ft-NGVD for Choke Canyon used the original area (capacity) data of 1992. For Lake Corpus Christi, extension above 94 ft-NGVD was calculated by the SWD studies group using the area-average method for data obtained from Frees and Nichols. The Nueces River Basin projects' releases are stage dependent. Therefore, a stage-storage-discharge (release) function can be estimated. The Storage-Elevation and Discharge (Release)-Elevation curves for the projects are shown in Figures E.21 and E.22. More details about reservoir features are listed in Table E.10.

Table E.10: Nueces River Basin Lakes Features

Project	Choke Canyon Reservoir	Lake Corpus Christi
Pertinent Feature	Elevation (NGVD-Feet)	
Top of Dam	241.0	106.0
Top of Flood (Control Pool)	> 220.5*	94.0
Spillway Crest	199.5	94.0 South side 94.5 North side
Top of Conservation Pool	220.5	< 94.0

*This is the surcharge pool for Choke Canyon Reservoir since the lake has no flood pool

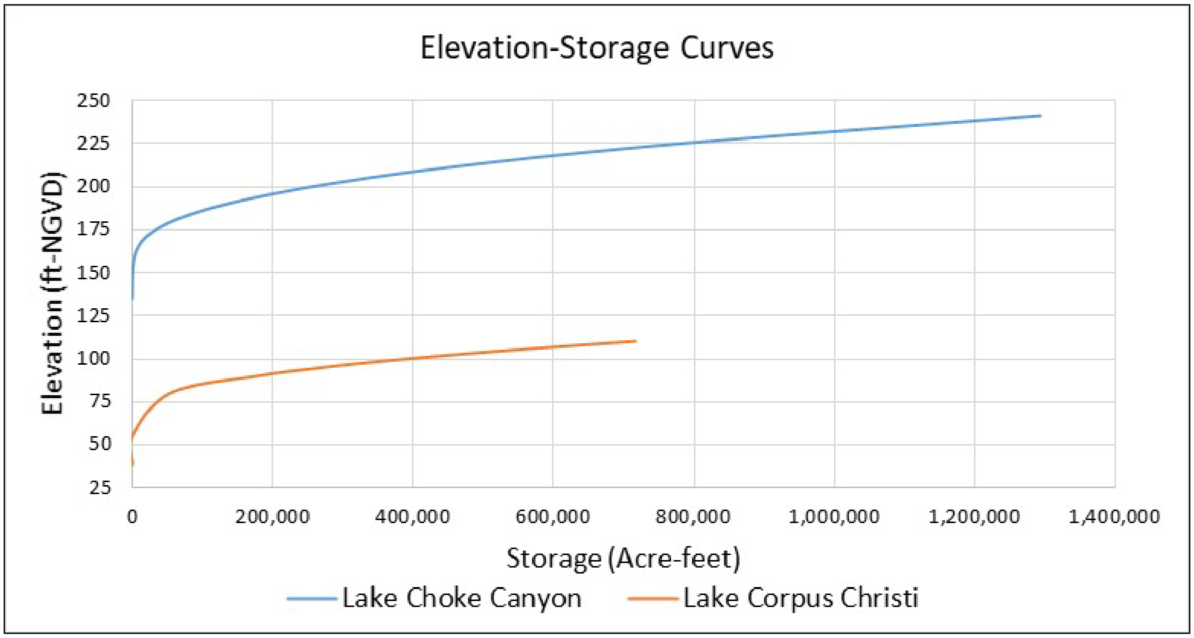

Figure E.21: Nueces River Basin Lakes Storage-Elevation Curves

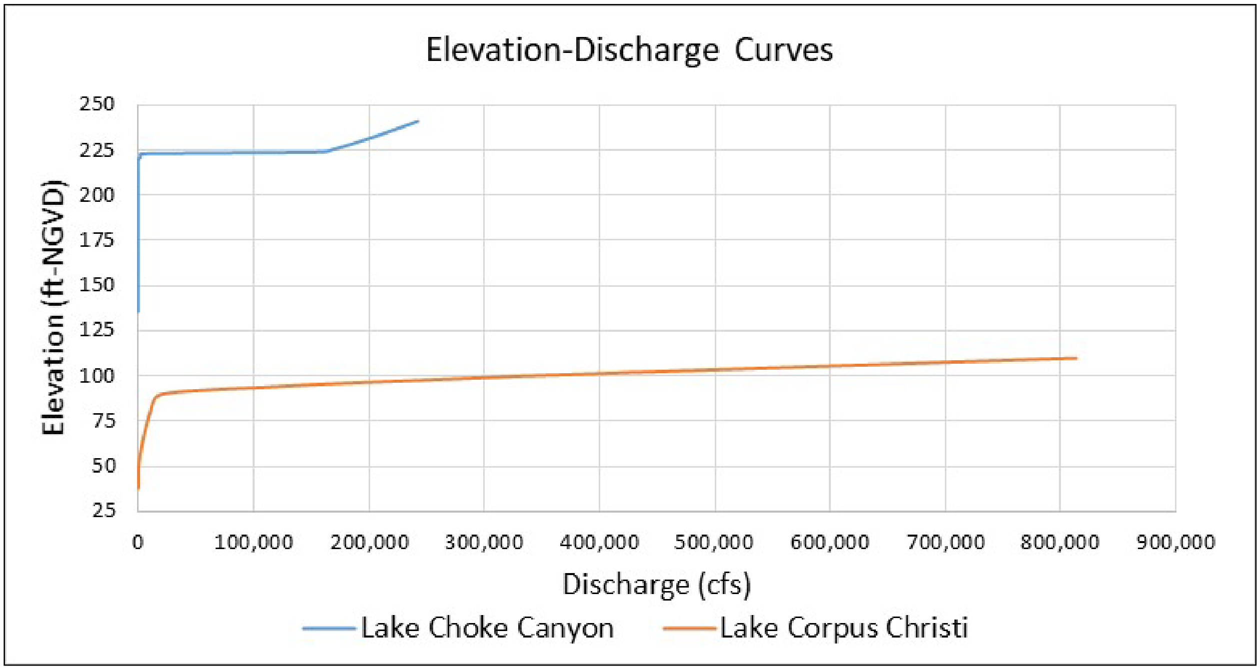

Figure E.22: Nueces River Basin Lakes Outflow Discharge-Elevation Curves

The importance of using accurate Storage-Discharge-Elevation (Stage) curves is that it results in more accurate estimates of high extreme peak values associated with high degree of uncertainty (*i.e.,* 1% ACE and beyond). Such high peaks are normally observed near or above the spillway crest. Validations of the adopted discharge-elevation curves used in RMC-RFA for the Nueces River Basin Lakes, are shown in Figures E.23 and E.24. The plots show that model releases are within range of operations. The adopted elevation-release curve for Choke Canyon Reservoir maintained no release up to elevation 220.0ft-NGVD. Release was then increased by 500cfs at pool elevation 221.ft-NGVD, to 4,000cfs (222.ft-NGVD), 20,000cfs (223.0ft-NGVD), and followed the spillway release rating curve for pool elevations above 224ft-NGVD. To achieve best estimate frequency curve for Lake Corpus Christi, Release is interpolated from the spillway rating curve between pool elevations 94ft-NGVD and 95-ft-NGVD; above elevation 95ft-NGVD, follow the spillway release rating curve, where releases were through the north and south side spillways.

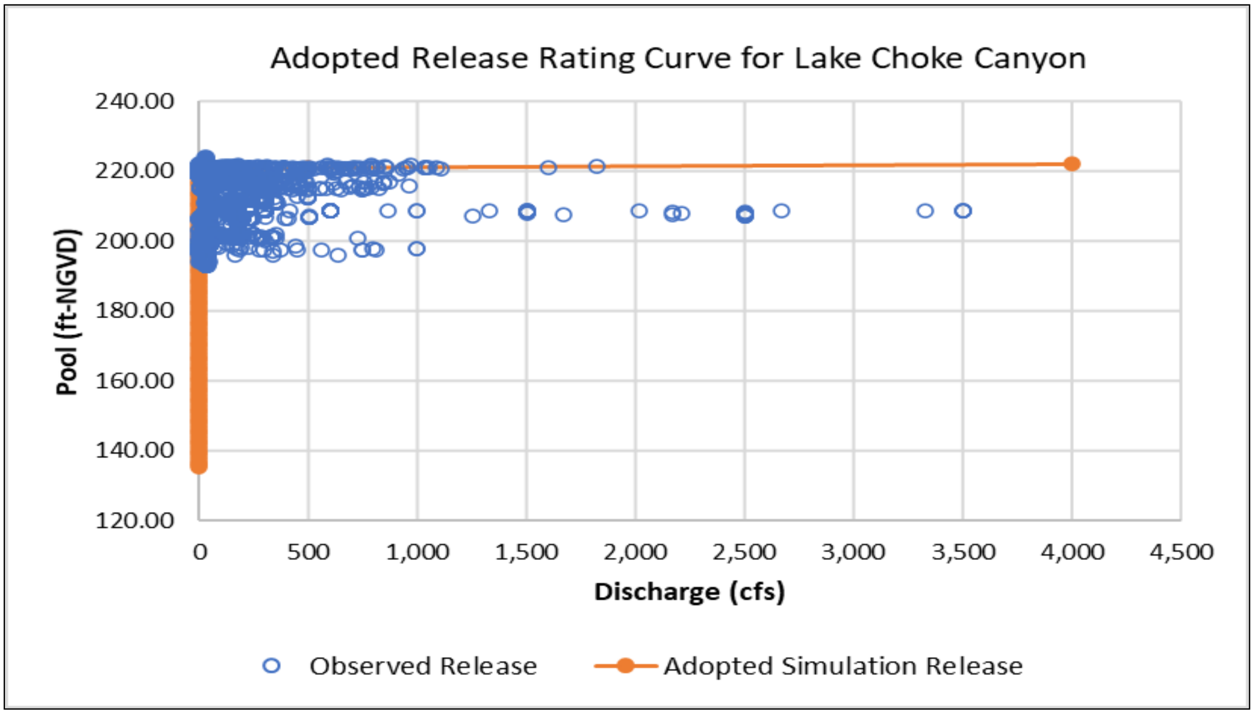

Figure E.23: Validation of the Adopted Elevation-Discharge (Release) Curve for Choke Canyon Reservoir

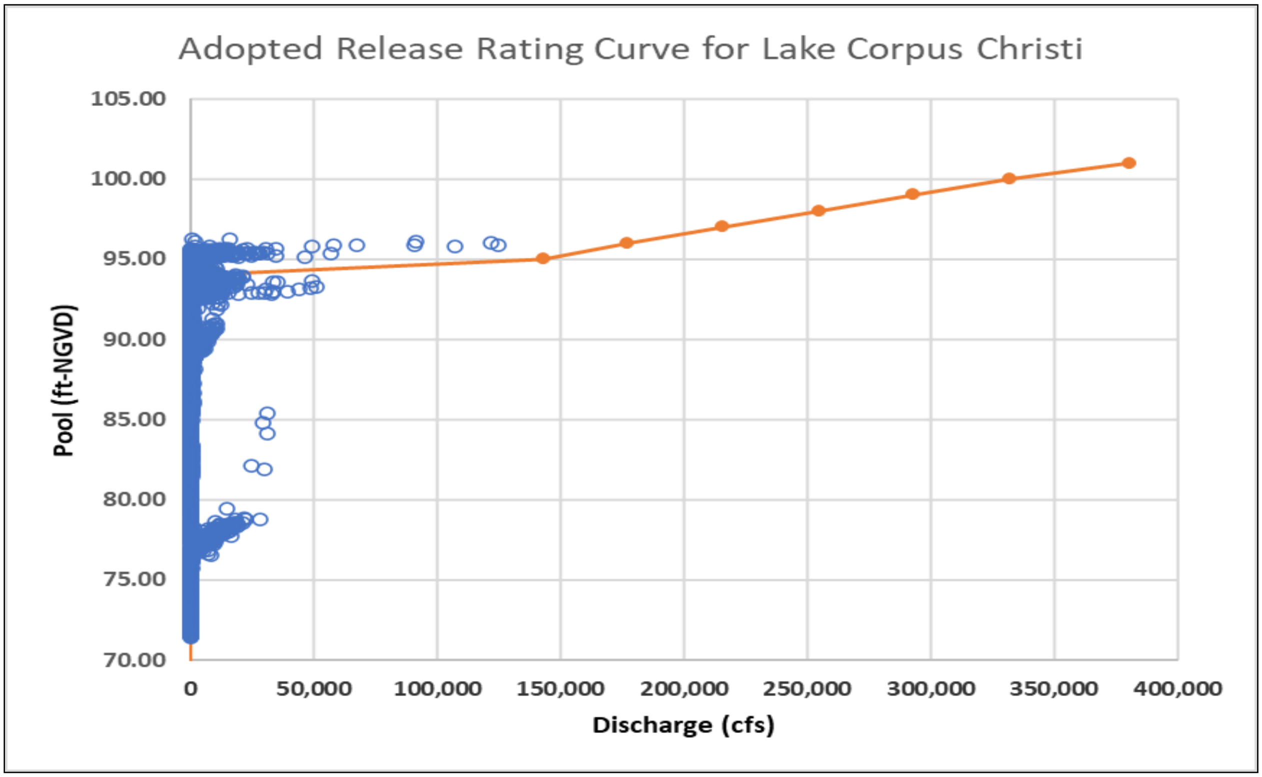

Figure E.24: Validation of the Adopted Elevation-Discharge (Release) Curve for Lake Corpus Christi

1.10 Results

The RMC-RFA program was used to simulate rainfall-runoff floods using the inflow-frequency curve and the adopted flood seasonality. The specified hourly inflow hydrographs in Section 9.8.1 and those found in the RMC-RFA program, are weighted equally to account for each unique shape (*i.e.,* volume and peak) and to have the same probability. Appropriate routing time windows were specified to calculate the full size of floods routed through the reservoir on hourly basis. The RMC-RFA model was simulated using the expected pool frequency curve only model option. This runs 10,000 realizations with 1,000,000 events per realization. This means RMC-RFA simulates a total of 10 billion events (10,000 x 1,000,000) to produce its best estimate of the expected curve. The following sections list detailed results about each project's new simulated expected stage-frequency curve.

To assess regulation, the total release for each project corresponding to each pool frequency, was developed by analyzing each project's observed and simulated releases, where annual maximum peaks were plotted using the Weibull position distribution and applying a graphical curve, which would approximately fit through the data points. Sets of the Weibull plotting position distribution figures for the projects are shown in sections 9.10.1 and 9.10.2.

The regulated (simulated/observed) releases were used to best estimate release frequencies below the spillway crest. High flood events that may exceed spillway crest elevation, would follow the discharge-elevation curve illustrated in Figure E.22.

Several iterations were made, using the RMC-RFA program to obtain the best simulated pool frequency curves. The best fit is defined as the curve that fits well through the more frequent events (*i.e.,* 10% ACE (10-year) through 2% ACE (50-year)) through the empirical stage points. The best estimate curve is a result of applying release schedules that would not violate the most upper and lower bounds of discharge peaks. As a result, and with degrees of uncertainty, the curves are believed to have captured good estimates beyond the 1% ACE (100-year) events. Adopted pool frequency curves are shown below.

1.10.1 Choke Canyon Reservoir

Table E.11: 2021 Choke Canyon Reservoir Computed Pool Frequency Estimate

Choke Canyon Reservoir		RMC-RFA Best Estimate
N-Years	ACE %	Feet-NGVD
2	50	220.57
5	20	221.89
10	10	222.46
25	4	223.02
50	2	223.34
100	1	223.62
250	0.4	224.01
500	0.2	224.39

Table E.12: 2021 Choke Canyon Reservoir Computed Frequency Discharge Release

Choke Canyon Reservoir		RMC-RFA Best Estimate (Expected)			
N-Years	ACE %	Elevation-NGVD	Spillway Release (CFS)	Gate Release (CFS)	Total Release (CFS)
2	50	220.57	0	2,900	2,900
5	20	221.89	0	12,050	12,050
10	10	222.46	0	22,000	22,000
25	4	223.02	0	37,950	37,950
50	2	223.34	50,500	0	50,500
100	1	223.62	69,660	0	69,660
250	0.4	224.01	102,774	0	102,774
500	0.2	224.39	123,160	0	123,160

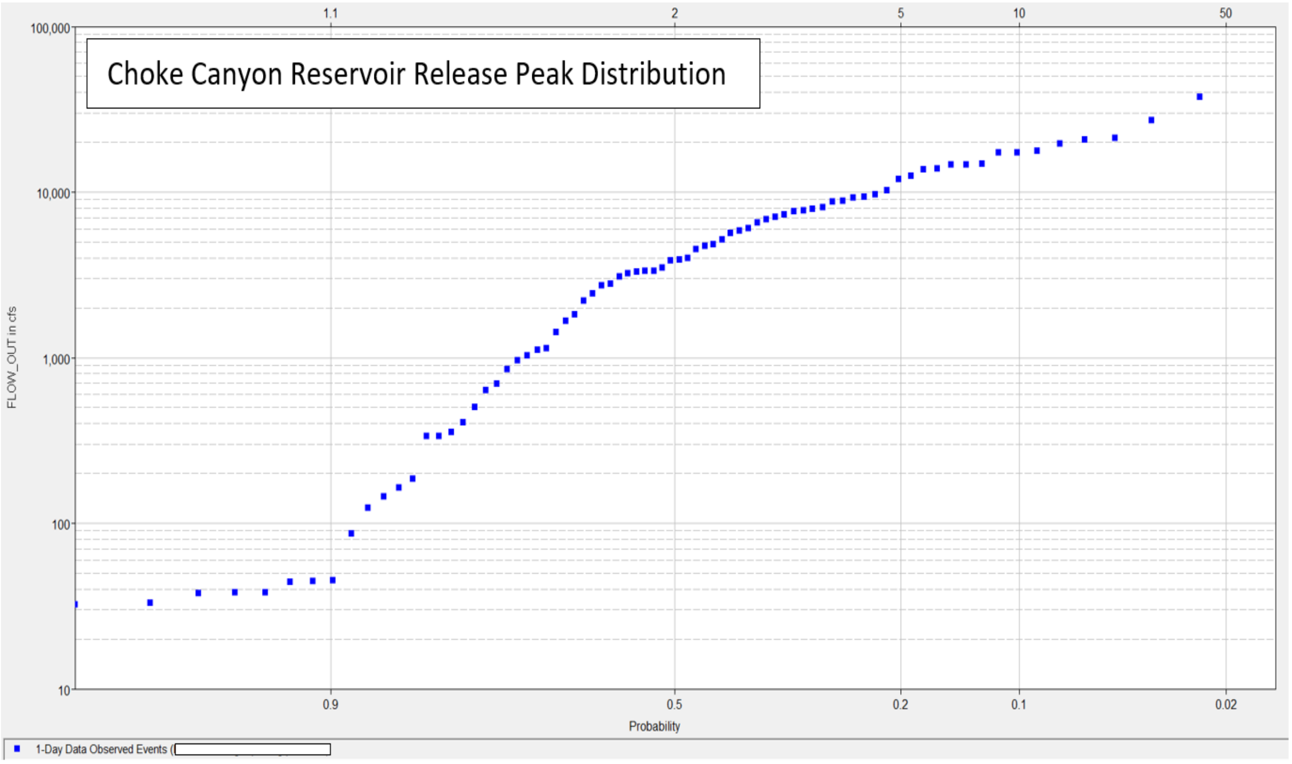

Figure E.25: Choke Canyon Reservoir Simulated Total Release Following Weibull Plotting Distribution

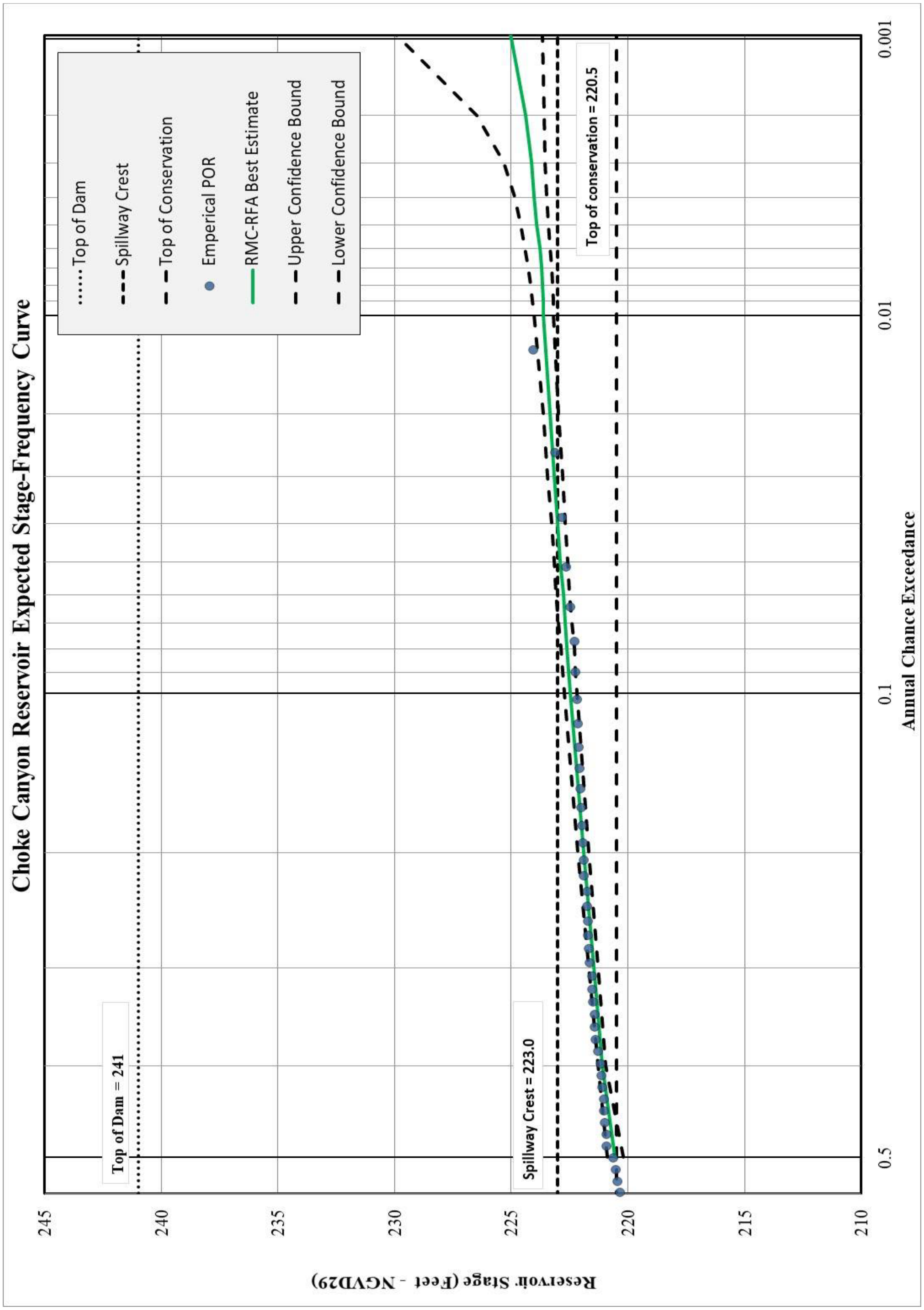

Figure E.26: Choke Canyon Reservoir Current Condition (2021) Stage-Frequency Curve for Rainfall Simulations

1.10.2 **Lake Corpus Christi**

Table E.13 2021 Lake Corpus Christi Computed Pool Frequency Estimate

Lake Corpus Christi		RMC-RFA Best Estimate
N-Years	ACE %	Feet-NGVD
2	50	94.06
5	20	94.24
10	10	94.39
25	4	94.48
50	2	94.67
100	1	94.85
250	0.4	95.50
500	0.2	96.83

Table E.14 2021 Lake Corpus Christi Computed Frequency Discharge Release

Lake Corpus Christi		RMC-RFA Best Estimate (Expected)			
N-Years	ACE %	Elevation-NGVD	Spillway Release (CFS)	Gate Release (CFS)	Total Release (CFS)
2	50	94.06	6,200	0	6,200
5	20	94.24	17,000	0	17,000
10	10	94.39	28,600	0	28,600
25	4	94.48	48,550	0	48,550
50	2	94.67	67,800	0	67,800
100	1	94.85	91,000	0	91,000
250	0.4	95.50	128,825	0	128,825
500	0.2	96.83	163,200	0	163,200

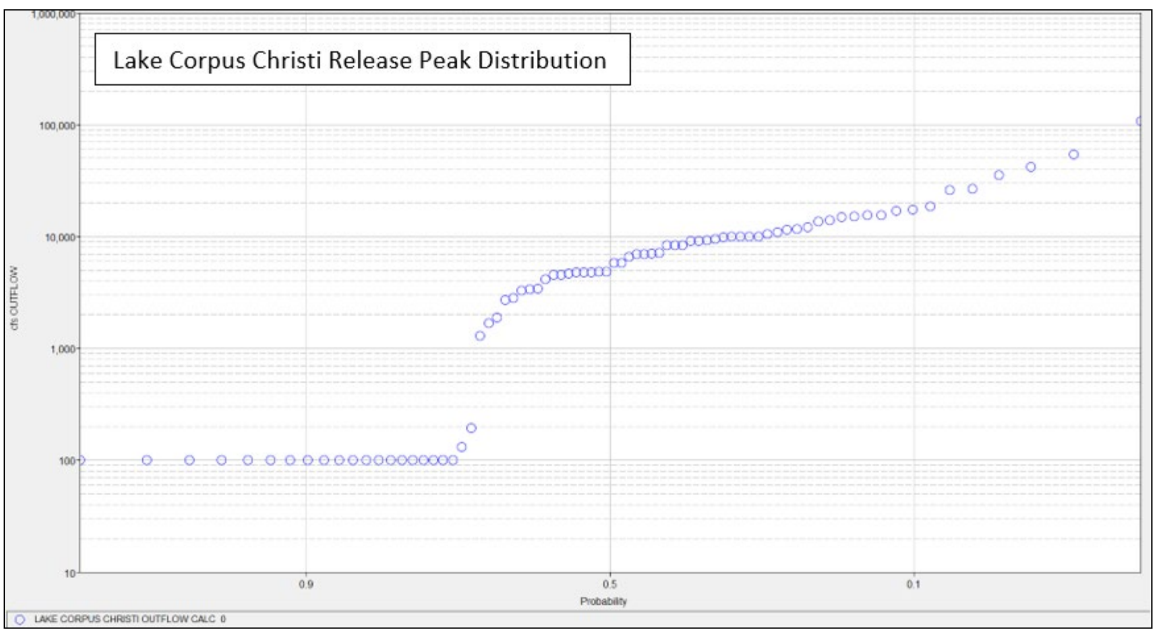

Figure E.27 Lake Corpus Christi Simulated Release Following Weibull Plotting Distribution

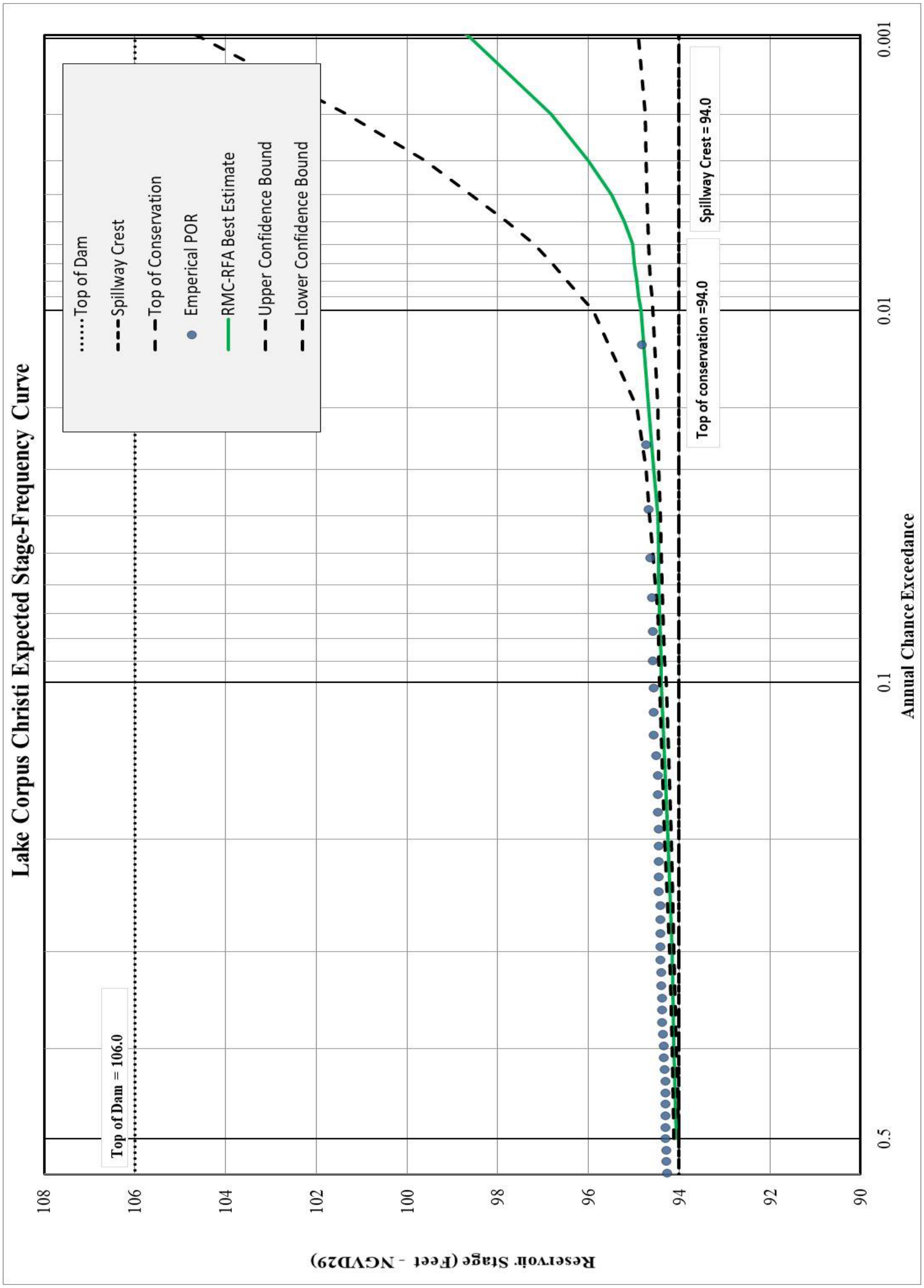

Figure E.28 Lake Corpus Christi Current Condition (2021) Stage-Frequency Curve for Rainfall Simulations

1.11 Results Validation

The pool frequency results displayed in section 9.10 went through rigorous analyses before being finalized. The following are some sensitivity analyses performed on both lakes to validate selections of the best estimate pool frequency results.

Choke Canyon Reservoir:

The best estimate pool frequency curve for this lake is impacted by operations and by the short period of observed record of the pool. The extended POR using RiverWare increased the number of AMS peaks by more than 50% and increased confidence in the selected 50% and 10% pool frequencies. Figure E.28 illustrates impacts of extending POR on pool frequencies. In addition, operations impact releases through the project. Examples of these impacts on the selected curve are shown in Figure E.29. Notice the drop in the best estimate curve when releases were increased for elevations below the spillway crest (WCM release plan). The volume frequency curves presented negligible changes to the curve against elevations (Table E.16). As a result, the selected curve shown in Figure E.25 was based on the following criteria:

Table E.15: Choke Canyon Reservoir Data Input

Model Input (Criterion)	Data Input Description
Discharge Gage	Daily average Unregulated inflow
Inflow Hydrograph	November 2001 and July 2007
Stage Gage	Simulated pool for WY (1943-1988) Observed pool for WY (1989 – 2019)
Volume Frequency Curve	15-Day Unregulated Inflow (matched the critical duration length)
Flood Seasonality	2,000cfs inflow threshold, maximum 4 events per year, and minimum 6 days between events.
Reservoir Starting Stage Duration	14feet of pool change threshold and 6 days of typical high pool duration.
Empirical Frequency Curve	Simulated pool for WY (1943-1988) Observed pool for WY (1989 – 2019)
Reservoir Models (Operations)	UP to elevation 220ft-NGVD (zero cfs) Elevation (220 to 221) ft-NGVD (500cfs) Elevation (221 to 222) ft-NGVD (4,000cfs) Elevation (222 to 223) ft-NGVD (20,000cfs) Elevation 224ft-NGVD and up (spillway rating curve)

Table E.16: Choke Canyon Reservoir Volume Frequency Curve Impacts on the Best Estimate Pool Frequency Curve

Annual Exceedance Probability	Return Period	15-Day	23-Day	Pool Change
AEP	Years	Pool (ft-NGVD)		Feet
50%	2	220.57	220.59	-0.02
20%	5	221.89	221.88	+0.01
10%	10	222.46	222.47	-0.01
4%	25	223.02	223.02	0.00
2%	50	223.34	223.35	-0.01
1%	100	223.62	223.57	+0.05
0.2%	500	224.01	224.27	-0.12

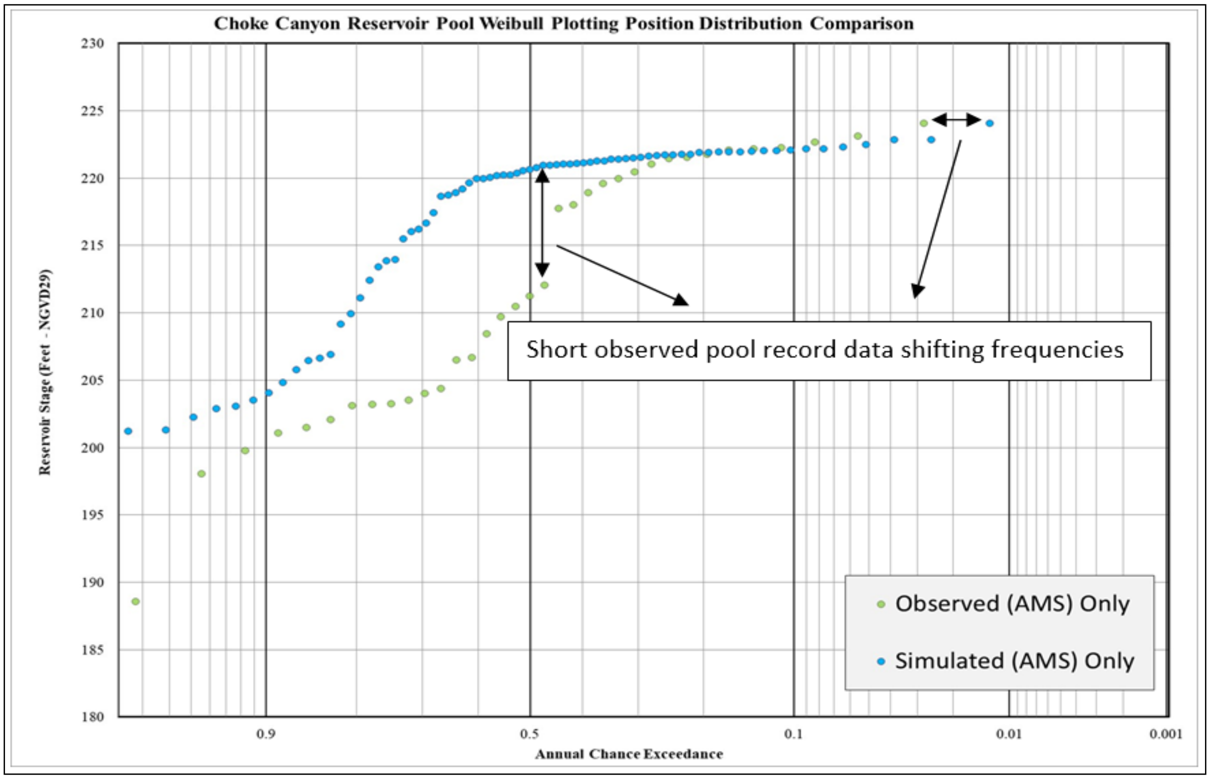

Figure E.29 The Impact of Short Pool Record Data on the Weibull Plotting Position Ditribution

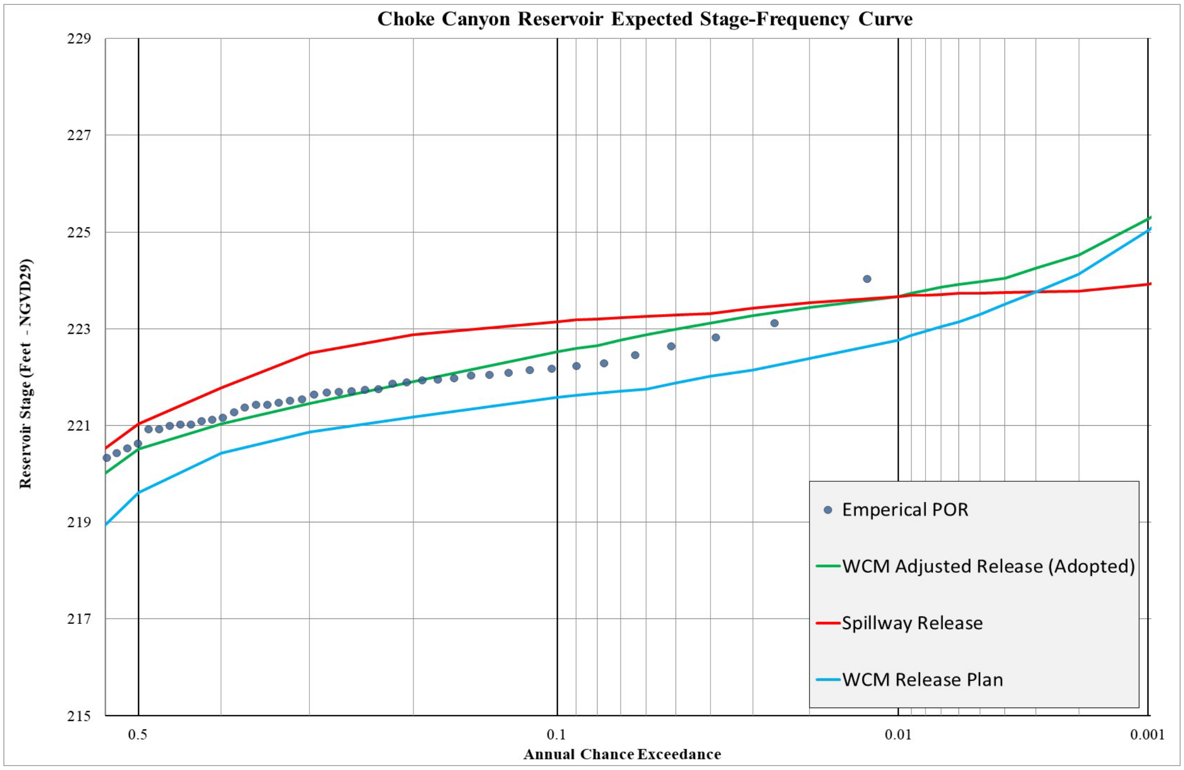

Figure E.30 Impacts of Change of Operations on the Best Estimate Pool Frequency Curve for Choke Canyon Reservoir

Lake Corpus Christi:

The best estimate pool frequency curve for this lake is impacted by unusual operations. There are extreme shifts of the AMS pool peaks due to emergency drawdowns and changes to conservation pool zone (Figure E.30). The simulated pool is a better representative of the Weibull plotting position distribution used to guide the best estimate frequency curve of the lake. Figure E.31 illustrates operation impacts on the shape of the best estimate curve. Increased releases below spillway crest (95-ft-NGVD) causes the curve to fit below the empirical data points. The selected curve performed best when releases followed the combined spillway rating curve through the north and south gates. The volume frequency curves presented negligible changes to the curve against elevations (Table E.18). The selected curve shown in Figure E.27 was based on the following criteria:

Table E.17: Lake Corpus Christi Data Input

Model Input (Criterion)	Data Input Description
Discharge Gage	Daily average Unregulated inflow
Inflow Hydrograph	November 2001, July 2002, and July 2007
Stage Gage	Simulated pool for WY (1943-2008) Observed pool for WY (2009 – 2019)
Volume Frequency Curve	15-Day Unregulated Inflow (matched the critical duration length)
Flood Seasonality	4,000cfs inflow threshold, maximum 6 events per year, and minimum 7 days between events.
Reservoir Starting Stage Duration	12feet of pool change threshold and 7 days of typical high pool duration.
Empirical Frequency Curve	Simulated pool for WY (1943-2008) Observed pool for WY (2009 – 2019)
Reservoir Models (Operations)	UP to elevation 94ft-NGVD (zero cfs) Elevation 95ft-NGVD and up (spillway rating curve)

Table E.18: Corpus Christi Lake Volume Frequency Curve Impacts on the Best Estimate Pool Frequency Curve

Annual Exceedance Probability	Return Period	15-Day	22-Day	Pool Change
AEP	Years	Pool (ft-NGVD)		Feet
50%	2	94.06	94.09	-0.03
20%	5	94.24	94.31	-0.07
10%	10	94.39	94.39	0.00
4%	25	94.48	94.60	-0.12
2%	50	94.67	94.70	-0.03
1%	100	94.85	94.91	-0.06
0.2%	500	96.83	96.38	+0.45

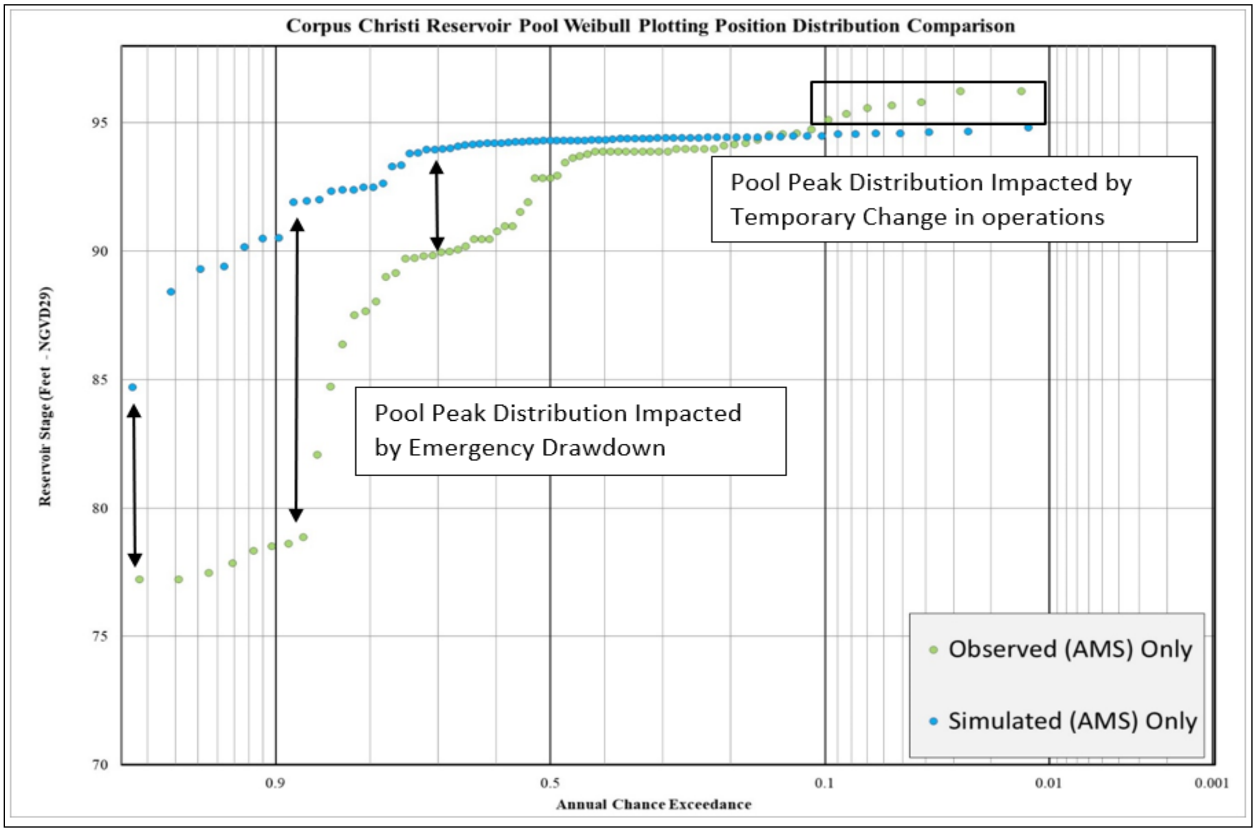

Figure E.31 The Impact of Instability Operations on the Weibull Plotting Position Ditribution

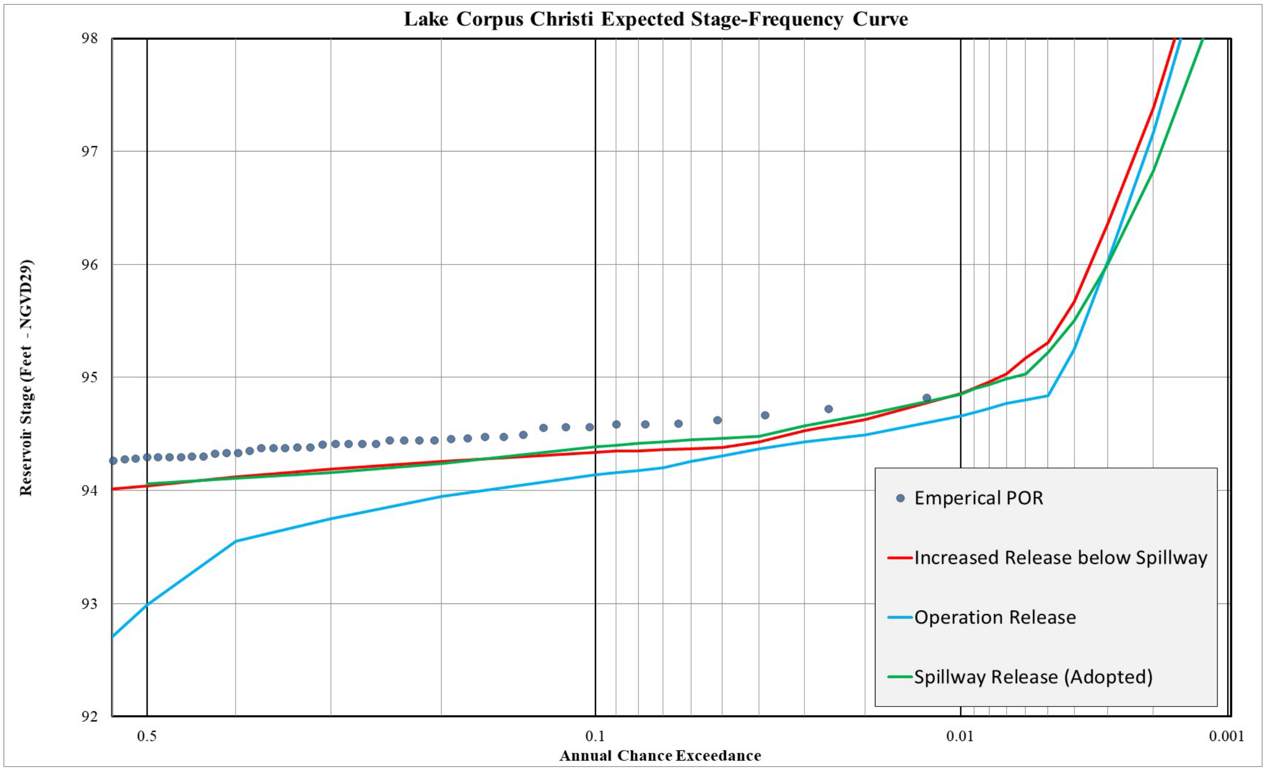

Figure E.32 Impacts of Change of Operations on Best Estimate Pool Frequency Curve for Lake Corpus Christi

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