ABSTRACT

Title of Thesis: STOCHASTIC SIMULATION OF WOLF CREEK DAM OPERATIONS FOR USACE

Thesis Directed By: Dr Gregory B. Baecher, Department of Civil Engineering and Environmental Engineering

The Wolf Creek Dam situated on the Cumberland River in the state of Kentucky, United States is a multipurpose dam generating hydroelectricity, providing flood risk reduction, supporting year-round navigation on the lower Cumberland River, and it creating Lake Cumberland for recreation and water supply. The latter is a popular tourist attraction. Because of piping and internal erosion problems in the dam's foundation, it is a USACE top-priority structure. This thesis experiments with and tests the applicability of a stochastic simulation of the dam using historical inflow data based on a model built on *GoldSim*™. The model uses standard operating rules of the Dam to spot possible failures to the turbines that could affect the performance of the dam. In addition, the model simulates the behavior of the dam 50 years in to the future during which time the components reach their close to their maximum life. Results of the study suggest that simulation models of this type may serve to provide information for reliability-based maintenance strategies, and to help identify adverse patterns of dam performance which may be addressed through asset management.

STOCHASTIC SIMULATION OF WOLF CREEK DAM OPERATIONS FOR USACE

by

Rahul Padmanabhan

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2019

Advisory Committee:
Dr Gregory B. Baecher, Chair
Dr Michelle Bensi
Dr Allison Reilly

Acknowledgements

I would like to acknowledge various individuals who helped me with the completion of my Master's Thesis. At first, I would like to express my sincerest gratitude my advisor Dr Gregory B. Baecher for his unwavering support throughout the span of two semesters when I worked under him. He provided me with proper guidance mentorship that allowed me to learn the depths of Reliability analysis of the Hydrological systems which has sparked my enthusiasm towards Risk analysis. I am also thankful to Dr Michelle Bensi and Dr Allison Reilly for accepting to be on committee. I would also like to extend my sincerest gratitude towards Robert Patev who played pivotal role in modelling the dam system. He provided me with crucial data that were extremely helpful in building the model. Additionally, he was kind enough to clarify every doubt I had regarding the working of the Wolf Creek.

Finally, I would like to express my gratitude towards all my friends and family for their unconditional support that has allowed me to successfully complete my research.

LIST OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 Introduction

1.1 Research Motivation

Dams are large structures which are pivotal to the production of electricity for a particular area. Failure to maintain their repair on time can cause serious damage to these structures and their operation. It is important to understand the cause of operational dam failures such as mechanical-electrical failure, instrumentation and SCADA misperformance, structural failure, or human operator errors, and to conduct regular surveys to determine how often these failures occur over the life span of these dams and what their consequences may be.

With dam systems becoming progressively more complex, failures can creep in from many points. The management team of the dam must have a clear understanding of the risks of failures and devise mitigation plans to treat these failures.

1.2 Research Purpose and Scope

The purposes of the research were to,

(1) <u>Test and evaluate stochastic simulation approaches to evaluating the operational reliability of hydropower dams</u>.

A case study using Wolf Creek dam on the Cumberland River of Kentucky has been used as the vehicle for this research in that it is an important structure to the US Army Corps of Engineers and many years of data are available for it.

(2) <u>Evaluate the application of Weibull reliability models to the management of hydropower dam assets.</u>

In the same way that many years' data are available for Wolf Creek dam, the US Army Corps of Engineers (USACE), the owner and operator of Wolf Creek, has had an ongoing effort to collect and maintain asset management reliability data on hydraulic gates, power generation, and navigation infrastructure in its portfolio. The hydraulic system of the Wolf Creek Dam consists a complex combination of machines. It is important to understand the inter-dependency of the components with one another to maximize the production of electrical energy.

(3) Seek to identify emergent behaviors of the dam and its components in the antecedents to adverse performance events.

This research has built a Monte Carlo based simulation model of the Wolf Creek dam on the *GoldSim* platform and uses the inflow data from the past 50 years to determine the potential adverse performances of the dam in the future by considering various scenarios. In doing so, the reliability of the dam can be improved by analyzing the results from a myriad of simulations and propose a framework to increase the safety and the capacity to consistently produce energy from the dam.

1.3 Thesis Overview

This thesis investigates the Wolf Creek project in the following chapters, described as follow:

- Chapter 2 Literature Review: This consists of related research work conducted in the past. It describes work pertaining to reliability of dams, risk analysis and work related to the Wolf Creek Project in the past.

- Chapter 3 Wolf Creek Project: This chapter sheds light on the dam project itself explaining briefly the water body it creates as well as the Hydrological System.
- Chapter 4 *GoldSim* Model: The software *GoldSim* was used to build a working model of Wolf Creek Dam. In this chapter, the working model is briefly explained, and suitable pictures are presented to illustrate the model.
- Chapter 5 Simulations and Interpretation: The model of the dam was made to run through numerous simulations and this chapter presents the outputs from these simulations.
- Chapter 6 Conclusion: The work done with the research is concluded and recommendation for future betterment of the Wolf Creek dam are proposed.
- Chapter 7 Results: Using the model, ten 1000-iteration simulations were conducted for a span of 50 years, nominally from 1960 to 2011. Subsequently, an additional set of ten 1000-interation simulations were conducted for a span of 100 years, nominally from 1906 to 2059. Selected graphical results are presented and discussed.
- Chapter 8 Analysis and Interpretation: The simulation results and output are discussed with respect to the three research purposes.
- Chapter 9 Conclusions: Implications of the research with respect to the three research purposes are considered.
- Chapter 10 Future directions for this work: Four important Direct shins for future work are identified and discussed.

2 Literature Review

The primary modeling approach in the present research was adopted from Hartford et al. (2016) and Hartford and Baecher (2004). This approach uses stochastic simulation to model hydropower operation over time, focusing on systems engineering aspects and reliability-centered asset management.

Komey, Deng, Baecher, Zielinski, & Atkinson (2015) with their paper presented analysis on systems reliability of flow control on dam safety. According to this paper, environmental factors and the operating rules of the reservoir affects the reliability of the spillway structure. From the research conducted by numerous simulations using *GoldSim* software, it was concluded in this paper that the reliability of the spillway is dependent on human factors among other things, such as incorrect decisions, failure to control instruments, loss of dam access during emergency etc.

Sivakumar Babu & Srivastava (2010) in their paper studied the earth dams on the Kachchh region of Gujarat in India and came up with a risk analysis of the dams using response surface methodology. In addition, they used first order reliability method and Monte Carlo simulations to determine the risks pertaining the earth dams.

Westberg Wilde & Johansson (2012) presented a paper in which they analyzed the structural reliability of the spillway of the dam. They use limit state functions that are defined from the failure modes in concrete. Efforts were taken in calculating the safety index of the dam by using a and the usage of direct integration of bivariate normal distribution to calculate the system reliability. They use the system reliability to find the probability of failure and the types of failure mode.

Jordan et al. (2014) in this paper conducted stochastic simulation of inflow hydrographs for Wivenhoe and Somerset dams. They used the *GoldSim* software to build the model and implemented stochastic analysis of rainfall bursts. Finally, they produced hydrographs of highest inflow location that have that highest probability of flooding. With the type of modelling adopted by the authors, they were able to open the possibility of modeling the variability of rainfall in the catchment area by using the model for the stochastic simulation the dam.

Ahmadisharaf & Kalyanapu (2015) presented a paper where they performed a case study on high hazard dams. By identifying overtopping as one of the major reasons for failure of dams. With their research on a high hazard dam situated in North Carolina, they tracked the temporal variation on overtopping and concluded that the risk of the dams overtopping increased drastically compared to what was witnessed prior to 1980.

3 Wolf Creek Project

Wolf Creek Dam is built on the Cumberland River in the state of Kentucky, USA. Completing its construction in August of 1952, the Wolf Creek dam is the 22nd largest dam in the USA and built and operated by the United States Army Corps of Engineers (USACE)

3.1 Project Background

Wolf Creek is a Concrete gravity and earthfill dam which is built in the vicinity of Jamestown located 10 miles off US 127 North. Figure 1 shows aerial view of Wolf Creek Dam.

Figure 1. Aerial view of Wolf Creek Dam

The dam spans 5,736 feet with a total length of the concrete section being 1,796 feet. The top of the dam is at elevation 773 feet whereas the top of the gates are at 760 feet. There are 10 spillway gates which are of radial (Tainter) type with a dimension of 50 x 37 feet. At discharge capacity the gates is 553,000 cfs. Table 1 contains the statistics of the Dam.

Table 1. Statistical information of the Wolf Creek Dam (from USACE)

Dam	
Type	Concrete- Gravity and Earthfill
Quantities	
Concrete , Cubic Yards	1,380,000
Earthfill, Cubic Yards	10,016,500
Dimensions	
Maximum height, feet	258
Length, feet(concrete,1796:earth,3490)	5736
Elevations (above mean sea level)	
Top of Dam	773
Top of Gates	760
Spillway Crest	723
Spillway Crest Gates:	
Number and Type	10, Radial
Size (width and height), feet	50 x 37
Discharge Capacity c.f.s	553,000
Sluices	
Number of Conduits	6
Size (width and height), feet	4 x 6
Total discharge capacity, c.f.s	9800
Hydropower	
Installation	270,000 kw in 6 units
Rating, each generator, kilowatts	45,000
Estimated energy output, average yearly kilowatt- hours	800,000,000
Reservoir	
Drainage are, square miles:	5789
Length of pool at Elv. 760 river miles	101
Length of shoreline,pool at Elev.760 miles	1255
Area, acres	
Top of Flood- Control pool(Elv.760)	63,530
Maximum power pool (Elev. 723)	50,250
Minimum Power Pool (Elev. 673)	35,820
Storage Capacities, acre feet	
Flood control (Elev. 760-723	2,094,000
Power drawdown (Elev. 723-673)	2,142,000
Dead (below Elev. 673)	1,853,000
Total (below Elev. 760)	6,089,000

g

3.2 Cumberland River

The Cumberland river is the water body that serves the Wolf Creek Dam. The reservoir of Lake Cumberland is 101 miles long and has a shoreline of 1,255 miles. The total storage capacity is about 6,089,000 acre-feet. Figure 2 shows the map of Cumberland River.

Figure 2. Cumberland River

Following are important statistics of the Cumberland River

- Capacity of the Reservoir = 2,094,000 acre-feet. It is used to hold flood waters to prevent causing flooding in the downstream area.
- Power Operation Allocation = 2,142,000 acre feet (with 50 feet drawdown)

- On average the dam produces enough energy to serve a population of 375,000
- Reservoir Level at Top of Power Pool is at about 52,250 acres with a minimum surface are of 35,820 acres. At times of high inflow, the floor storage is used which take the surface to about 63,530 acres.

4 Major Components of the Dam

The Wolf Creek dam consists of the following components the constitutes the hydro power plant. Figure 3 shows the Hydroelectric System.

1. Reservoir
2. Spillway Gates
3. Turbines

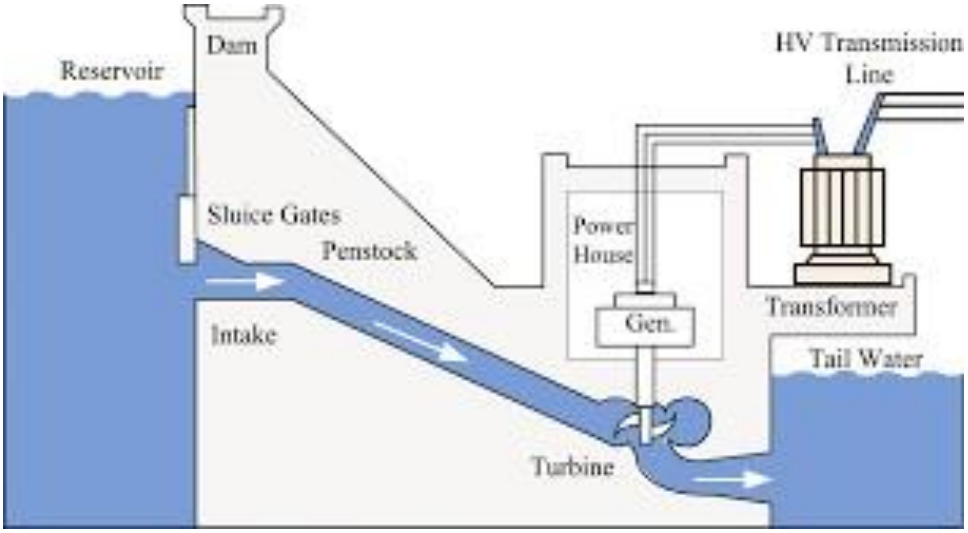


Figure 3. Hydroelectric System

4.1 Reservoir

Reservoir on the Wolf Creek acts as a system for various functions for the hydro power plant. The reservoir is built to store inflow water, water for irrigation or consumption and outflow that is used for power generation. Following are the various levels of storage in the reservoir.

- Full reservoir level is the highest level of storage which holds the active storage, inactive storage and flood storage.

- Maximum water level is the level of water that is reached during a designed flood condition.
- Minimum drawdown level is the minimum amount of water that is required for power generation and below which the water wont allowed to draw down.
- Dead storage level is the amount of water left in the water that cannot be drained by the force of gravity.
- Surcharge is the reserve capacity between operating and the maximum water level to accommodate for peak flood levels.

Figure 4 shows the schematic diagram of the Reservoir level

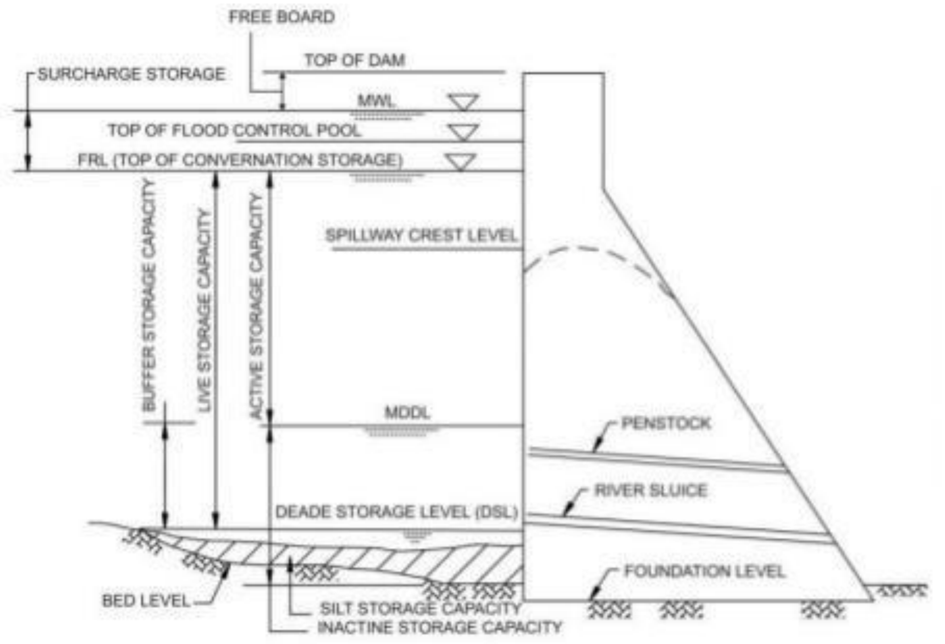


Figure 4. Schematic Diagram of the Reservoir Levels

Important terms for reservoirs

- Water Level (h) = the amount of water stored in the reservoir and measured using a special instrument.

- Inflow (q) = the amount of water that enters the reservoir through various natural sources.
- Discharge = amount of water leaves the reservoir for various reasons power generation, irrigation and flood control
- Storage (s) = the amount of water stored in the reservoir.

4.2 Spillway Gates

Spillway is the structure in the dam which is used to allow water through the reservoir for various reasons. It is generally used when the water in the reservoir reaches a level of overtopping and the spillways are opened to avoid flooding and destruction to the dam as well as the settlement nearby. In a spillway system, there are mainly two ways of releasing water which are Controlled and Uncontrolled release. During a controlled release, the water is released through an opening and is made to pass in to the downstream into the catchment area without entering the turbine. In case of uncontrolled release, the water gets released when the water goes above a certain level caused by overflow.

4.3 Turbine

Turbines are the powerhouse of the dam system. They convert the mechanical energy generated by the inflowing water in to electrical energy. In the case of Wolf Creek Dam, the dam system contains six Francis turbines which produce energy. The turbines consist of five internal components which are as follows:

1 Stator
2 Rotor

3 Excitor

4 Transformers

5 Governors

Francis turbines function well over a range of heads and discharges. Along with high efficiency, they have become possibly the most widely used turbine worldwide. Figure 5 shows the diagram of a Francis Turbine.

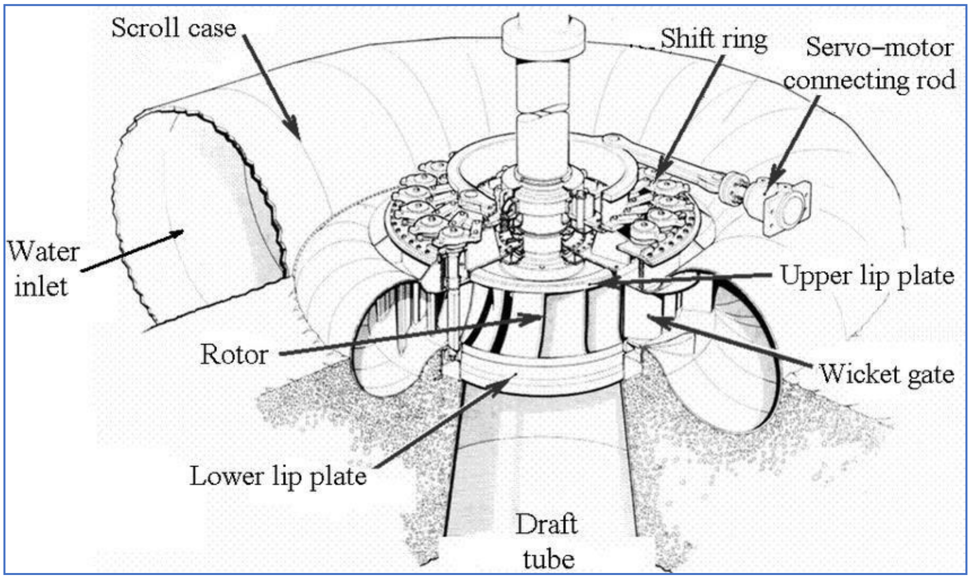


Figure 5. Francis Turbine

5 Water Control Plan

5.1 Primary Objective

According to the water manual of the Wolf Creek, the dam has majorly two objectives which are as follows:

- To store water in event of flood and to decrease the potential damage caused to the downstream are of the Cumberland River.
- To generate enough hydro electric energy.

5.2 Inactive Pool

In the Wolf Creek dam, the Inactive pool operates from the bottom of the reservoir until an elevation of 673 feet. If the water drops below the top of this pool, the water is prevented from releasing. Another usage of the inactive pool is to provide head for production hydroelectricity and to oppose lake sedimentation. Additionally, this pool also opens the avenue for a prospering aquatic life, recreation, and to counter the drought periods.

5.3 Power Pool

It is the part of the reservoir that is used for the production electrical energy. In the Wolf Creek this pool spans from 673 feet to 723 feet. The difference of 50 feet in the middle is called the operating zone. Usually, the pool is made to fill up to the elevation of 723 feet from winter weather up until spring. During summer when the requirement for electricity is at its peak, the water stored in the pool is used for power generation causing a steady drawdown. Table 2 shows the Hydraulics and Hydrology of the dam

Table 2. Hydraulics and Hydrology

Drainage Area	
Project	
Total	5789 sq mi
Local Uncontrolled	5451 sq mi
Control Point- Celina, Tennessee	
Total	7307 sq mi
Local Uncontrolled	583 sq mi
Downstream Project- Cordell Hull	
Total	8096 sq mi
Local Uncontrolled	1372 sq mi
Top of Pool Elevation	
Flood Control	760 NGVD
Hydropower	723 NGVD
Inactive	673 NGVD
Surface Area at Top of Pools	
Flood Control	63,530 acres
Hydropower	50,250 acres
Inactive	35,820 acres
Length of Reservoir at Top of Pools	
Flood Control	101 miles
Hydropower	98 miles
Inactive	92 miles
Shoreline Length at Top of Pool	
Flood Control	1255 miles

This pool is later divided into various zones which are called the “SEPA Power marketing zone”.

5.4 Regulation Curve

It is a guide curve that works as the guidance for Wolf Creek dam operations. The curve consists of hardlines and softlines which divide the information presented by the graph. The hardlines divide the reservoir into 3 pools and softlines categorize the power pool.

5.5 Flood Control Pool

The flood control pool spans from 723 feet to 760 feet which the highest point of the dam. Normal practice governs the pool to be empty to help prepare for the event of flood and to reduce the damaging effects of the flood.

5.6 Normal Regulation

When the water inside the system is flowing at normal levels, the water surface levels is made sure it maintained at the pool limits. The water entering the turbine is also monitored and the flow is regulated based on the requirements of power. Additionally, the SEPA band also helps locating suitable locations for water surface.

5.7 Flood Regulation

According to the manual there are two mode of operation the during event of flood:

- During flood events, the outflow from the reservoir is reduced to protect city of Celina and the major damage center of Nashville from floods.
- When flooding is at high level, the Emergency Flood operations is initiated where the protection of the dam is of the highest priority over downstream locations.

5.8 Drought Regulation

In the event of droughts in the Cumberland River Basin, following are drought regulations and the priorities for the basin:

- Water Supply
- Water Quality
- Navigation
- Hydropower
- Recreation

5.9 Wolf Creek Dam Operating Rules

Normal and Drought Conditions

- To maintain headwater elevation within the limits of the hydropower pool and release all water through the turbines as governed by hydropower generation schedule.
- Limit Change in hydropower generation to three units per hour, up or down.
- Make a special report to Water Management personnel if minimum desired hydropower releases of at least 1000 cfs is scheduled.

Flood Periods

- When spillway gates are being operated, maintain uniform openings of all gates as closely as possible, with no more than foot difference among the gate openings.
- When sluices are operated, they will be either fully closed or fully opened.
- Limit the rate of increase of combined spillway and sluice releases to 2000 cfs per hour, unless operating under the Emergency Operation Schedule. Limit decreases

in these releases to 4000 cfs per hour and, if practical, limit this decrease to 2000 cfs per hour.

- In conjunction with Dale hollow, limit the flow at Celina to 30,000 cfs during crop season and 40,000 cfs during flood season. I f during flood control season, more than one half of the flood control capacity of Wolf Creek and Dale Hollow is being used and if the Center Hill flood control pool is near empty.
- Limit total project releases to full capacity of 60,000 cfs unless larger releases are required to the Emergency Operation Schedule (EOS)
- If the Operating under the Emergency Operation Schedule, limit the rate of increase in the total outflow to 20,000 cfs per two wo hour period until pool elevation reaches the Limiting Surcharge Curve.
- Once the Limiting Surcharge Curve is reached, it must be followed without deviation.

6 *GOLDSIM* Model

The Wolf Creek Dam water manual formed the basis of the model. Using the descriptive operating rules, the working model of the dam was built that uses the daily inflow data from 1950 to 2014 to simulate the dam operations in the future.

The model is divided into three modules which are as follows:

6.1 Model Input Parameters, Data & Documentation

Includes Inputs such as Initial Pool Elevation, Upstream daily flow and functions such as Initial Storage Capacity and Total Outflow all were acquired from the USACE for the Wolf Creek Dam.

Inputs

Initial Pool Elevation = 700 ft

Upstream Daily = 65 years Daily inflow data starting from 1950 until 2014

Functions

Initial Storage capacity = It is the function of initial pool elevation

Total Outflow = It is the function which is the sum of total turbine flow and spillway flow.

The above data form the input for the Reservoir system which uses them to generate various relevant Graphs. Figure 6 shows the input module of the model.

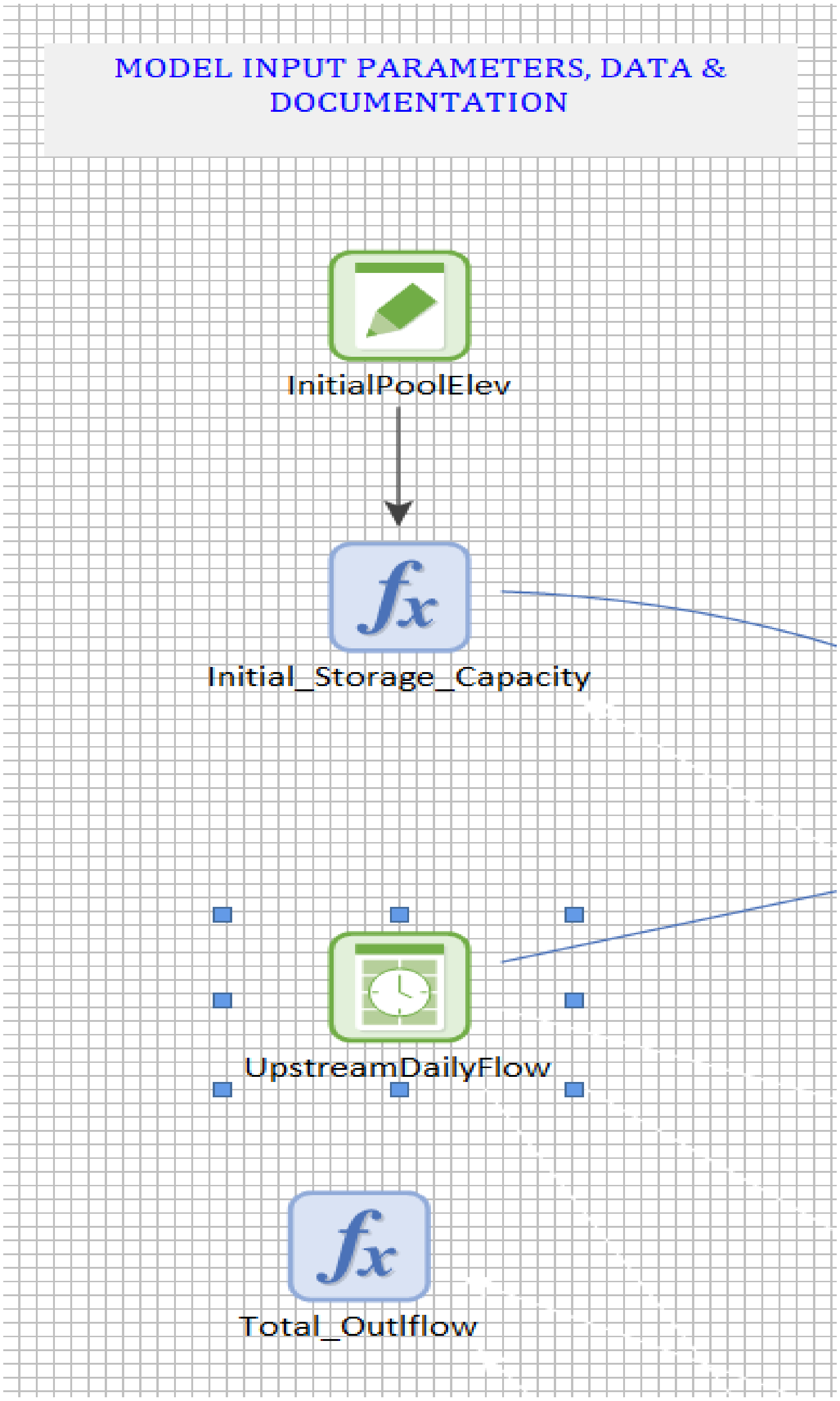


Figure 6. Input Module

6.2 Reservoir System

The Reservoir system uses the data from the Input module. It consists of the Gate opening and closing conditions for the spillway gates. Based on the elevation of water in the pool

Input

Top of the dam embankment: 773 ft

Storage Capacity = It is 229 data plots which illustrates the amount of water present at various elevation points in reservoir pool.

Reservoir Elevation: It used as an input for Reservoir Pool Elevation Function.

Function

Reservoir Pool Elevation = It is the function of Wolf Creek

Figure 7 shows the reservoir system of the model

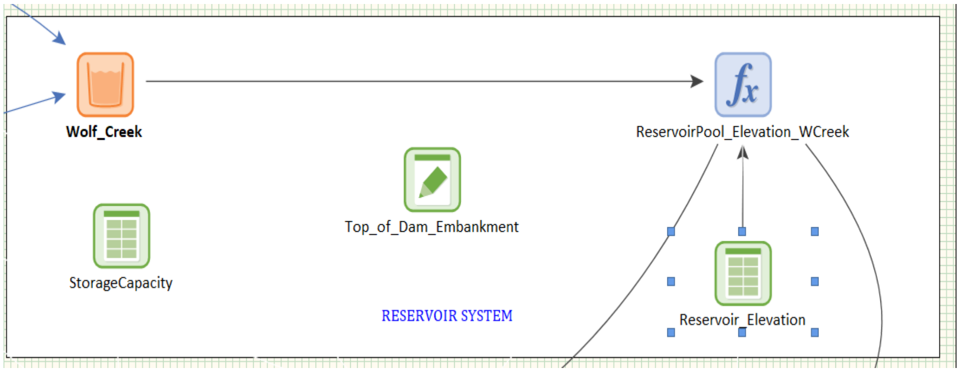


Figure 7. Reservoir System

6.3 Reservoir Operating Conditions

Following is the is figure of the operating rules function in the module:

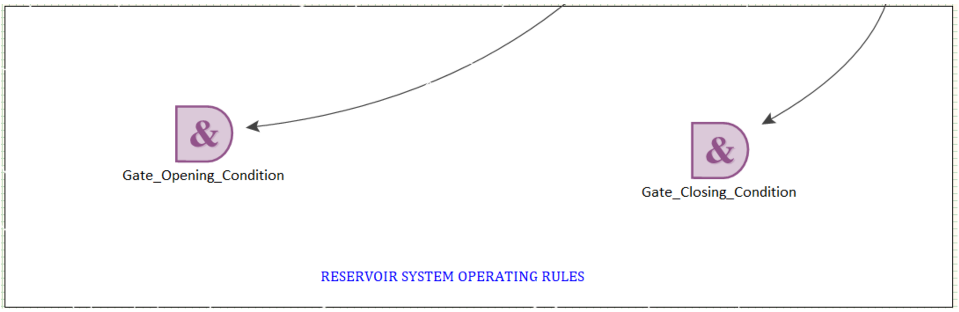


Figure 8. Reservoir Operating Rules

Operating Rules for the Gates are illustrated in the Water Manual:

6.3.1 Gate Opening Condition:

- ReservoirPool_Elevation_WCreek>=723ft

Above the 723 ft the gates are opened to avoid flooding as it is above the Powel Pool elevation.

- UpstreamDailyFlow>=Turbine_Flows

When the inflow into the system is more than the amount that should enter the turbine, the spillway gates open to allow the water to pass into the downstream catchment area.

- Gate Closing Condition

ReservoirPool_Elevation_WCreek <673ft

The spillway gates close when the water falls below the lower lower limit of the power pool.

UpstreamDailyFlow<Turbine_Flows

When the inflow into the system is below the turbine flows

The gates are active when the water in the pool is either above or below the power pool.

The 50 ft buffer in the middle which governs the gate operating conditions makes sure that gates don’t constantly open and close when the water has slight variations in its elevations inside the pool as that would cause the gates to break due to wear and tear.

6.4 Power Generation Module

It is the acts as the powerhouse of the model and accommodates the working of the six turbines. Figure 9 indicates the Power Generation module. Figure 9 shows the Power generation module

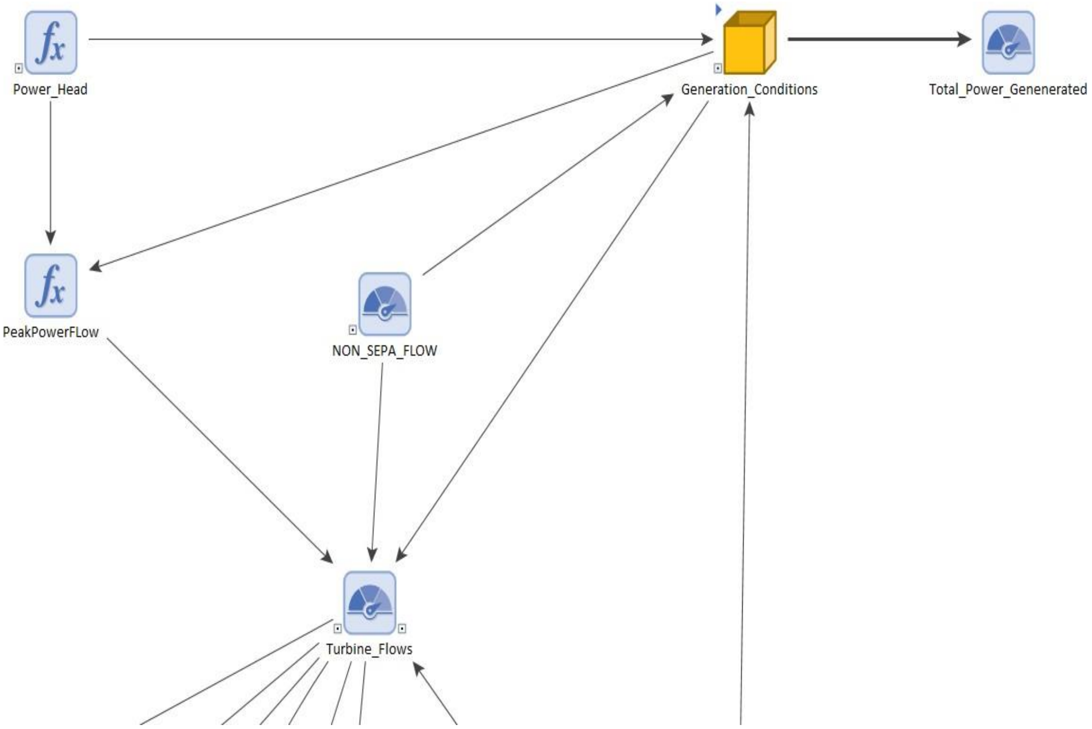


Figure 9. Power Generation Module

It consists of two functions that which are as follows:

- Power head = It is the difference between the Reservoir Pool Elevation and 537 ft which is the lowest part of the reservoir.
- Peak Power Flow = It is the function Power head.
- SepaFlow = When the power generated is less the 3860 times the power produced by the six turns.

Figure 10 shoes the Turbine system of the model

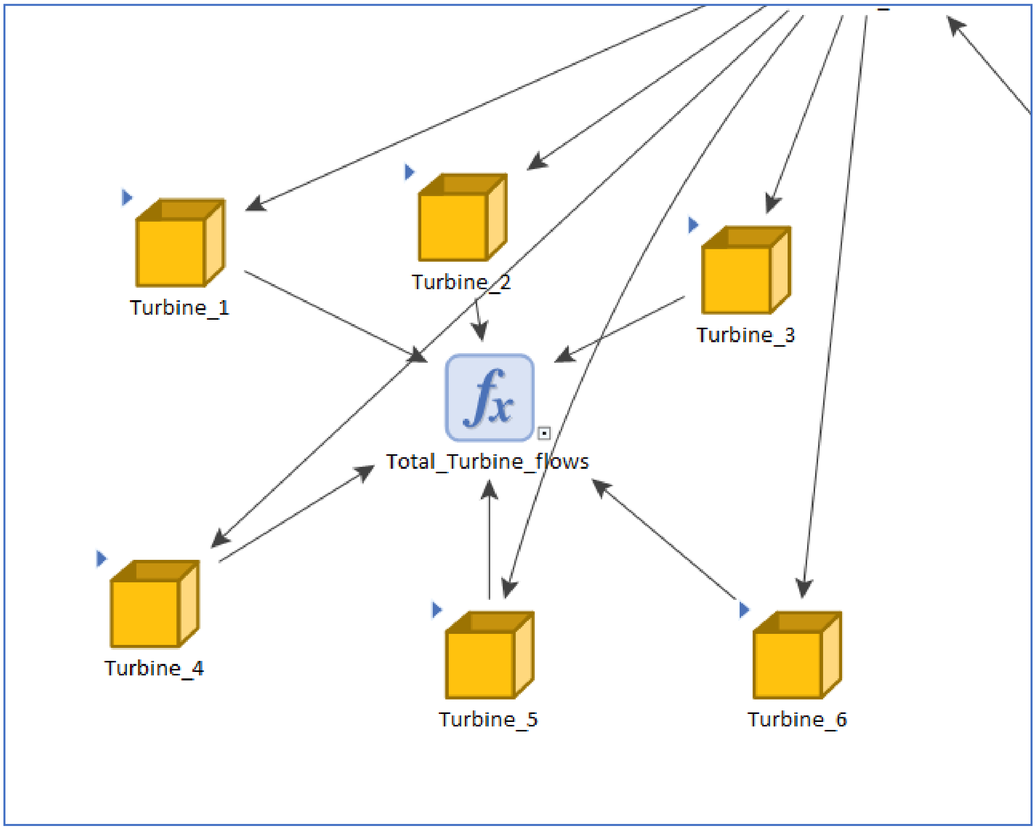


Figure 10. Turbine System

Total Turbine Flow = It is the sum of the all the six turbines

6.4.1 Turbine System

The Wolf Creek Dam consists of 6 Francis Turbine which work together to produce the energy required for the Jamestown Area. Inside the turbines, there are 5 components which are stator, rotor, governor, excitor and transformers. In the following pages the turbine system is delineated:

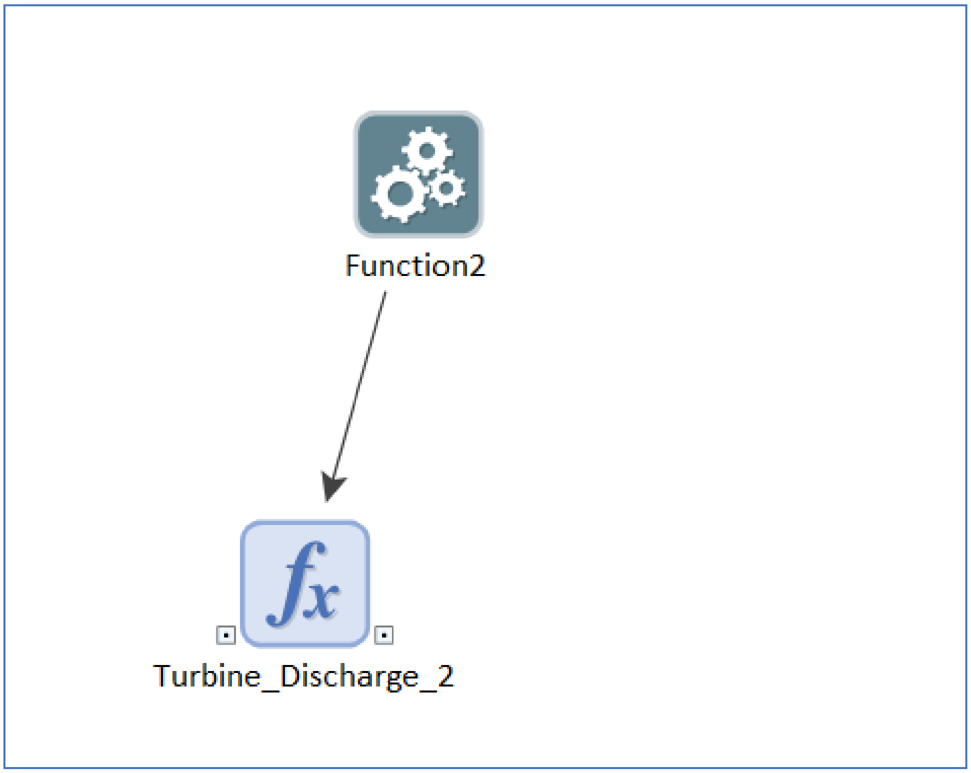
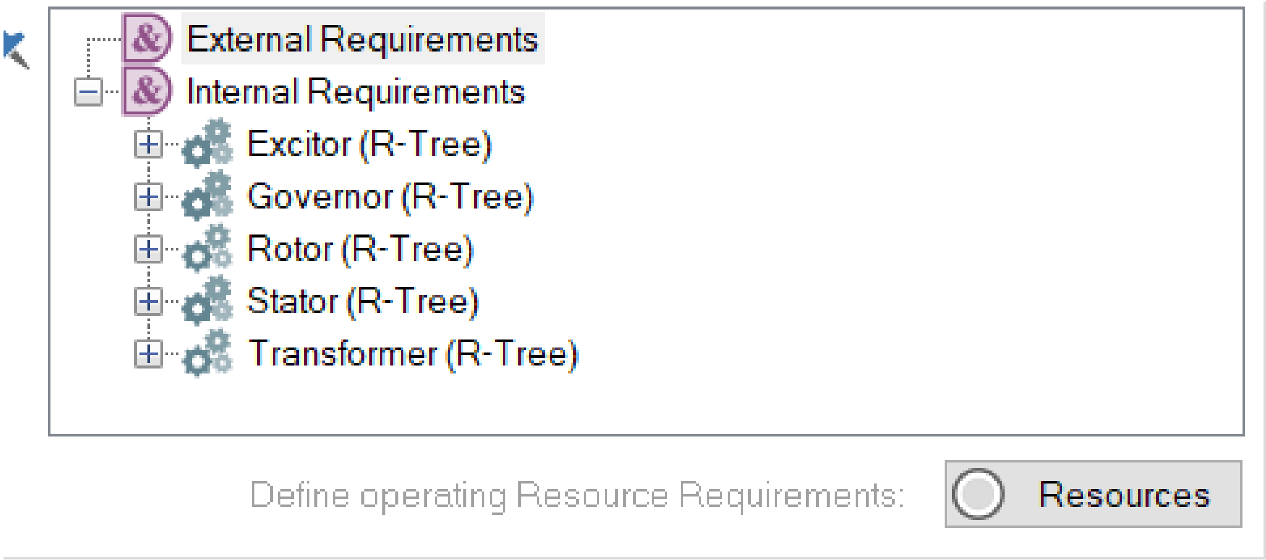


Figure 11. Turbine-1

The function constitutes for turbine failure it has Weibull Distribution acting as Reliability Component. Turbine discharge is the function that governs the inflow of water and it programed to fail when the flow is 50 m3/s. Figure 11 shows the system of Turbine 1.

6.4.2 Turbine System Fault Tree

The turbine system consists of components such as stator, rotor, excitor, governor and transformer and they are given Weibull parameters in their failure modes. This system is designed such that if one of the 5 components fails, then the whole system fails. Characteristic life of the components are based on Weibull parameters and they are given specific mean repair time during failures. The amount of water through the turbine is governed by the SEPA curve in addition to the upstream daily flow. Figure 12 shows the fault tree of the turbine components.



External Requirements
Internal Requirements
  Excitor (R-Tree)
  Governor (R-Tree)
  Rotor (R-Tree)
  Stator (R-Tree)
  Transformer (R-Tree)

Figure 12. Fault Tree of the turbine components

6.5 Grid Demands

The rating tables from SEPA is used for the function for addressing the power demands of the area. Figure 13 shows the Grid demand Function.

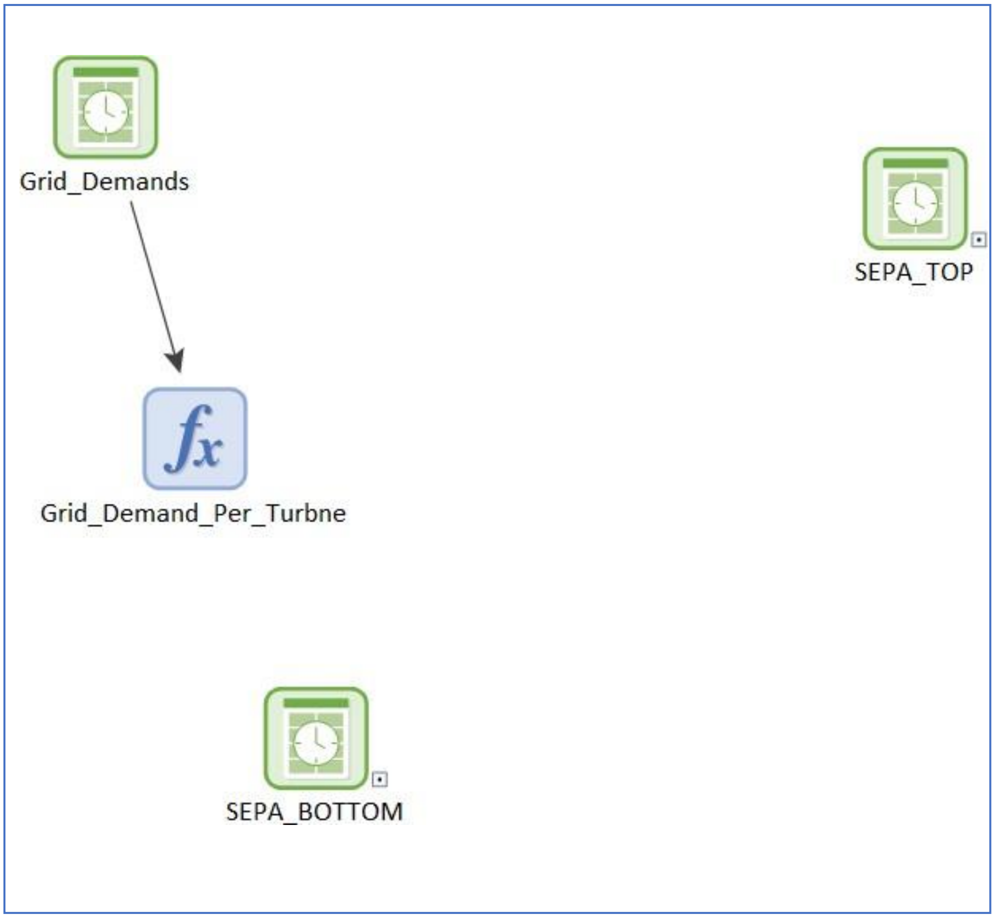


Figure 13. Grid Demand Function

7 Results

Using the model, simulations are conducted for a span of 50 years from 1960 to 2011 and the results are as follows: Figure 14 shows the graph of inflow outflow and pool elevation

1. Inflow vs Outflow vs Pool Elevations
2. Inflow History
3. Elevations
4. Flows
5. Turbine Discharge
6. Power Generation vs Flows

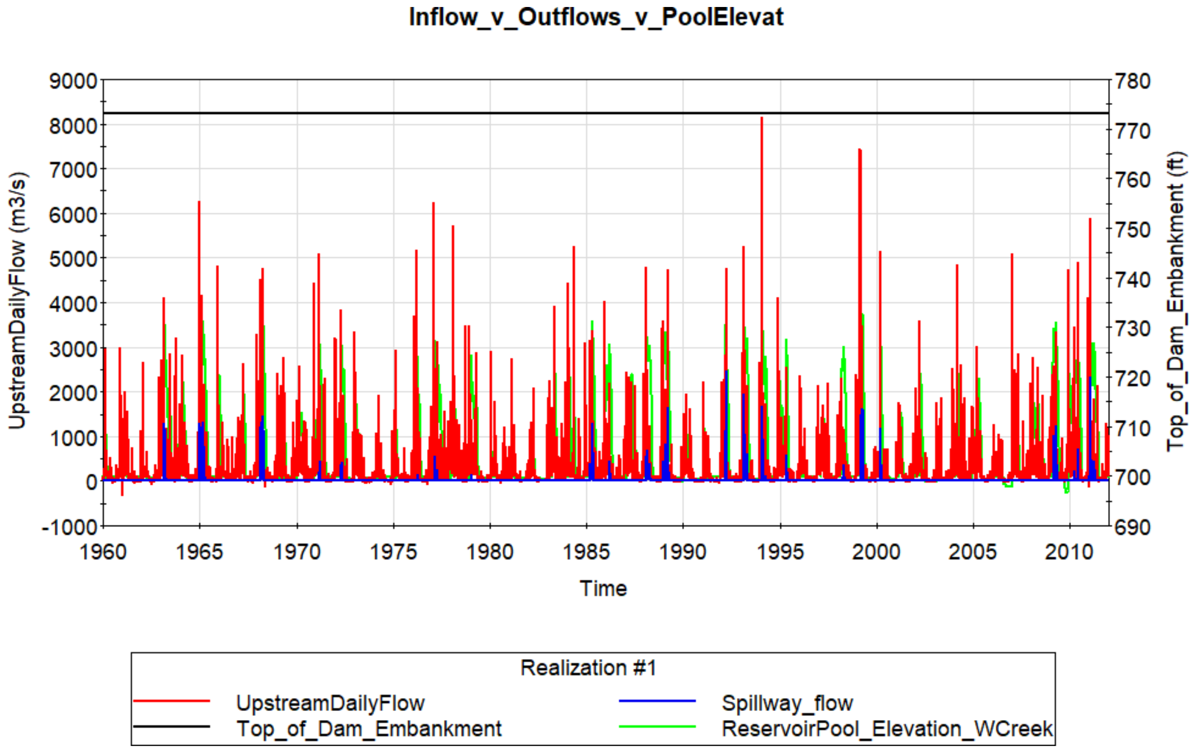


Figure 14. Inflow vs Outflow vs Pool elevation

The graph above depicts the upstream daily flow, spillway flow for the 52 years of simulation. From analysis it is visible that the dam does not overtop over the 50 years but does come dangerously close to the top of the dam embankment. This opens an avenue for simulating the dam for the following 50 years (100 years total) from the present day to see if the dam overtops in the future. Figure 15 shows the elevations of the dam and figure 16 shows the inflow history.

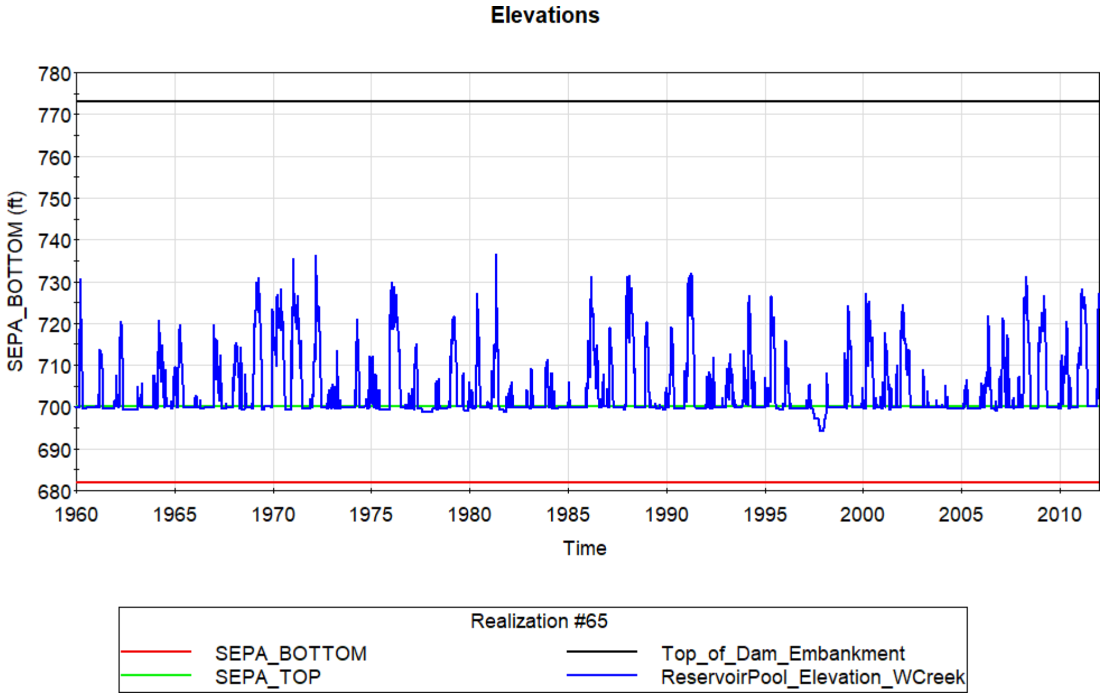


Figure 15. Elevations

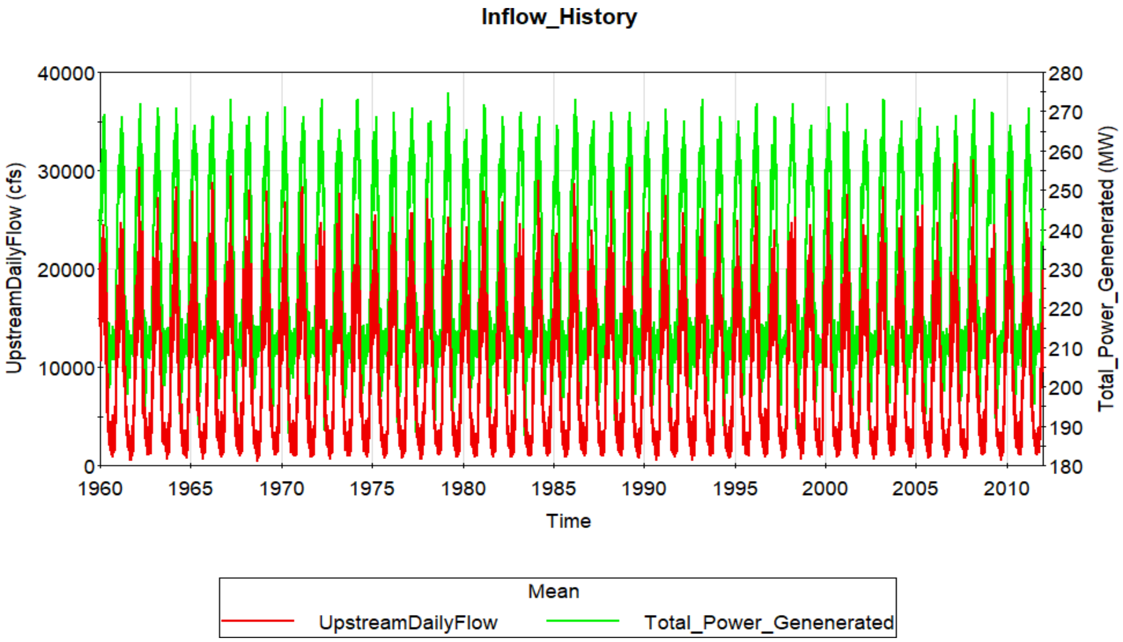


Figure 16. Inflow History

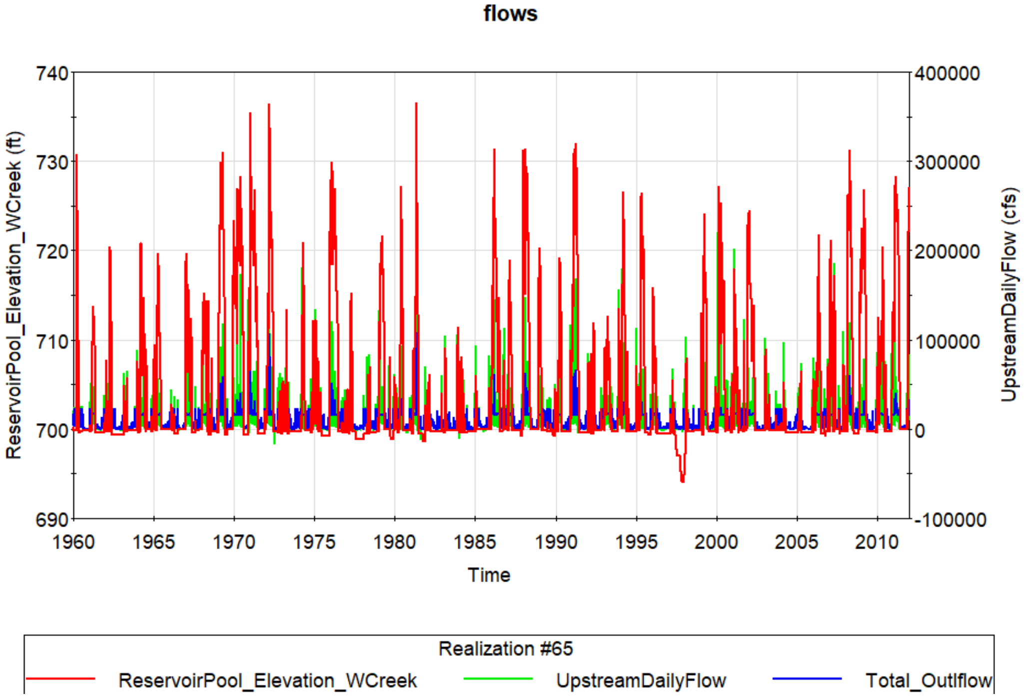


Figure 17. Flows

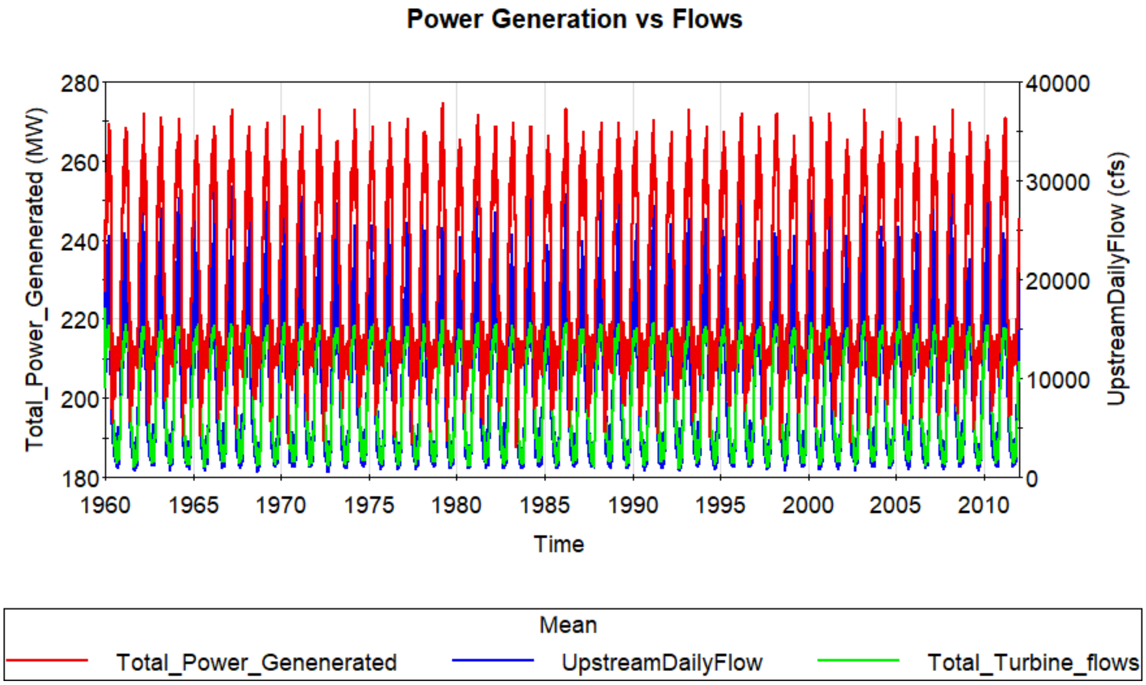


Figure 18. Power Generation vs Flows

The *GoldSim* Model also simulates the turbine and their failures. The turbines are modelled such a way that if one of the components fail, then the whole turbine system fails. Weibull data where used for the turbine components.

With six working turbines in the system, following are the results for Turbine Discharge and the number of failures over the simulation period. Failure rates of the system are based on the Weibull parameters. Figure 18 shows the power generation vs flows graph.

Turbine – 1

Following is the graph that shows the discharge of water through turbine-1

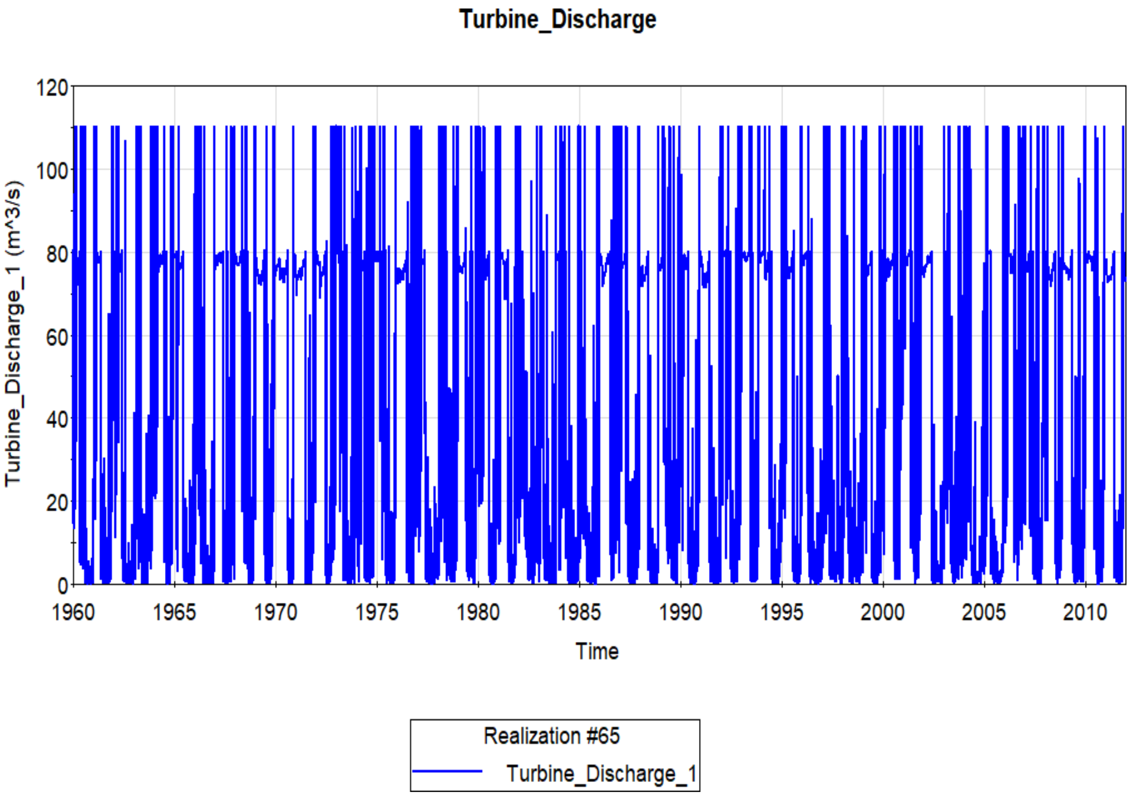


Figure 19. Turbine Discharge-1

Figure 19 shows the wavering flow of water through various months of the year from 1960 to 2010. It indicates that when the turbine fails, the model is programed to allow no discharge to flow through the turbines.

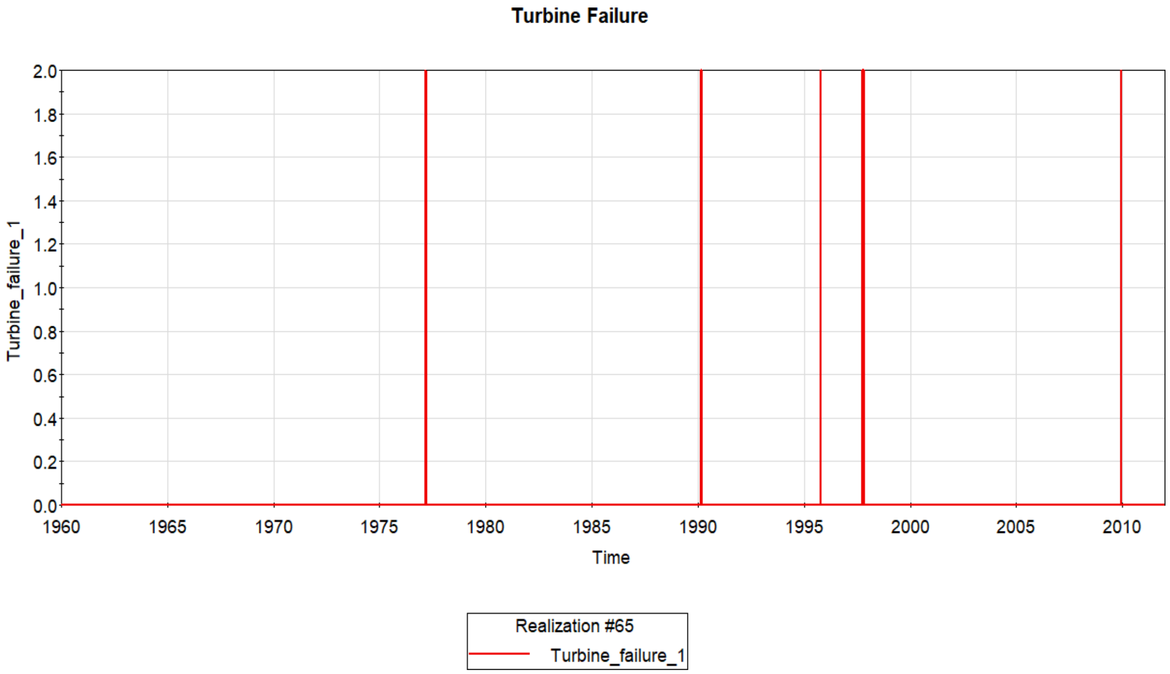


Figure 20 Turbine Failure-1

Figure 20 shows the number of failures in the turbine. As indicated the turbine fails 5 times over the 50 years with just one failure in the first 40 years of service. As the machine goes above 40 years, the turbine ages according to the Weibull model and fails more number of times as most of the components are reaching their max life.

Turbine – 2

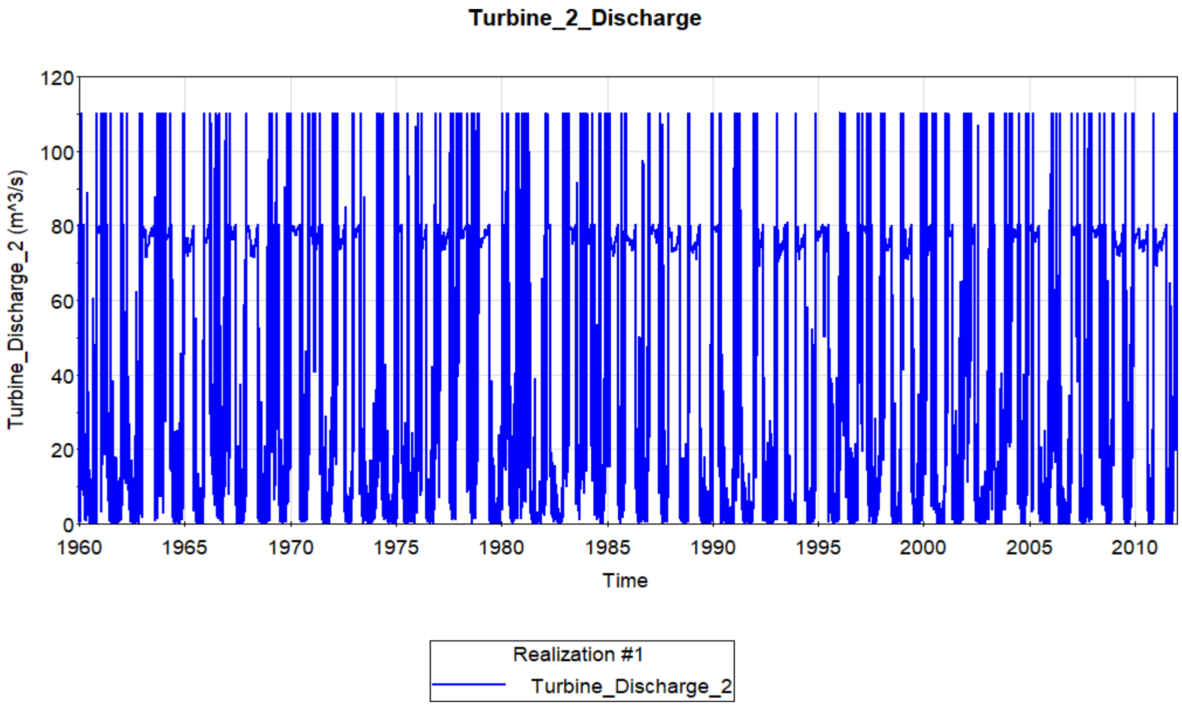


Figure 21. Turbine Discharge-2

Figure 21 shows the wavering flow of water through various months of the for Turbine year from 1960 to 2010. It indicates that when the turbine fails, the model is programed, as above for Turbine-1, to allow no discharge to flow through the turbines.

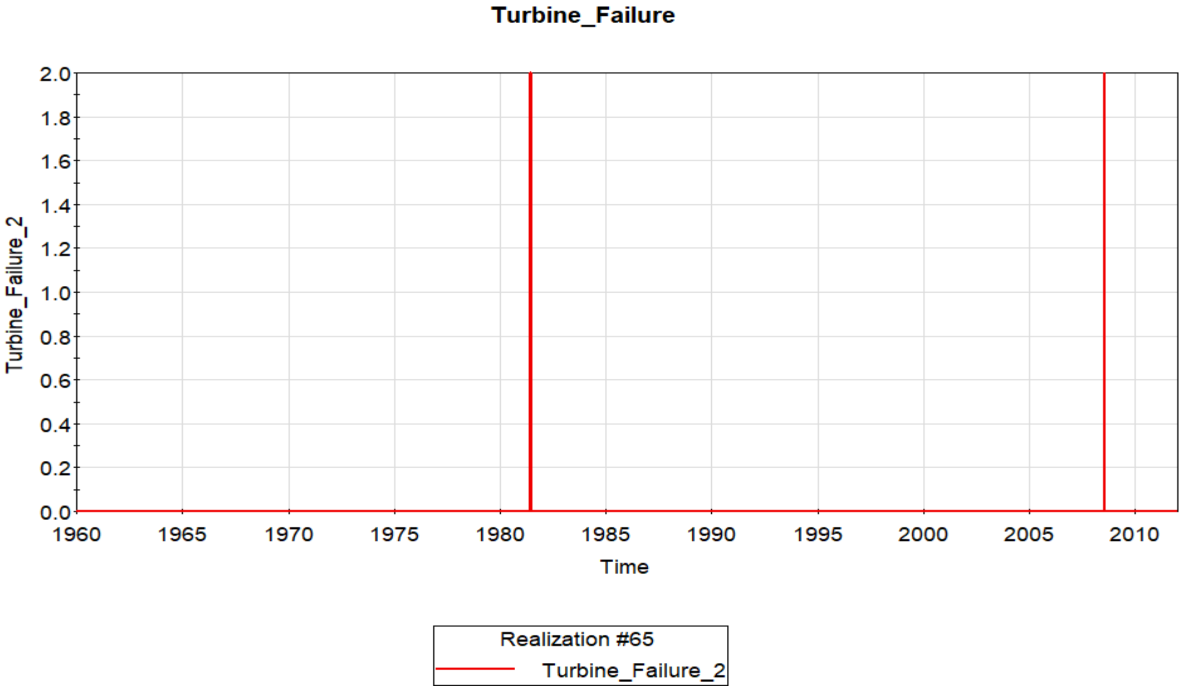


Figure 22. Turbine Failure 2

Figure 22 indicates the failures in Turbine 2. Over the 50 years, the turbine fails only two times with same Weibull parameters for the components. On an average, this turbine has failed once in about 25 years which could mean that the governor must have failed the first time as it has a life span of 25 years.

Turbine 3

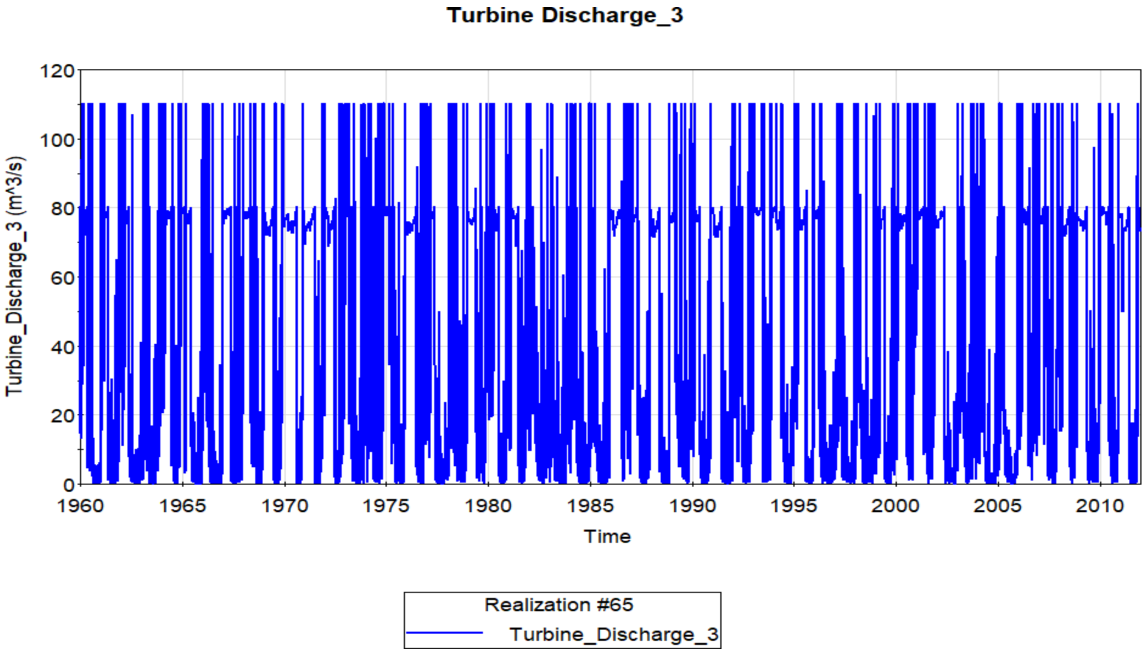


Figure 23 Turbine Discharge 3

Figure 23 shows the discharge in Turbine 3. On closer analysis we can understand that the turbines must have experienced failures in their components that are not far apart even though their failure is random.

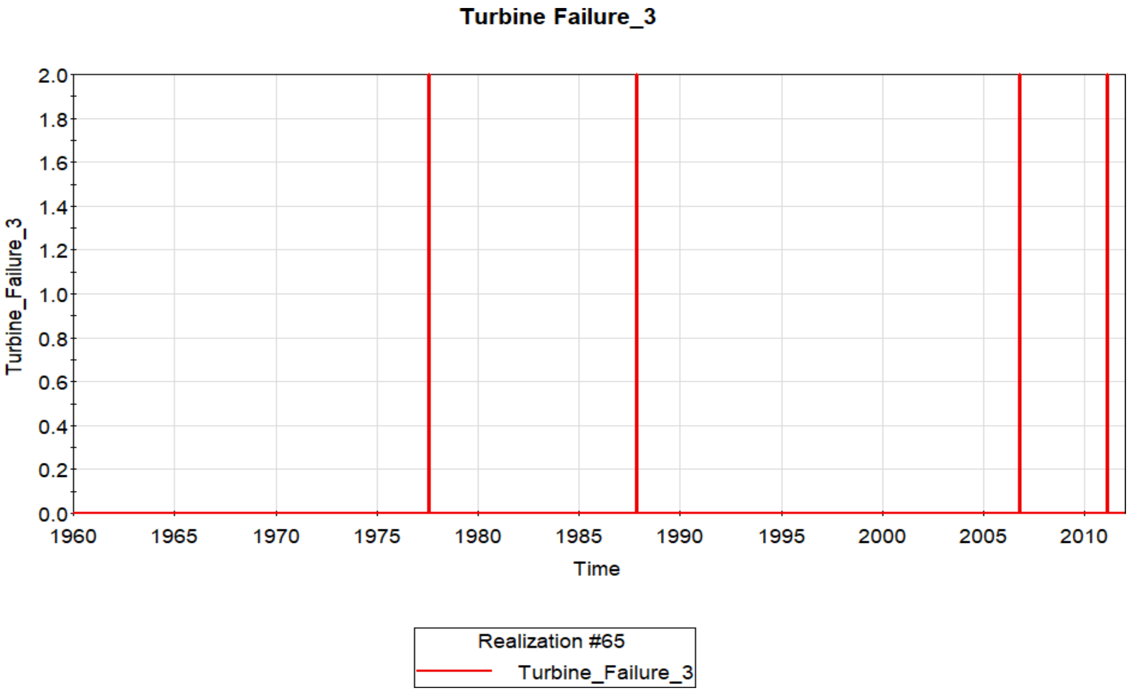


Figure 24. Turbine Failure 3

Figure 24 shows the number of failures in turbine 3. There have been 4 failures in the 50 years and the failures have a difference of about 10 years when compared to the failures at the end which have a gap of about 5 year. By analyzing the Weibull Parameters of the components, it is most likely that all are different components that have failed since they have much longer life than the difference in years from the failures.

Turbine -4

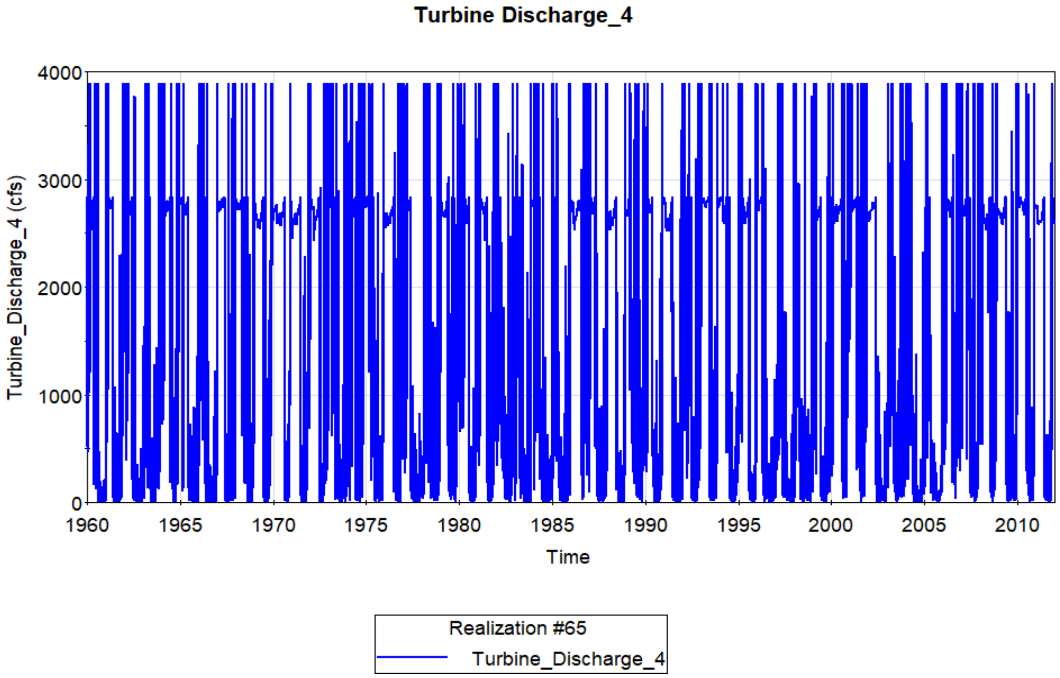


Figure 25. Turbine Discharge 4

Figure 25 provides the Turbine discharge of Turbine 4 for last 50 years. We can see that it hasn’t failed for the first 25 years with major number of failures coming towards the end.

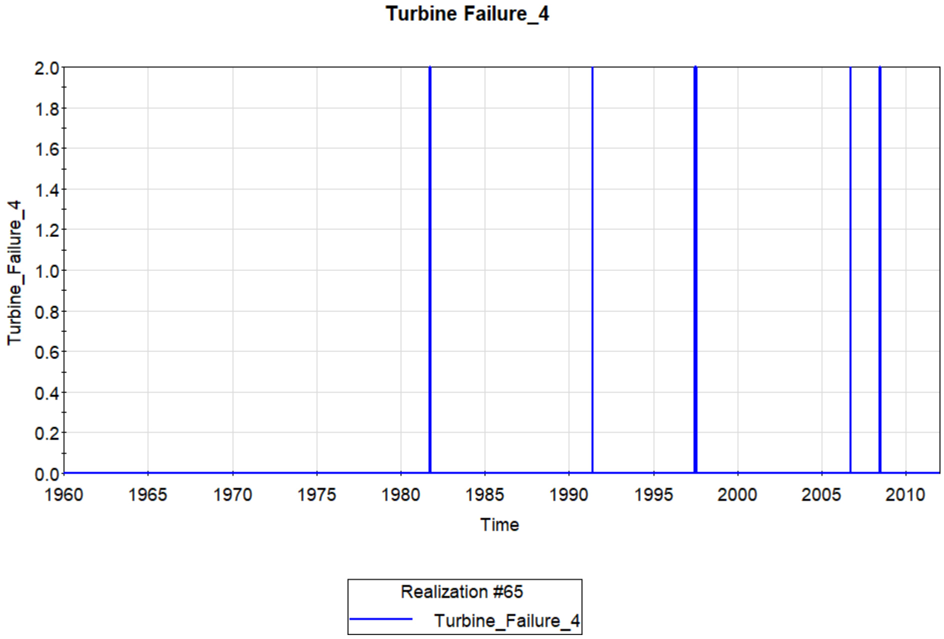


Figure 26. Turbine Failure 4

Figure 26 shows the failures in Turbine 4. One sees in this chart is few Turbine 4 failures in the first 50 years of operation, but as the Weibull aging begins to manifest, we see increasing failure rates in the second 50 years. Chances are that the governor must have filed twice indicating regular repair requirements for that component.

Turbine - 5

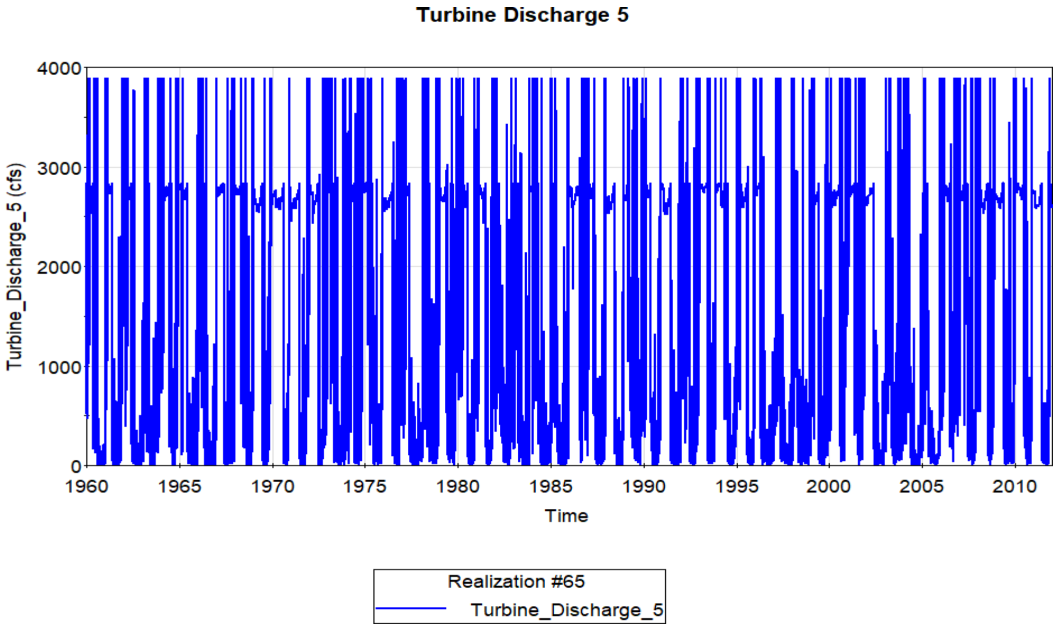


Figure 27. Turbine Discharge 5

Figure 27 shows the discharge of turbine 5 which is indicating that turbine hasn’t failed as much as other turbines as there are fewer points of zero discharge from the turbines

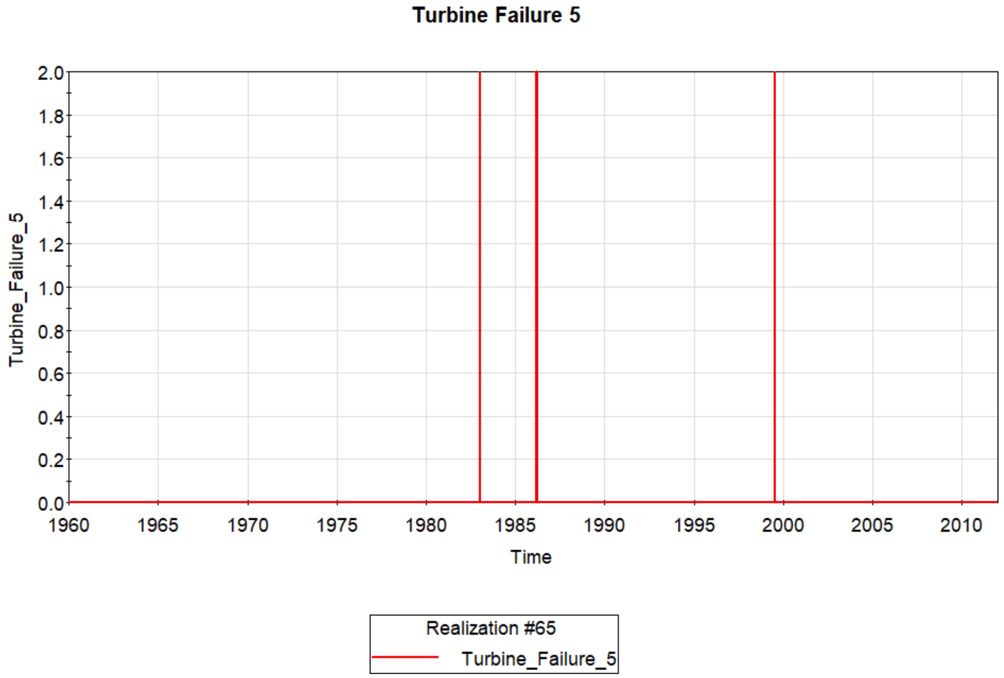


Figure 28. Turbine Failure 5

Figure 28 indicates that there were only three failures in Turbine 5. The first failure has occurred at about 23 years indicating that the governor must have failed. The second failure most likely is the stator as it has a life of 40 years in usual.

'

Turbine 6

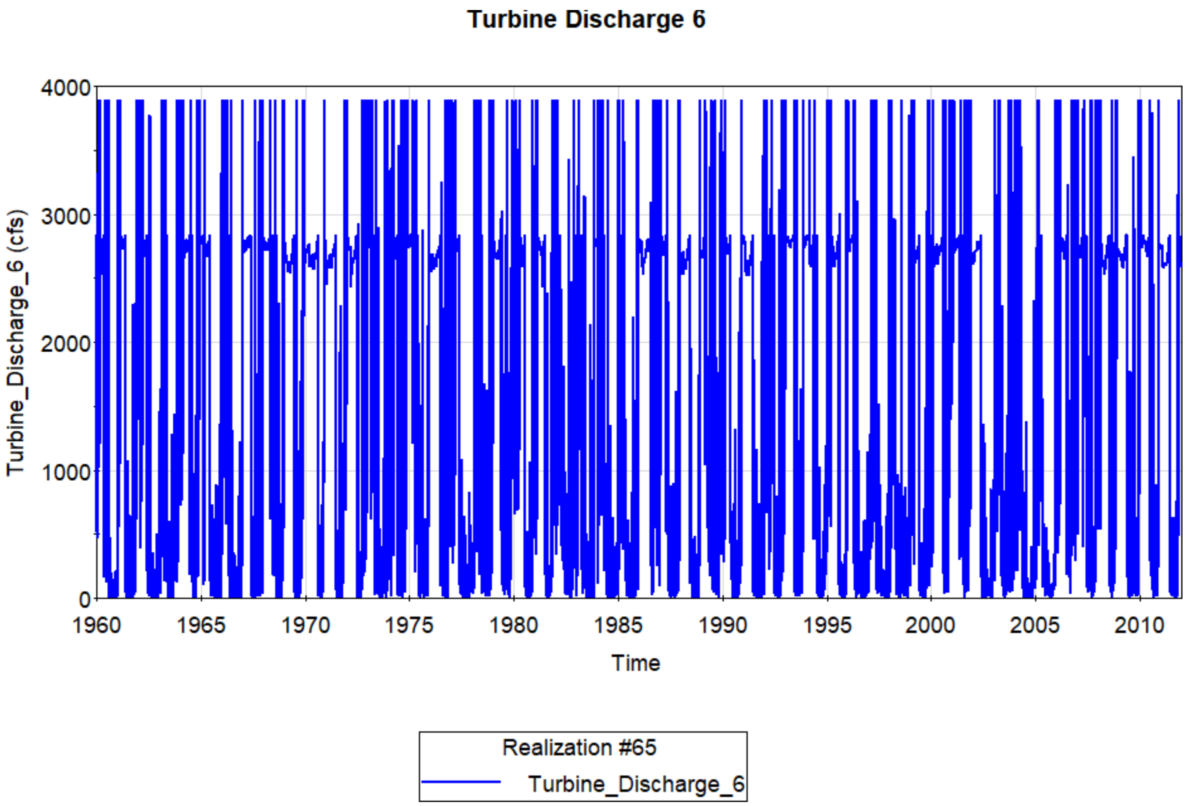


Figure 29. Turbine Discharge 6

Figure 29 shows the discharge from turbine 6 for the first 50 years of the service indicating failures within the first 20 years.

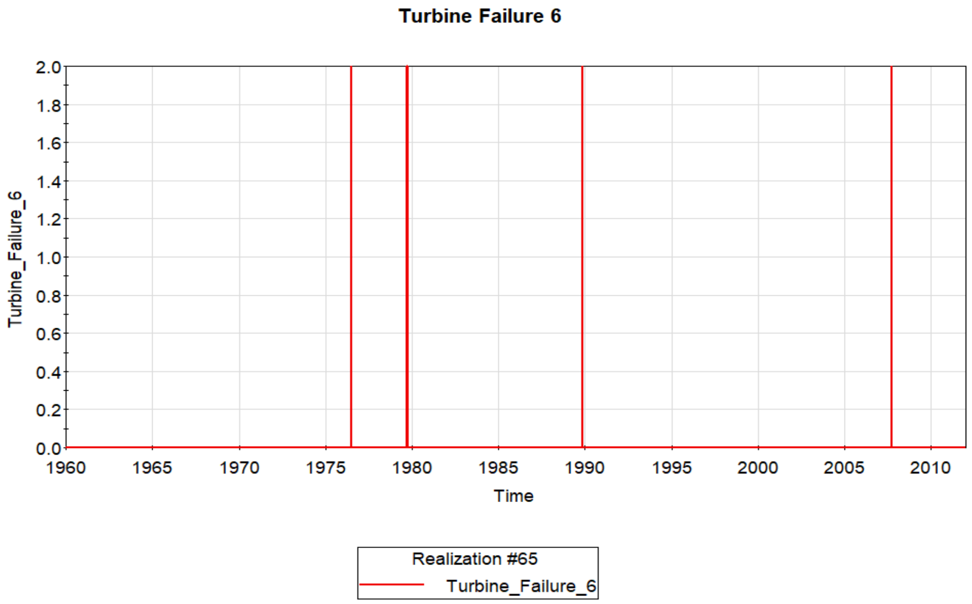


Figure 30. Turbine Failure 6

Figure 30 shows that Turbine 6 has failed four times in total in the first 50 years of service and the with two failure in the first 20 years which could possibly mean that the governor and the rotor must have failed. Looking at other failure, it might once indicate that stator would have failed gain since it is not too long after the first failure and it is having the least amount life when compared to other components...

The model was used to simulate the system and the six turbines from the years from 2019 to 2069 :

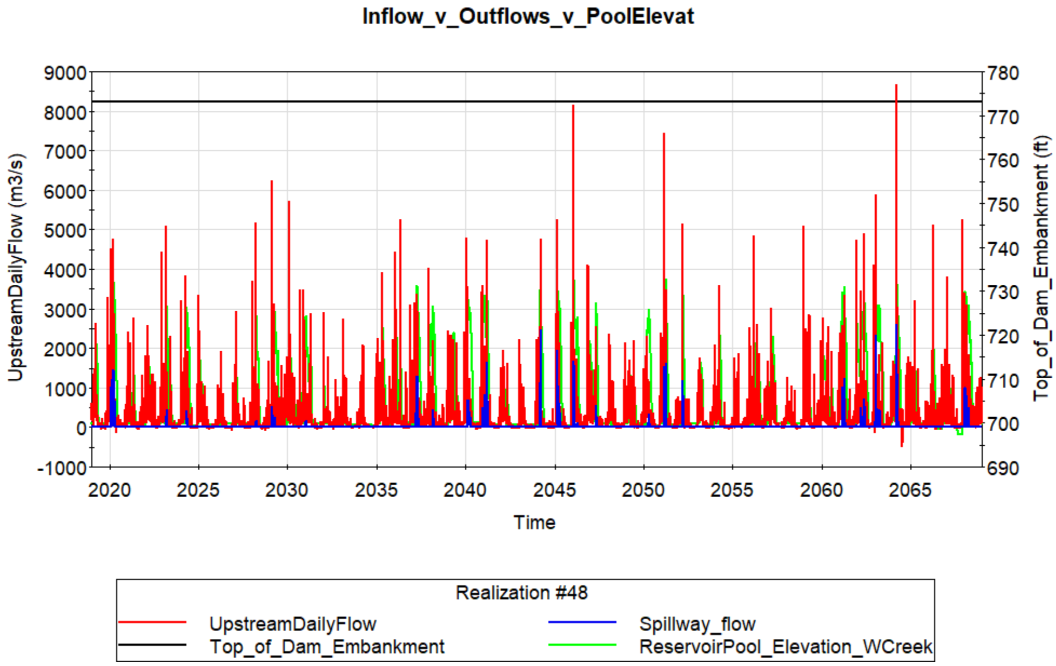


Figure 31. Inflow vs Outflow vs Pool Elevation

Figure 31 shows the Inflow, outflow and Pool elevation of the dam from 2019 to 2069. Form the graph we can see that the dam has over topped once compared to no overtopping in the last 50 years. Additionally, that dam has also very close to over topping in the year 2046 as well.

Turbine 1

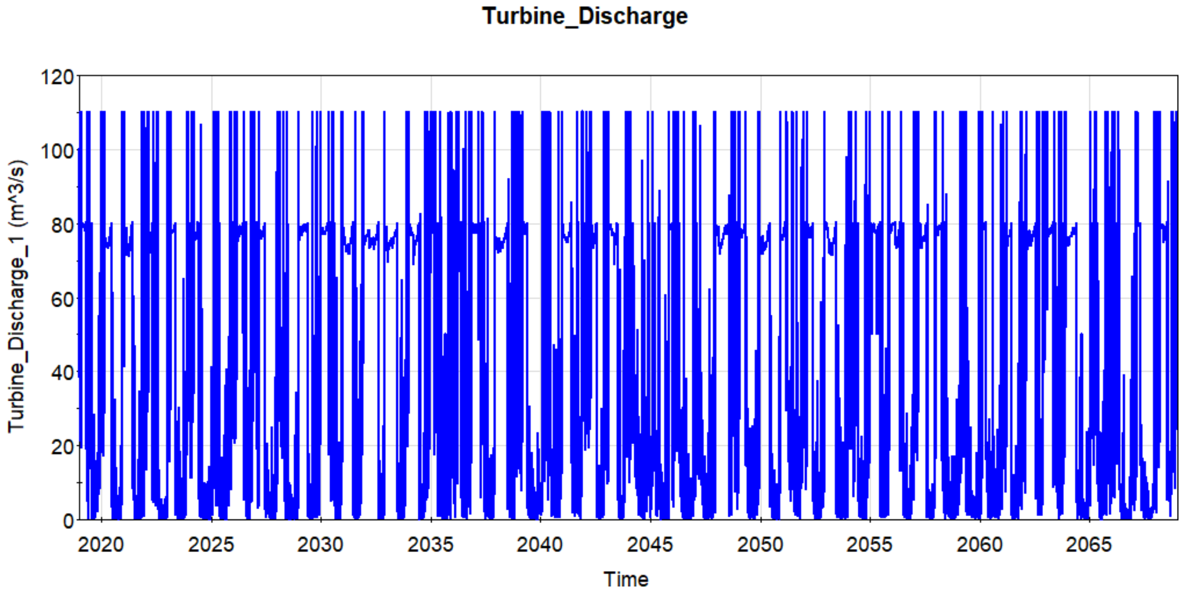


Figure 32. Turbine Discharge -1

Figure 32 shows the discharge in Turbine 1 from 2019 to 2069. Form the above graph, we can see that the turbine has failed many times towards the later stages of the 50-year period when compared to the failure rates in the last 50 years.

‘

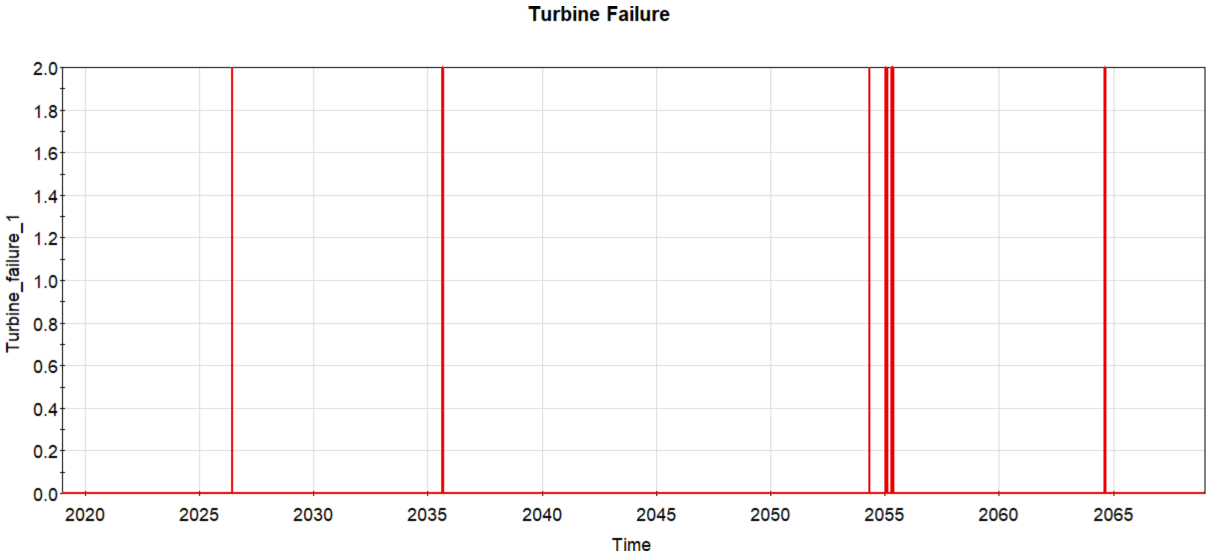


Figure 33. Turbine Failure – 1

Figure 33 shows that the turbine has failed 6 times which is more than the number of times it failed in the last 50 years. It can also be seen that turbine has failed within the first 10 years and then failed three after 40 years with failures happening with very little gap in between them. This may indicate that components such stator or excitors must have failed which have a life span of 60 years that might be the reason why they didn’t fail in the first 50 years.

Turbine 2

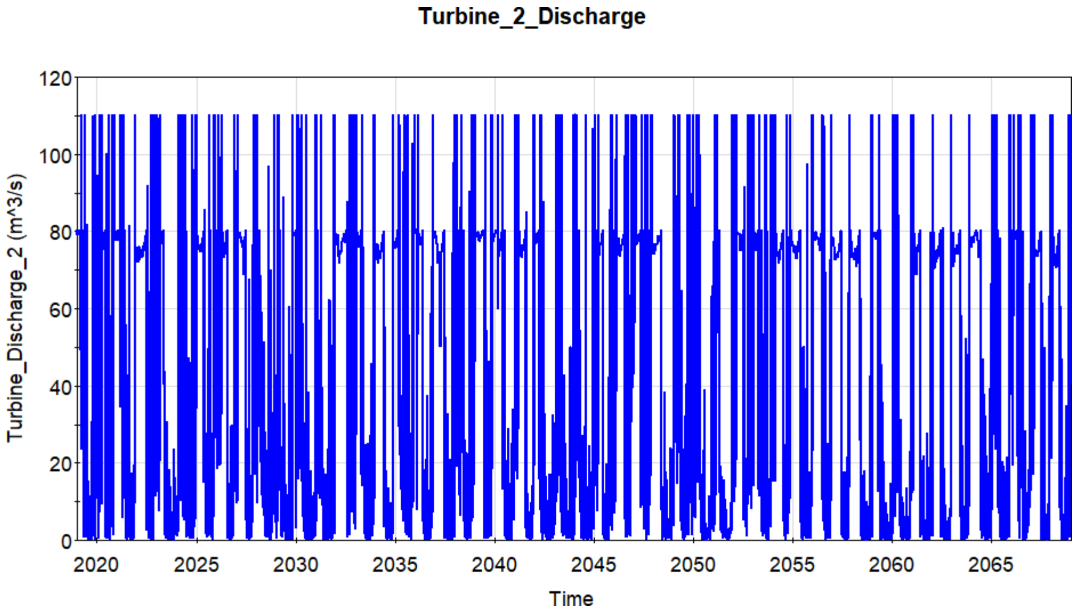


Figure 34. Turbine Discharge 2

Figure 34 shows the discharge from Turbine 2. Form the graph we can see that there were a few failures in the first 20 years of service with the last failure occurring after a very long time.

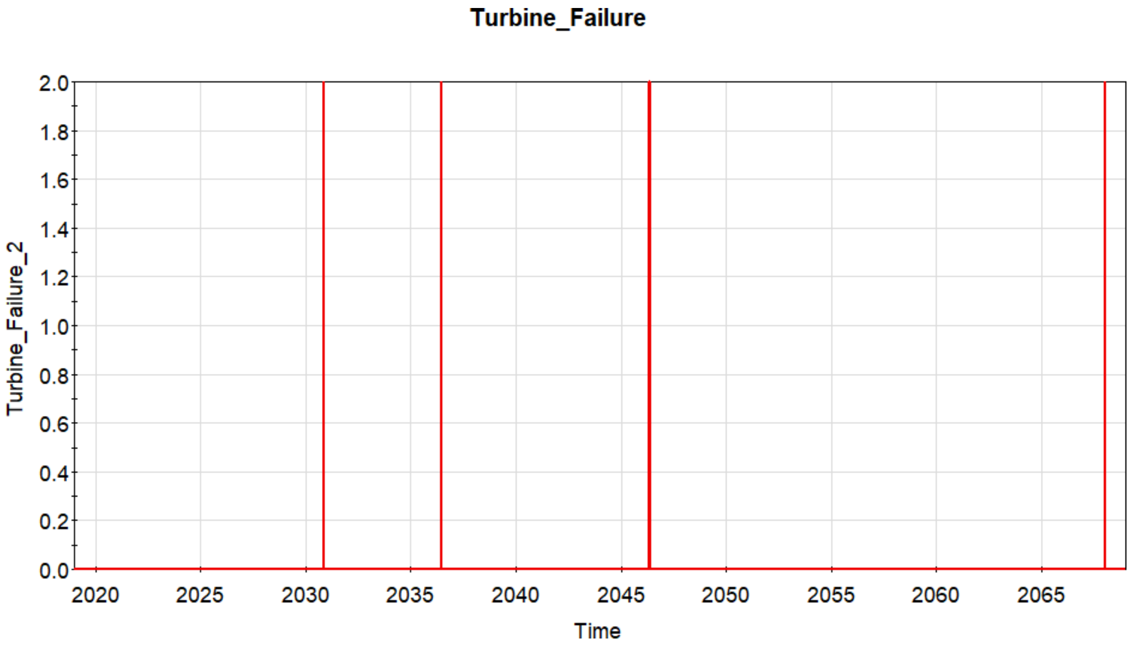


Figure 35. Turbine Failure 2

Figure 35 shows us that the turbine 2 failed four times totally and which is twice as much as it did in the first 50 years of the service. With four failure occurring, it could mean that components such as the Rotor which have life span of 98 years have started to fail which didn't fail in the first 50 years.

Turbine 3

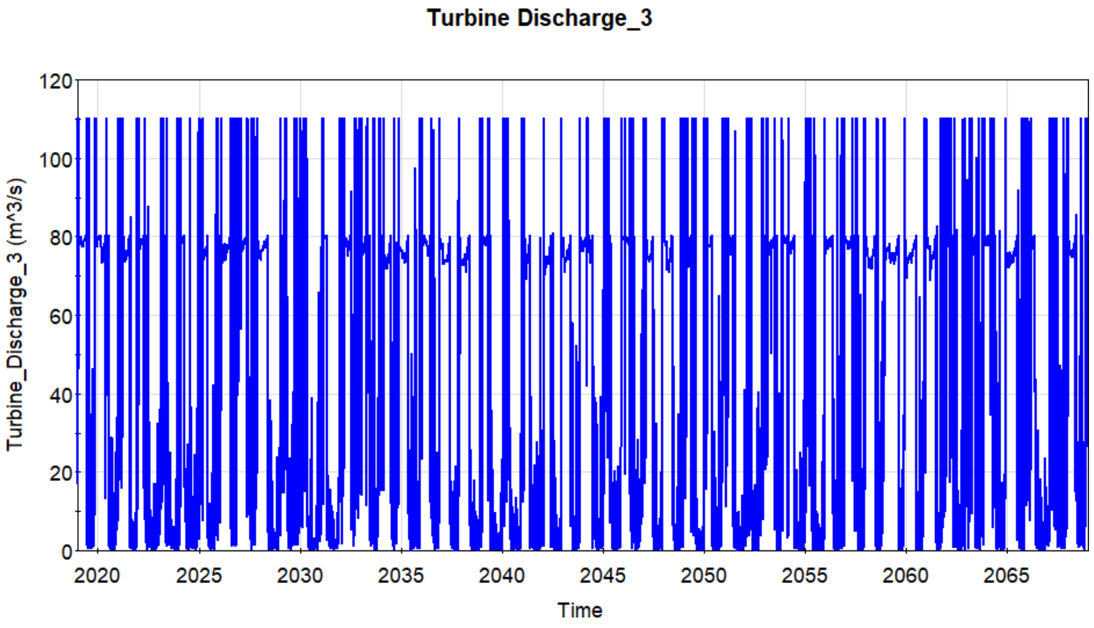


Figure 36. Turbine Discharge 3

Figure 36 shows the turbine 3 discharge. From the graph, we can see that see that the turbine failed quite a few times with many closely spaced failures towards the end of the 50 years.

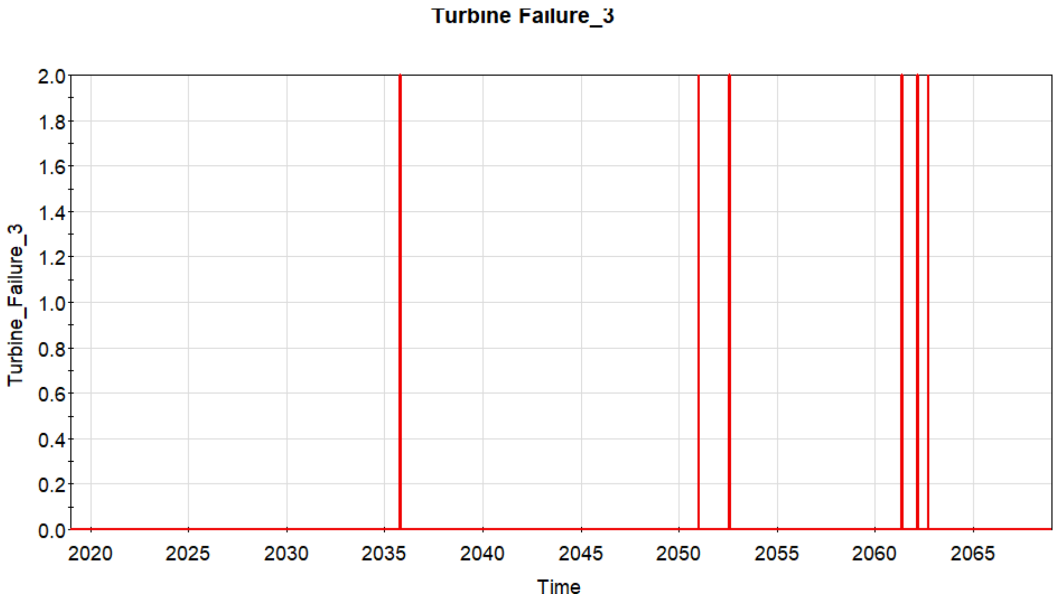


Figure 37. Turbine Failure 3

Figure 37 shows that the turbine 3 failed 6 times in the last 50 years with three failures between the span of 5 years from 2060 to 2065. These failures are very closely spaced which could mean that shorter life components like governor have failed with longer life components such as the Rotor which must failed with them at a similar time indicating major repair requirements.

Turbine 4

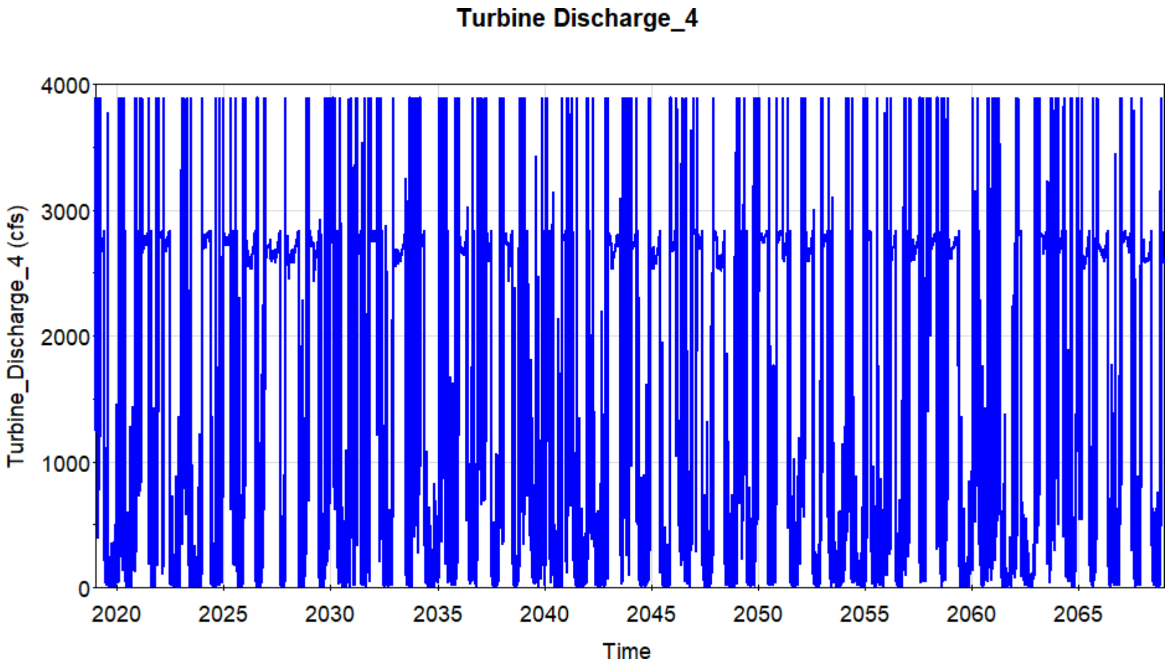


Figure 38. Turbine Discharge 4

Figure 38 shows the Turbine 4 Discharge. From the graph we can see that there were very few failures in the system and the all occurred in the later stages of the 50 year service.

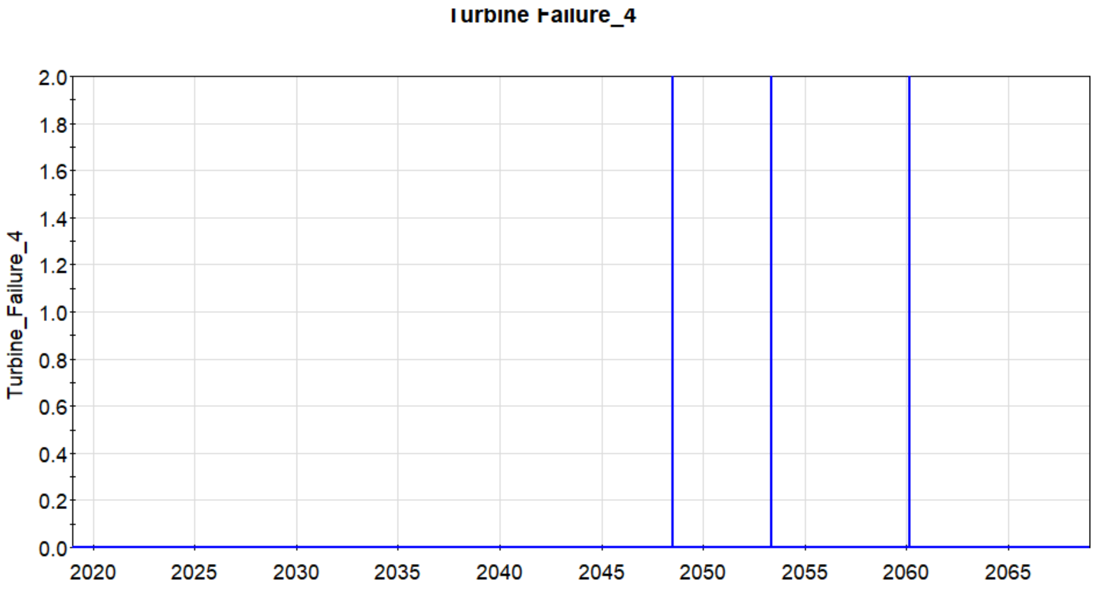


Figure 39. Turbine Failure 4

Figure 39 shows us that there were three failures the in the 50-year span and there were no failures in the first 25 year. This turbine failed lesser number of times than it it did in the past 50 years. Since the no components failed in the first 25 years, it could mean that components such as the Rotor or transformer must have failed first as they have long life spans.

Turbine 5

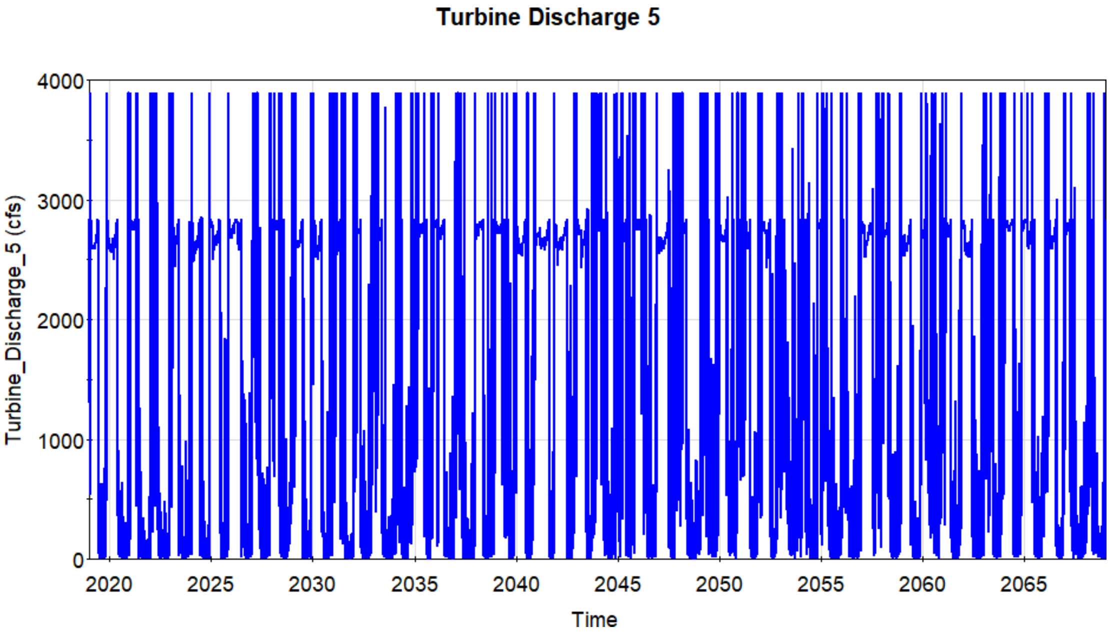


Figure 40. Turbine Discharge 5

Figure 40 graph shows the discharge from Turbine 5. From the graph we can see that turbine has zero discharge lines very close to each other meaning the failures very tightly spaced in the end of the 50-year period.

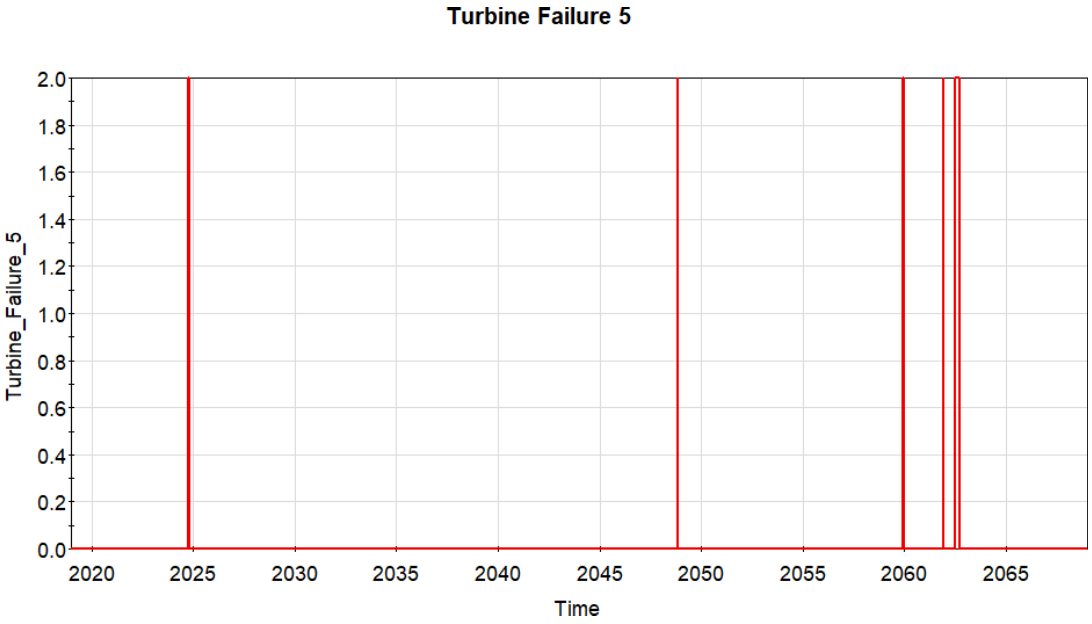


Figure 41. Turbine Failure 5

Figure 41 shows us that turbine 5 failed six times which is twice as much as it did in the past 50 years. This means that as the Weibull aging occurs, the components are more susceptible to failures and can cause a clash of many components to fail at the same time causing heavy repairs and long period of inactivity.

Turbine 6

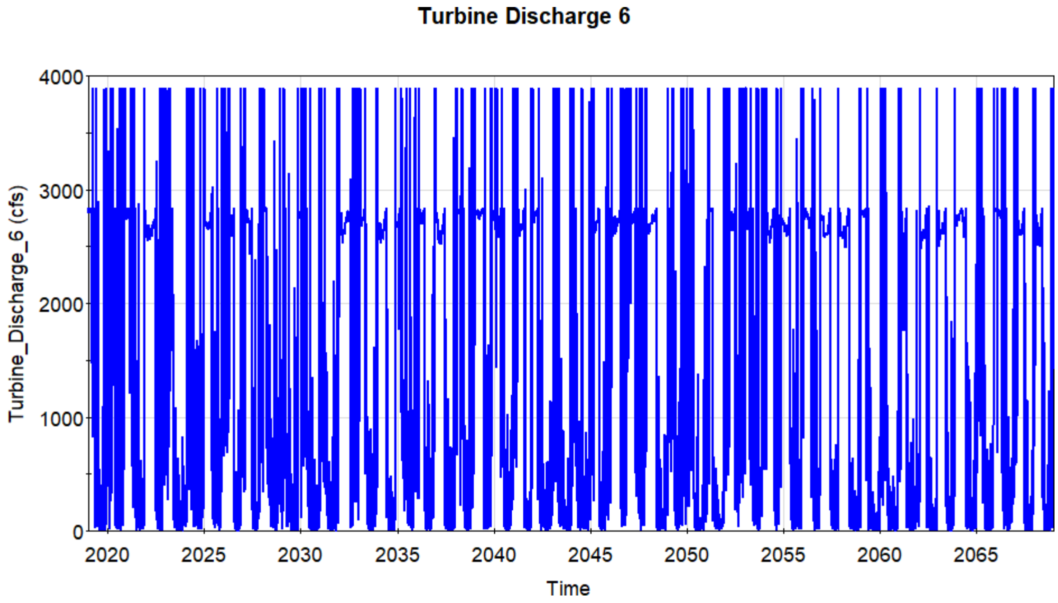


Figure 122. Turbine Discharge 6

Figure 42 shows the discharge from turbine 6. On analysis we can see that there was steady flow in the first 15 years, but the system faced regular failures later on throughout the rest of the working time of the 35 years remaining.

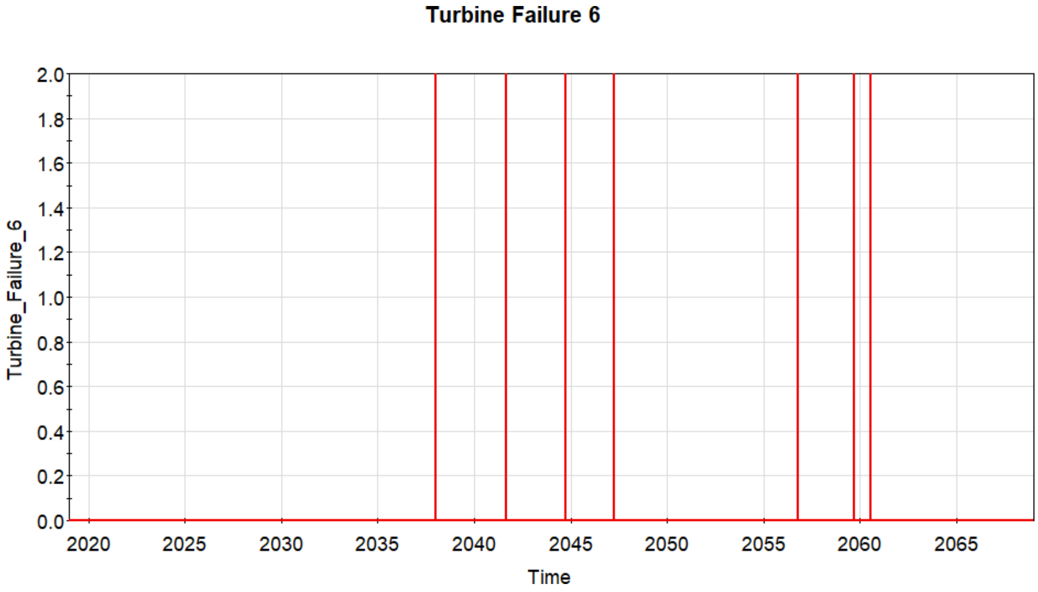


Figure 43. Turbine Discharge 6

Figure 43 shows that the turbine failed 7 times in the 50-year span with the possibility that all the 5 different components must have failed as the graph from past 50 years shows only 4 failures that occurred out which 3 failure happened in the first 25 years of service.

8 Analysis and Interpretation

The 100-year simulations were conducted 10 times to observe similar overtopping in the system as observed in the chapter before. Out of the 10 simulations, the GoldSim model predicted the dam to overtop three times. It was noticed that the overtopping occurred in the different years each time. Out of the three occurrences of overtopping, one of them occurred in the year 2045 but other two overtopping both occurred after 2050.

On further analysis, it was observed that overtoppings occurred in Spring months such as April and May when the water flowing through the system is the highest compared to other months of year. Additionally, the state of Kentucky records highest levels of rainfall in those months.

Following figure 44 are the graphs of the overtopping observed in the years in discussion.

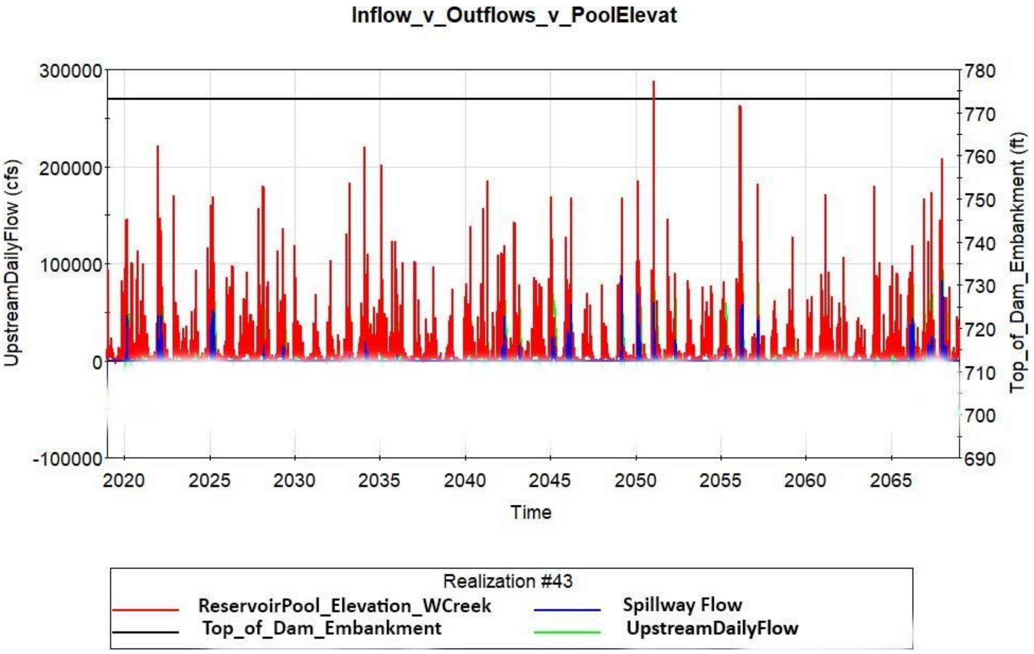


Figure 44. Inflow vs Pool elevation for 2051

From the above graph we can see that the dam overtopped in the early months of 2051 and the reservoir elevation came close to the top of the dam in the early months of 2056 as well.

On the other hand, it is also interesting to notice that in the years when such overtoppings are observed, multiple turbines have failed.

In the case of the overtopping in 2054, the dam system had two turbines that failed due to Weibull aging. In addition, when the dam overtopped in the year 2051, the dam system had four turbine failures. Even though, the components had not reached close to their maximum life, we can see that those turbine failures occur exactly during the time when the overtopping occurs which causes serious damage to the system all at the same time. Following figure 45 are the graphs that depicts the overtopping of the year 2054.

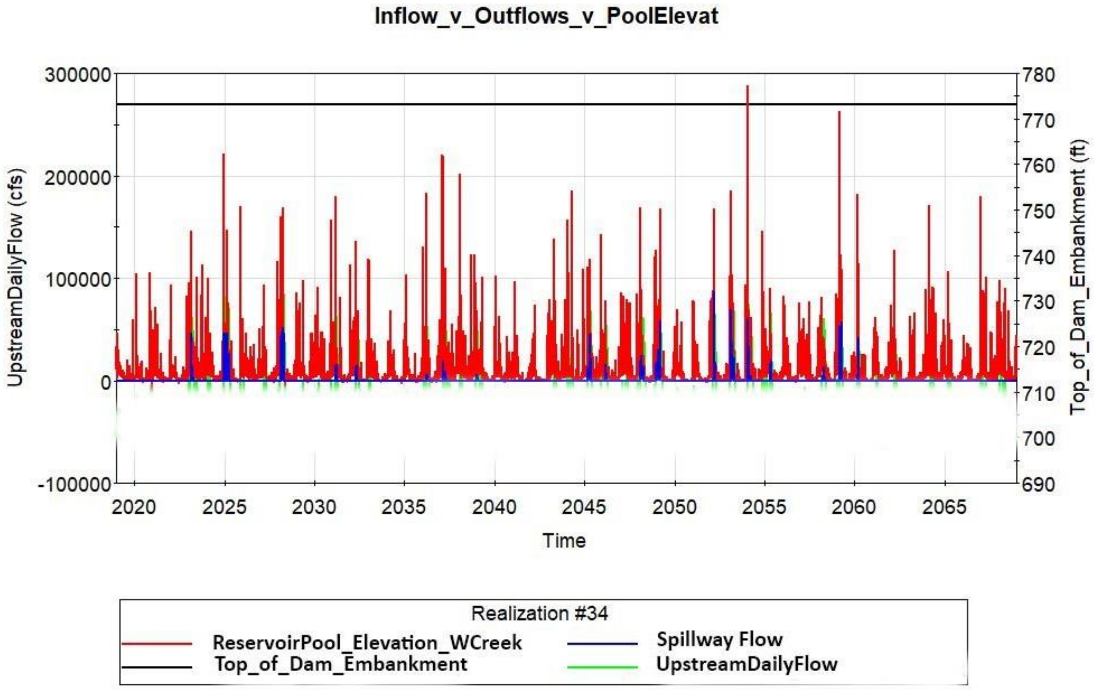


Figure 45.Inflow vs Pool elevation for 2054

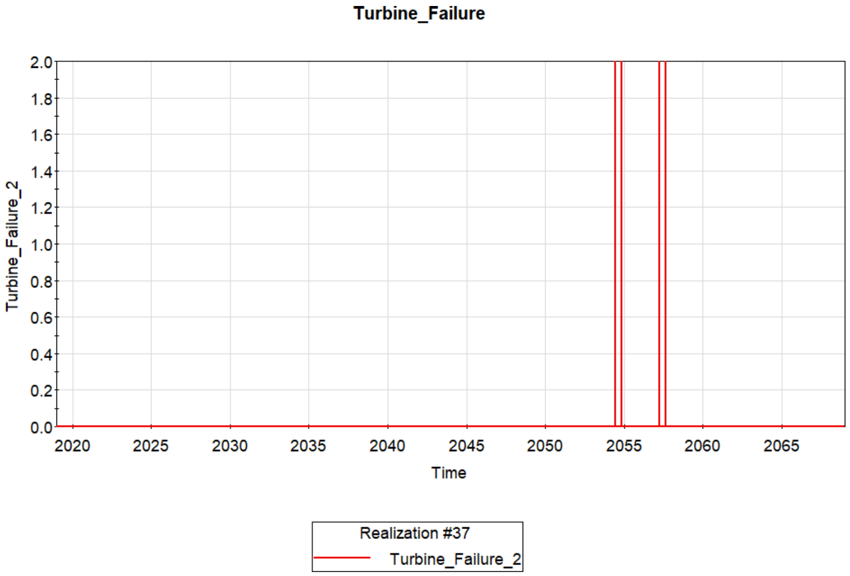


Figure 46. Failures in Turbine 2

One can see from Figure 46 that the turbine fails multiple times in the same year when the dam overtopped. Even though the gate opening condition governs that the spillways gate opens when the dam water goes above 723 ft, it is possible that the water during that time went above the discharge capacity of the spillway gates or the gates must not have opened on its own. Gates not only fail due to reliability issues but also fail due to errors in communication and control as well as human actions. With possibilities of such calamity to occur in the future, it is crucial that USACE is prepared with a maintenance schedule that can accommodate for repairs multiple failure in turbines as well as be prepared to mitigate the flooding of the dam on time.

9 Conclusion

This thesis aims to provide a structure and procedures to conduct simulation-based reliability analysis for investigating operational risks in complex dam systems. The use of Weibull distribution hydropower components provides a versatile tool for developing reliability curves using the Reliability Module of *GoldSim*.

The first conclusion of the present work is that the simulation approach appears to offer insights into the reliability of hydropower operations that may otherwise not be easily apparent. The simulation allowed for the systems-engineering aspect of hydropower operation to be investigated. It also allowed for the interplay between natural hydrological conditions and the time-dependent reliability of mechanical and electrical systems to be investigated. While these things are possible to analyze in more traditional approaches, the simulation approach makes a much more easily accomplished.

By utilizing Weibull Curves, the operator can be assisted with safety recommendations for hydropower components and to devise future strategies for an efficient system. The baseline Weibull distribution also permits the development of fault trees for hydropower plants to model both reliability and availability of these systems to assist and establish reliability centered maintenance practices. The information from this thesis can also be used to assist in developing improved maintenance and replacement policies for the USACE inventory of hydropower assets.

Wolf Creek dam has not overtopped in the last 50 years. However, going forward, the model suggests that continuing deterioration of the operating reliability of gate and turbine components, it is possible that overtopping could occur in future years unless steps are taken to maintain or replace component equipment. In the simulations, such overtoppings occur as soon as 25 years from present.

With recent issues of massive rain in the Jamestown area, the dam has experienced record level water that were later released into the Cumberland River. In the past, Wolf Creek dam has undergone significant repairs costing $600 million on its foundation. Results from the simulation indicate that such repairs to the mechanical and electrical systems have a strong possibility of being needed in the next 50 years

Number of Failures in the 6 turbines compared to the last 50 years vs next 50 yearss

Turbine	**Last 50 years**	**Next 50 years**
Turbine -1	5	6
Turbine – 2	2	4
Turbine – 3	4	6
Turbine – 4	5	3
Turbine – 5	3	6
Turbine – 6	4	7
Total	23	

Table 3. Number of Failures in the Turbines

As the above table suggests, the number of failures in the turbines increase in the next 50 years compared to the past records. In various turbines, the consecutive failures occur in years very close to one another which indicates a huge problem as constant repairs may be required in the future. With increasing possibility of natural calamities, these failures may occur sooner than expected in greater causing more money to be shelled out for repairs. The results from this thesis indicate that Weibull Data has helped conducting efficient risk analysis of complex dam systems and show that more investment must be made to improve the reliability of dam components for establishment of stable hydropower establishment.

10 Future directions for this work

A variety of future directions for this work suggests themselves. Among the more important of these are the following four:

1. Investigate the influence and importance of operator actions and human reliability on hydropower operations.
2. Evaluate the benefits of reliability-centered maintenance plans for dam operation under the condition of Weibull aging and for asset management.
3. Because the spillway gate systems may remain dormant for years at a time, the effect of dormant-reliability models on gate operations should be considered.
4. In the present study the interaction of hydrology and mechanical-electrical system operation was investigated. However, hydropower facilities like Wolf Creek are also subject to a number of other constraints, the most important of which are variations in grid demands, and the maintenance of downstream and environmental flows. Neither of these is considered here but both are important to the reliable operation of hydropower assets.

APPENDIX

Weibull data for Gate Components (adapted from Hartford et al. 2016)

Flow-control in hydropower and related dam systems is a complex system involving civil, mechanical, electrical, communications and control components. These systems components interact in complex ways, and failures of flow-control systems involve not only reliability failings of physical components but also the interactions of these components with communications and control, and with human actions and errors. An analysis of the performance of the system needs to incorporate all these aspects

Commonly, fault tree analysis (FTA) for mechanical and electrical gate components uses Weibull distributions to model the reliability or availability of interim or top events (Patev et al., 2013)^{b}. FTA commonly uses a two parameter Weibull distri- bution on time to failure, t,

and zero elsewhere. The parameter b is a shape factor or the slope of the Weibull pdf, which determines which member of the family of Weibull failure distributions best fits or describes the data. The parameter a is a scale factor or the location of the pdf which determines the central tendency of the distribution and the mean time between failures

The slope or shape parameter, b, indicates which class of failures is present:

b , 1.0 implies infant mortality,

b = 1.0 implies random failures independent of age, and

b . 1.0 implies wear out or old-age failures.

The characteristic life or alpha, a, of a component is related to the Mean-Time-To-Failure (MTTF) and the failure rate, l. This relationship is,

$$\mathrm{MTTF} = (1/l)\ ;\ aG(1 + 1/b) \qquad (2)$$

Note that the relationship between the characteristic life a and MTTF depends on b. For b = 1, MTTF = a. That is, for random failures independent of age, the failure rate, l = 1/a; thus, for this case, a might be thought of as a ‘return period’.

The current USACE mechanical and elecdtrical (ME) reliability methods use generic component failure rate data from US Department of Defense Military Standard 756B (DoD MIL-STD-756B) documents. These failure rate data are processed for components that function in different operating environment, different failure modes, and different maintenance practices than at USACE navigation projects. Therefore, the reliability of the ME system from this data set yields conservative results and very often overestimates the time-dependent reliability of the entire ME system.

In response, USACE has undertaken work to develop improved reliability models for the ME gate components at inland navigation and flood risk management facilities. Table A shows a list of typical causes for failure events in the ME fault trees for spillway gates (Patev et al., 2005).

As noted in Section 8.2.3, failure data were collected by Schultz (2013) for mechanical and electrical components at 295 USACE flood control projects. These data have been processed for use in FTA for spillway projects. An estimate of the shape parameter, b, and characteristic life (in years), a, using both traditional Weibull plotting methods and Bayesian inference methods are shown in Tables B and C. These are representative estimates of the rates of gate component failures for both mechanical and electrical equipment (Mosleh and Zhu, 2013). For a description of the procedure for estimating the parameters of the Weibull distribution using the Weibull Plotting method see Kumamoto and Henley (1996), and for Bayesian inference see Dodson (2006).

The use of the Weibull distribution is a versatile and very powerful tool in developing baseline reliability curves for hydropower components. The most common use in engineering applications is the two parameter Weibull Distribution where the shape parameter and the characteristic life,The various shape parameters for different CDF of the Weibull . A three parameter Weibull is also frequently used to model a shift in the reliability for a set time period

Typically, characteristic life is based on assumptions such as the components having similar maintenance practices, no replacement of smaller internal parts, consistent or protected environmental and operating conditions and that all components are composed of materials that were properly selected and designed. Note that there is uncertainty in defining consistent or proper maintenance and the environment and environmental and operating factors.

aa	Component	Life(yrs)	β	α(yrs)
Exciters	Rotating DC	100	4.8	61
	Static	50	2.5	38
	Brusless AC	75	3.1	65
	Controllers	75	3.2	65
	Controllers analog	50	2.6	43
	Controllers digital	20	3.3	20
Stator	Windings less than 6900kV	75	3.3	62
	Windings greater than 6900kV multi turn	50	3.2	40
	Windings greater than 6900kV multi bars	50	3.4	44
	Cores	100	3.8	95
	Frame	100	3	30
Rotor	Windings	100	2.9	98
	Spider	100	2.66	109
Transformers	Up to and including 230 kV	100	3.3	66
	Above 230 kV	100	4	64
	GSU	100	3.4	77
	Station Service	100	3.5	82
Circuit Breakers	Inside powerhouse - vacuum	40	3.6	31
	Inside powerhouse - SF6	50	2.6	59
	Outside powerhouse - Gas	60	2.3	55
	Outside powerhouse - Oil	75	3	57
Turbines	Francis Type	100	3	102
	Kaplan	75	2.9	58
Governors	Digital	25	3.2	25
	Mechanical	100	2.5	80
Gates	Wicket gates	75	3.4	74

Table A1. 1. Summary of Weibull Parameters for Hydropower Equipment

References

1. Hartford, D. N. D., and Baecher, G. B. (2004). *Risk and uncertainty in dam safety*. Thomas Telford, London.
2. Komey, A. (2018). “A systems reliability approach to modeling operational risks in complex engineered systems,” PhD Dissertation, University of Maryland College Park.
3. Ahmadisharaf, E., & Kalyanapu, A. J. (2015). Investigation of the Impact of Streamflow Temporal Variation on Dam Overtopping Risk: Case Study of a High-Hazard Dam. https://doi.org/10.1061/9780784479162.103
4. Jordan, P., Seed, A., Nathan, R. J., Hill, P., Kordomenidi, E., Pierce, C., & Leonard, M. (n.d.). Stochastic Simulation of Inflow Hydrographs for Wivenhoe and Somerset Dams. *Ancold 2014*, 1–8.
5. Komey, A., Deng, Q., Baecher, G. B., Zielinski, P. A., & Atkinson, T. (2015). Systems Reliability of Flow Control in Dam Safety. *12th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP12 Vancouver, Canada, July 12-15, 2015*, (September), 1–8. https://doi.org/10.14288/1.0076195
6. Sivakumar Babu, G. L., & Srivastava, A. (2010). Reliability Analysis of Earth Dams. *Journal of Geotechnical and Geoenvironmental Engineering*, *136*(7), 995–998. https://doi.org/10.1061/(asce)gt.1943-5606.0000313
7. Westberg Wilde, M., & Johansson, F. (2012). System Reliability of Concrete Dams with Respect to Foundation Stability: Application to a Spillway. *Journal of*

Geotechnical and Geoenvironmental Engineering, *139*(2), 308–319. https://doi.org/10.1061/(asce)gt.1943-5606.0000761