RELIABILITY-BASED HYDRO RESERVOIR OPERATION MODELING

by

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Abstract

A wide variety of factors make reservoir operation a complex and dynamic problem, including multiple operational objectives, hydrological uncertainties and dam safety considerations. Concerns have grown in recent years regarding reliability of existing hydropower storage and discharge facilities, as many of these facilities are aging and their failure could significantly impact reservoir operations and pose threats to dam safety. A number of reliability methods were investigated in this study and a formal reliability analysis process has been adopted to assess the reliability of water release facilities using censored failure data. The nonparametric product-limit estimation method was used to analyze the time-dependent reliability of different types of spillway gates and hydropower turbines, and parametric model fitting techniques were subsequently applied to fit reliability functions. Failure and repair events were simulated using Monte Carlo simulation, which provided random variables to capture the uncertainty of availability for hydro facilities. The reliability analysis process was integrated into a simulation-optimization operations planning model to develop a reliability-based modeling framework that quantitatively treats risk and uncertainties in hydro operations. A specific reservoir system in British Columbia was selected as to illustrate the model application. Results and analyses provided guidelines for evaluating and comparing alternative reservoir operating plans that incorporate reliability assessment and failure simulation. It is demonstrated that dam overtopping is more likely to occur due to a simultaneous occurrence of high inflow events and spillway gate failures than being caused by an extreme inflow event. The presented work highlights the needs to systematically collect and archive reliability data and to conduct reliability analysis for hydropower water release facilities whenever new information and data become available.

Preface

The author contributed to the model development, results analysis, and manuscript composition for the research presented in Chapter 2 and 3. A version of Chapter 2 was published in the proceeding of the 11th International Conference on Hydroinformatics, under the title "Reliability Analysis Approach for Operations Planning of Hydropower Systems" as in Zhou et al., 2014. The model framework and results described in Chapter 2 were also presented at the 2014 HydroVision International Conference in Nashville, USA. Chapter 3 is prepared as a manuscript to be submitted to a technical journal related to water resources engineering.

The Operations Planning Tool (OPT) model was originally developed as an in-house application at BC Hydro. The legacy application was redeveloped by the author, Dr. Ziad Shawwash and Daniel Archila, benchmarked with Operational Planning Engineers at BC Hydro, and was enhanced for research purposes.

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List of Abbreviations

AMPL	A Mathematical Programming Language
BC Hydro	The British Columbia Hydro and Power Authority
CDF	Cumulative Density Function
CM	Commercial Management
DP	Dynamic Programming
ETA	Event Tree Analysis
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
GUI	Graphical User Interface
HCV	Hollow Cone Valve
HLH	Heavy Load Hours
HVAC	Heating Ventilation and Air Conditioning
IDF	Inflow Design Flood
LLH	Light Load Hours
LLOG	Low Level Outlet Gate
LP	Linear Programming
MIP	Mixed Integer Programming
MILP	Mixed Integer Linear Programming
OPT	Operations Planning Tool
PDF	Probability Density Function
PMF	Probable Maximum Flood

PRV	Pressure Reducing Valve
RIAC	Reliability Information Analysis Center
SPOG	Spillway Operating Gate
TTF	Time to Failure
TTR	Time to Repair
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
WUP	Water Use Plan

Glossary

CPLEX	An IBM developed optimization software package
Rating curve	Rating curves are used by operations planning engineers to relate discharge to storage levels and gate opening, which are typically developed by hydraulic analysis of water release structures
Freshet	A period in the year characterized by large increase in streamflow caused by heavy precipitation and snowmelt
Stage	A terminology of dynamic programming meaning the time step when decisions are made
State	A terminology of dynamic programming denoting the information that summarized the knowledge required about the problem in order to make current decisions at a particular stage

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To my parents, Ning and Zhihong

Chapter 1: Introduction

Many existing hydropower storage and discharge facilities were built decades ago and the risk of failure of these aging infrastructure facilities is increasing. Most of these facilities are located in remote areas and are subject to severe environmental conditions which can cause early degradation of components such as spillway gates. A preliminary analysis and on-site test data show that the probability of a single spillway gate failing to open on demand is estimated to be 1 in 10, which is considered to be very high (Lewin, Ballard and Bowles 2003). Malfunction and insufficient capacity of discharge facilities could result in dam overtopping, a mechanism which has contributed to approximately 34% of all dam failures in USA (Association of State Dam Safety Officials 2013). Because of this, application of reliability analysis to hydropower systems, particularly water discharge facilities, is crucial for managing risks in reservoir operations planning.

1.1 Water Discharge Facilities

Hydropower systems comprise a broad set of components such as dams, storage reservoirs, water discharge facilities, pumping stations, pipelines, channels, penstocks, hydroelectric generating turbines, fish ladders and other facilities. Water discharge facilities are among the most essential components since they release excess water to prevent dam overtopping and reduce the impacts of high-flow events.

Water discharge facilities in dams can be classified into uncontrolled and controlled spillways. An uncontrolled spillway does not have gates or valves. It releases water when reservoir level rises above the crest of the spillway. The controlled spillways, on the other hand, provide more flexibility in reservoir operations. Spillway gates act as movable water barriers and actively control and regulate the rate of flow. They are critical components, but are not always reliable on demand. The failure of spillway gates could be caused by loss of electrical power, failure of automatic control systems, corrosion of wire ropes or other defects.

Radial and sluice gates are the most commonly used discharge facilities in hydropower systems. Radial gates, sometimes called tainter gates, consist of a curved plate reinforced by beams and supported by vertical and horizontal girders. The operating machinery is normally located above the gate and typically consists of wire rope hoists, chain hoists, or hydraulic cylinders (Novak, et al. 2001). Extreme weather conditions could freeze the trunnion that serves as a pivot point when the gate rotates, which is problematic for radial gate operations. In 1989, the radial gate in Seton Dam opened accidentally when the hoist motor activated without warning (USBR 2002). Ice around the power supply raised the conductors, forcing the contacts closed and turned on the motor. The hoist raised the gate past the fully open position, causing the gate to hit the upper structure and blow the circuit fuses. Debris and other obstructions can also block radial gates, significantly reducing the discharge capacity.

Sluice gates open and close vertically, using hoist mechanisms such as lifting screws, chains, and pulleys. The purpose of most sluice gates is to provide compensation of flows in the event of power plant shutdown. These spillway gates are generally operated when the reservoir elevation is high. Sluice gates are easy to operate; however, friction forces between aging wheels and rollers can lead to gate jamming during operation.

1.2 Operations Planning

The operation of large and complex hydropower systems requires careful study and continuous planning. BC Hydro owns and operates 31 hydroelectric projects and two gas-fired thermal power plants which serve 95% of the BC's population, as well as exporting to the neighboring province of Alberta and the USA (BC Hydro 2015). Operations planning of hydropower systems at BC Hydro aims to maximize the value of hydropower generation in a reliable and safe manner while meeting environmental and social objectives.

Mathematical and computer models are essential to support operators in making optimal operation decisions. Since the establishment of the Harvard Water Program in the 1960s (Maass, et al. 1962), two powerful methodologies – simulation and optimization, have been researched and applied to water resources planning and operations with positive results. Both modeling techniques can assist planning reservoir operations in long-term, short-term and real time scales.

1.2.1 Simulation Models

Simulation models are based on predefined rule curves that are developed to comply with physical constraints and are typically guided by operational experience. Computer models are used to simulate reservoir operations and reproduce the performance of reservoir systems given hydrologic inputs and operating rules under varying conditions (Wurbs 1996). Alternative runs of a simulation model are often made to evaluate alternative storage and operating plans.

Many simulation models are customized for specific reservoir systems. The Potomac River Interactive Simulation Model (PRISM) was developed by a research team at Johns Hopkins

University to simulate the operation of several reservoirs and allocation of water within the Washington metropolitan area (Palmer, et al. 1982). The US Bureau of Reclamation (USBR) also developed a number of simulation models used at specific projects in several western states. Among the most famous ones are the Projects Simulation Model (PROSIM) for simulating operations of the Central Valley Project in California (USBR 1990) and the Colorado River Simulation Systems (CRSS) which simulates operations of the major reservoirs in the Colorado River Basin for water supply, low flow augmentation and flood control (USBR 2012).

There are also generalized reservoir operation simulation models designed to be applied to different systems, including the Water Rights Analysis Package (WRAP) (Texas A&M University 2005) and ResSim (USACE 2013). Commercial software products such as STELLA (Taffe 1991) also provide simulation modeling environments for developing reservoir system simulation models.

1.2.2 Optimization Techniques

While simulation models are generally descriptive and demonstrate what will happen if a specified operating plan is adopted, optimization modeling techniques enhance capabilities to develop models that are prescriptive. An optimization model has the advantage of being able to search through a large number of feasible decision variables to find the optimal operating plan using systematic and efficient computational algorithms. With fast growing computer power and advanced development in operation research, optimization models are becoming more popular as effective tools for reservoir operations. Following published literature, the term optimization is used synonymously with mathematical programming, referring to a mathematical formulation in which a formal algorithm is used to compute a set of decision variables which minimize or maximize an objective function subject to constraints. Most reservoir system optimization models involve linear or dynamic programming methods or extensions thereof.

Linear programming (LP) has been widely used in hydropower reservoir operations planning, being one of the most robust optimization techniques. LP can efficiently solve large-scale problems, converge to global optimums and can deal with nonlinearities by piecewise linear approximation. Shawwash et al. (2000) developed the short-term optimization model (STOM) using linear programming to determine the optimal hourly generation schedule to maximize the value of hydro resources. STOM was later adapted to develop the Generalized Optimization Model (GOM) which BC Hydro uses as in-house software for medium and long term reservoir planning. Linear programming optimization models have also been built for operating multi-purpose reservoirs involving conflicting criteria such as flood control, recreation, and fish habitat preservation (Labadie 2004). The weighting method is used in LP to explicitly capture the tradeoffs which exist between conflicting and non-commensurate objectives, by assigning weights to each objective (Revelle, Whitlatch and Wright 2004).

Sometimes hydro system optimization problems require some of the variables to be integer values. Typically, these integer-valued variables are one and zero to model the “on” and “off” status of generating turbine units or failures of discharge facilities. The mixed integer programming (MIP) technique extends the capability of LP, representing the nonlinear and discrete nature of hydro operations planning. Needham et al. (2000) applied MIP to deterministic flood control operations in the Iowa and Des Moines Rivers, but they noted that the computational time of MIP could be excessive for real-time operation.

Another powerful optimization technique applied to reservoir operations is the dynamic programming (DP) method (Yakowitz 1982). While LP uses a directed search of the feasible extreme values defined by the constraints, DP utilizes the Bellman's principle of optimality (Bellman 1957). DP involves decomposing a complex problem into a series of smaller sub-problems which are solved sequentially over each stage, transmitting essential information from one stage to another using the "state" concept. DP overcomes the difficulties of nonlinearity, non-convexity and discontinuity in reservoir operations. Stochastic dynamic programming (SDP) has been developed for hydropower operations considering the uncertainty of reservoir inflows using transition probability matrices. Several researchers have successfully applied SDP to single reservoir operation problems, such as Stedinger et al. (1984) and Huang et al. (1991). However, applications of SDP to multi-reservoir systems suffer more from a larger state dimensionality than in the deterministic case, especially when spatial correlation of unregulated inflows must be maintained (Labadie 2004).

The approach of chance constrained programming attempts to include risk in optimization, where risk constraints that consider the uncertainty of hydrologic inputs are modeled as random variables. ReVelle et al. (1969) developed a linear decision rule (LDR) which removed the dependency of risk constraint on reservoir storage levels by creating its deterministic equivalent. Loucks and Dorfman (1975) evaluated the solutions of various chance constrained models and showed that results of LDR to be conservative. Srinivasan and Simonovic (1994) developed a reliability programming (RP) model to minimize the economic loss due to reservoirs failing to meet required reliabilities for hydropower supply and flood control. However, difficulties to estimate economic loss limited the use of RP methods (Labadie 2004).

Even though both deterministic and stochastic optimization models have been developed and used for operations planning, the reliability of water discharge facilities is generally treated deterministically, which appears to be inadequate. The influence of successfully operating discharge facilities on demand is significant to reservoir operations. Therefore, we propose that a reliability analysis framework should be taken into consideration as part of the decision making process in operations planning.

1.3 Reliability Analysis

In recent years, reliability analysis methods have gained recognition in both academia and in engineering practice. Reservoir operations planning for satisfying hydropower system requirements should be evaluated from a reliability and risk perspective because many variables, such as reservoir inflows and availability of facilities, are characterized by randomness and uncertainty.

Hydrological aspects of risk and uncertainty have been widely discussed in literature. Methods for analyzing flood frequencies are covered in hydrology textbooks (Bras 1990, Bedient and Huber 1992, Linsley, et al. 1992, Maidment 1992), providing estimation for the exceedance probability of inflow and reservoir storage during specified time. But over the years, the interest and accomplishment of uncertainty and reliability analysis has focused only on hydrology.

Uncertainties other than natural randomness of floods and rainfalls have not been considered until recently (National Research Council 2000). The National Research Council noted that hydraulic system performance, stage-discharge errors, geotechnical reliability are all relevant concerns for reservoir operations and flood management, and a framework is needed to understand the full range of risk and uncertainty.

The uncertainty of flow control systems in reservoir operations is related not only to hydrology, but also to reliability of mechanical and electrical components of discharge facilities, as well as human factors. The ability to estimate the reliability of a facility is important for understanding its expected performance over time, supporting operators and engineers to quantitatively assess uncertainty in operations planning.

Several researchers investigated the applications of reliability analysis with respect to dam spillway gates and other discharge facilities. Yen et al. (1980) applied the concepts of reliability to hydraulic design of conduits using the first-order second-moment (FOSM) method to determine the probability of failure. Cheng (1982) later discussed various methods for risk calculation of dam overtopping including return period analysis, Monte Carlo simulation and mean-value first-order second-moment (MVFOSM). Stedinger et al. (1989) applied the concept of Event Tree Analysis (ETA) to describe the random factors contributing to major floods, reservoir operations, and possible downstream damages. They presented an evaluation of the failure probability using Monte Carlo simulation. Lafitte (1993) developed the Fault Tree Analysis (FTA) that identified the events which could cause failure for spillway gates as well as the associated operating equipment. Putcha and Patev (1997) applied the concept of time-dependent reliability to navigational miter gates where load and capacity are treated as random variables as a function of time. Failure mode and effects analysis (FMEA) was developed for risk-informed analysis that maps out the consequences of specific failure events during the operation of dam systems (Hartford and Baecher 2004). Estes et al. (2005) investigated the adaptation of an existing condition indexing (CI) methodology to assess overall risk and failure probability of spillway gate systems in dams.

1.4 Scarcity of Reliability Data

Reliability analysis is dependent on the amount of available data to perform a valid analysis. For any particular data set, depending on the context and the objective of the analysis, a specific reliability approach can be fitted to the data (Ansell and Phillips 1989).

In the field of reliability engineering, systems can be classified into two classes based on the setup: manufactured systems such as aircrafts and automobiles, and infrastructural systems such as bridges, levees and hydropower reservoir systems (Tung, Yen and Melching 2006). Reliability analysis for manufactured systems has a longer history (Shewhart 1931) and is relatively more developed than infrastructural systems. The manufacturing industry has collected reliability data which contains sufficient information on components and systems. Dhillon and Viswanath (1990) presented a review of failure data sources produced by quality control and manufacturing groups. One can also refer to the NPRD-95 (RIAC 1995), IEEE gold book (2007) and the Handbook of Reliability Prediction Procedures for Mechanical Equipment (NSWC 2011) for similar data. On the infrastructural side, public attention on the safety of the nuclear industry and earthquake hazards has provoked development of reliability approaches on infrastructural systems. Yet, most of the reliability methodologies and related data are focused on structural analysis (Madsen, Krenk and Lind 1985, Marek, Gustar and Anagnos 1995, Melchers 1999).

Unlike manufactured systems, facilities of hydropower systems the operations of which interrelate with natural process are often custom-made, making it difficult to find historical information on the reliability of the system. At present, few hydropower dam owners or operators keep adequate and sufficient records with regard to failures of water discharge facilities during their operational lifespan. Poorly documented failure case history makes it difficult for traditional reliability methods to deliver accurate estimates of the reliability of such facilities. Past experience and previous studies in published literature are a less costly source of data, but often are only applicable to specific projects of interest. Therefore, the development of reliability analysis procedures which are customized to provide adequate results with limited data is needed to handle the scarcity of reliability data in hydropower and the utility industry.

1.5 Research Goals

The main objective of this research is to integrate the reliability analysis of water discharge facilities into hydro reservoir operation modeling in order to quantitatively treat risk and uncertainty in operations planning. A comprehensive reliability-based modeling framework is developed based on currently available data. Through this research, the BC Hydro’s Operations Planning Tool (OPT) is enhanced, adding new features including discharge facility failure and repair simulation. To achieve the research objective, the following tasks were undertaken:

- Review reliability analysis literature for spillway gates.
- Investigate the physical and operational constraints of hydropower reservoir systems.

- Identify the hydrologic risk and reliability of water discharge facilities in reservoir operations.
- Identify available data sources and collect failure data to conduct reliability analysis.
- Consult with Operations Planning engineers about operating rules and orders.
- Build hydropower system model configurations for specific projects.
- Validate the modeling framework by testing model performance.

1.6 Organization of Thesis

This is a manuscript-based thesis organized in four chapters and three appendices. The introductory chapter provides a general problem statement including an overview of storage reservoir discharge facilities, operation modeling techniques, a review of reliability methodologies and current status of data scarcity, the research goals and thesis organization. Chapter 2 describes the reliability analysis approach for operations planning of hydropower systems. A version of this chapter was published as a paper in the proceeding of the 11th International Conference on Hydroinformatics. Chapter 3 develops a reliability-based optimal operation modeling framework for reservoir discharge facilities. A case study and modeling results are included in this chapter. Conclusions and recommendations on future work are presented in Chapter 4. Appendix A presents the failure records of spillway gates for the reliability analysis conducted in Chapter 3. Appendix B extends the availability analysis of spillway gate facilities. Appendix C outlines the formulation of the hydro operation model.

Chapter 2: Reliability Analysis Approach for Operations Planning of Hydropower Systems

This chapter is based on a technical paper published in the proceeding of the 11th International Conference on Hydroinformatics[1]. The abstract and references are not included in this chapter. References cited in Chapter 2 can be found in the Bibliography section of the thesis.

2.1 Introduction

BC Hydro owns, operates and maintains 40 dam facilities throughout British Columbia as the major part of its generating system (BC Hydro 2014). Most of BC Hydro's hydropower facilities are in their middle service life, but some are reaching the wear-out phases and BC Hydro is currently rehabilitating a number of these aging facilities such as the John Hart generating station in Vancouver Island (BC Hydro 2014). There has been a spillway gate upgrade and replacement program since 2005 to address reliability issues across BC Hydro's fleet of facilities (BC Hydro 2014). The upgrade program is initiated to ensure the reliability of gate operations in times of flood when high inflows exceed the ability of generating units to pass the flood. The upgrades include spillway gate hoists and towers, various electrical, mechanical and structural components as well as the control systems. These spillway gate facilities are critical for safe and reliable operation of hydropower systems. They mainly act as movable barriers impounding the water in the reservoir and control the amount of water that can be discharged from the reservoir.

[1] Zhou, Jiyi., Ziad K. Shawwash, Daniel Archila, Paul Vassilev, Gillian Kong, Vladmir Plesa, Alaa Abdalla. "Reliability Analysis Approach for Operations Planning of Hydropower Systems." *Informatics and the Environment: Data and Model Integration in a Heterogeneous Hydro World.* New York: HIC2014, 2014.

Uncertainties that exist in hydro operations planning mainly arise from natural and operational uncertainties. Natural uncertainties are associated with the inherent randomness of natural processes such as random occurrences of heavy precipitation and flooding events. Operational uncertainties include those associated with operational decisions and release policies, maintenance, and human errors. As hydro system operations planning cannot be assessed with certainty, conventional deterministic modeling practice is inappropriate (Tung 1996).

Reliability analysis methods have gained recognition in both the academic field and in engineering practice in recent years. Among many reliability approaches, event tree and fault tree analysis are two widely used methods which, albeit approximate, consider quantitatively all major factors that influence the total system reliability. Event tree analysis (ETA) is an inductive logical model that includes all possible chains of failure events resulting from an initiating event. Stedinger et al. (1989) applied the concept of ETA to describe the random factors contributing to major floods, reservoir operation, and possible downstream damages. They presented an evaluation of the failure probability using Monte Carlo simulation and importance sampling. Fault tree analysis (FTA) is a deductive failure analysis technique, in which component failures are analyzed given a particular system failure event. Lafitte (1993) identified events that could cause failure and developed a FTA framework for spillway gates and associated operating equipment. Reliability Block Diagram (RBD) is another diagrammatic or a graph method to show how component reliability contributes to the success or failure of a complex system. The purpose of using RBD is to concisely illustrate various series-parallel block combinations that result in the successful operation of a facility (USDOD 1998). In this paper, reliability of individual components is assessed as well as the interrelationships between components using

RBD. A spillway gate system is analyzed and relative contribution of each mechanical or electrical component failure to the overall system failure is presented. To produce system reliability diagrams, an overall understanding of its components is necessarily required. An alternative approach to assess reliability of a system is also presented using historical failure data of water discharge facilities, where the Kaplan-Meier estimator (Kaplan and Meier 1958) is applied. The Kaplan-Meier estimator is a nonparametric method which provides powerful results as the reliability function is not constrained to fit any particular predefined probability distribution. The Kaplan-Meier estimator provides an elegant solution to estimate system reliability particularly when incomplete data is encountered.

The operation of a large and complex hydroelectric system including non-power release facilities requires careful management and continuous planning. Hydropower operations planning is guided by safety of lives and property, load obligations and maximizing the value of generating resources. The operation process involves a wide range of input information such as inflows, generation unit availability and market price, etc. A computer model, the Operations Planning Tool (OPT), is developed to simulate the operation of the hydroelectric system to maximize the financial value of the system output while meeting physical and operational constraints. Risk is commonly defined as the combination of failure probability and consequences (Muhlbauer 2004, Reeve 2009). Failure probability of hydropower facilities can be assessed using the reliability analysis approaches we present in this paper. The magnitude of consequences depends on how the operator and the hydro system responses to failure and it can be evaluated using the OPT modeling results. A reliability-based modeling framework is developed to formally treat risk and uncertainty in hydro operations planning, and it is demonstrated how reliability analysis approaches for hydro facilities can be integrated into operations planning models.

2.2 Reliability Analysis

Reliability is commonly defined in literature as the ability of an item to successfully perform its function over a period of time (Billinton and Allan 1992, Rausand and Hoyland 2004, Pham 2006). More specifically for hydropower systems, reliability is the probability that the system will successfully operate within a specified period of time under given operating conditions without failure. Mathematically, reliability can be expressed as:

$$R(t) = P(T > t) \tag{2-1}$$

where T is a non-negative random variable denoting the failure time, and t is the designated period of time given the operating conditions. Assuming that $f(t)$ is the probability density function (PDF) for the failure time T, the reliability function can be calculated as:

$$R(t) = \int_{t}^{\infty} f(u)du \tag{2-2}$$

The reliability function $R(t)$ can also be defined as the complement of the cumulative distribution function (CDF), $F(t)$, corresponding to $f(t)$:

$$R(t) = 1 - F(t) = 1 - \int_0^t f(u)du \tag{2-3}$$

2.2.1 Lifetime Distribution

This section presents two continuous probability distributions that can be used to model the uncertainties of hydropower facilities. The Weibull distribution is selected for modeling component failure times and the lognormal distribution is used to model maintenance and repair times.

2.2.1.1 The Weibull Distribution

The Weibull distribution is one of the best-known distributions in reliability analysis. It is widely used due to its flexibility to model failure behaviors with changing hazard rates. The Weibull distribution can adequately describe observed failure times of different types of equipment and phenomena. The CDF of the Weibull distribution is formulated as follows:

$$F(t) = P(T \leq t) = 1 - e^{-\left(\frac{t-\tau}{\alpha}\right)^{\beta}}, \alpha > 0, \beta > 0, t \geq \tau \geq 0 \tag{2-4}$$

where α is the scale parameter, β is the shape parameter which determines the shape of the distribution and τ is the location parameter. For $\tau = 0$, Equation 2-4 becomes a two-parameter Weibull distribution (Murthy, Xie and Jiang 2004, Pham 2006). The reliability function of the two-parameter Weibull distribution is:

$$R(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}}, \alpha > 0, \beta > 0 \quad (2\text{-}5)$$

As a special case, when $\beta = 1$, the Weibull distribution is equivalent to the exponential distribution. The exponential distribution has a constant failure rate which is known as its "memoryless property" (Bedford and Cooke 2001). It means that a used component which has not failed is as good as a new component – a rather restrictive assumption which limits the application of exponential distribution.

2.2.1.2 The Lognormal Distribution

The lognormal distribution is based on the normal distribution and it is a more versatile distribution than the normal distribution as it has a wide range of shapes. O'Connor and Kleyner (2012) analyzed repair time data of maintainable systems and found that repair times tend to be lognormally distributed. The PDF of the lognormal distribution is given as:

$$f_{LN}(t) = \frac{1}{\sigma t\sqrt{2\pi}} e^{-\frac{1}{2}[\frac{\ln(t)-\mu}{\sigma}]^2}, -\infty < \mu < \infty, \sigma > 0 \quad (2\text{-}6)$$

where parameters μ and σ are the mean and standard deviation of the log of the distribution, respectively.

2.2.2 System Reliability Models

Malfunction, damage and instability of hydropower facilities including generating turbines, spillway gates, and other equipment can significantly affect reservoir operations and increase operational risk. These facilities are typically made up of many mechanical and electrical components which have complex failure modes that are associated with uncertain variables such as operating environment, interactions between components and maintenance regimes (Bedford and Cooke 2001). One of the main challenges to assess the reliability of hydro facilities is to obtain failure data. Failure data can be established in one of the two ways: from experimental testing and from operational field data. If these are unavailable, it is necessary to use generic data collected and analyzed by other organizations. This requires reliability analysis to be completed using data from larger systematic samples of similar systems. Billiton and Allan (1992) reviewed a number of well-known sources of reliability data including published data handbooks such as the US Army report, US-MIL-HDBK-217, and data banks such as the Canadian Electrical Association (CEA) generation/ transmission data bank.

The overall system reliability of a spillway facility or turbine generating system can be represented as a series-parallel combination of individual components using RBD. In a serial system, the components are connected in such a manner that if any one of the components fails, the entire system fails. Such a system can be schematically represented by an RBD as shown in Figure 2.1.

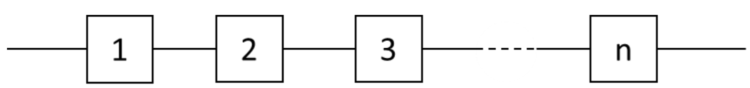

Figure 2.1 Reliability Block Diagram of a Serial System

For a series of n independent components, the system reliability for t is:

$$R_{series}(t) = \prod_{i=1}^{n} R_i(t) \tag{2-7}$$

where $R_i(t)$ is the reliability of the ith component in the series. Serial system reliability is inversely proportional to the number of components included in the RBD. In other words, the more components there are, the lower the system reliability becomes.

In a parallel system, the system fails only when all of the system components fail. The RBD for the simplest parallel system is shown in Figure 2.2.

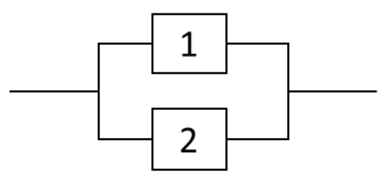

Figure 2.2 Dual Parallel Redundant System

In this dual parallel redundant system, successful operation is guaranteed if either one or both components function well, therefore the overall system reliability is equal to the probability of component 1 or 2 surviving. The general expression of system reliability for parallel redundancy is given as:

$$R_{parallel}(t) = 1 - \prod_{i=1}^{n} [1 - R_i(t)] \tag{2-8}$$

where $R_i(t)$ is the reliability of the ith component and n is the number of components in parallel. In some parallel configurations, m out of n components may be required to be working to make sure that the overall system is functioning. This is called *m*-out-of-*n* redundancy (Scheuer 1988). If all components are identical and their reliabilities are equal to $R(t)$, the reliability function of the system equals the summation of their binomial probabilities (Kuo and Zuo 2003):

$$R_{SYS}(t) = \sum_{j=m}^{n} \binom{n}{j} R(t)^j [1 - R(t)]^{n-j} \tag{2-9}$$

A serial system structure for spillway gates is reflective of the interrelations between mechanical and electrical components of the gates and a malfunction of any component will contribute to the total system failure (Kalantarnia, Chouinard and Foltz 2014). Figure 2.3 illustrates the system reliability of a typical spillway radial gate and the reliabilities of its major mechanical and electrical components over 10 years using RBD. It is assumed that all the components are in series. The RBD is modeled with reference to the tainter gate machinery (USACE 2001) and is developed for sufficient level of details for which data, such as failure rates and probability distribution parameters, are available from published data sources. The two-parameter Weibull distribution is used to analyze the reliability for each component, where parameters α and β were selected from the Nonelectronic Parts Reliability Data handbook (Denson, et al. 1991). These parameters were adjusted to applicable operating and environmental conditions typically encountered in the BC Hydro system using K factors (Green and Bourne 1972). For more complex systems, the minimal cut set method based on the rules of Boolean algebra can be used to evaluate the system reliability to avoid repeated calculations for individual components (Bauer, Zhang and Kimber 2009).

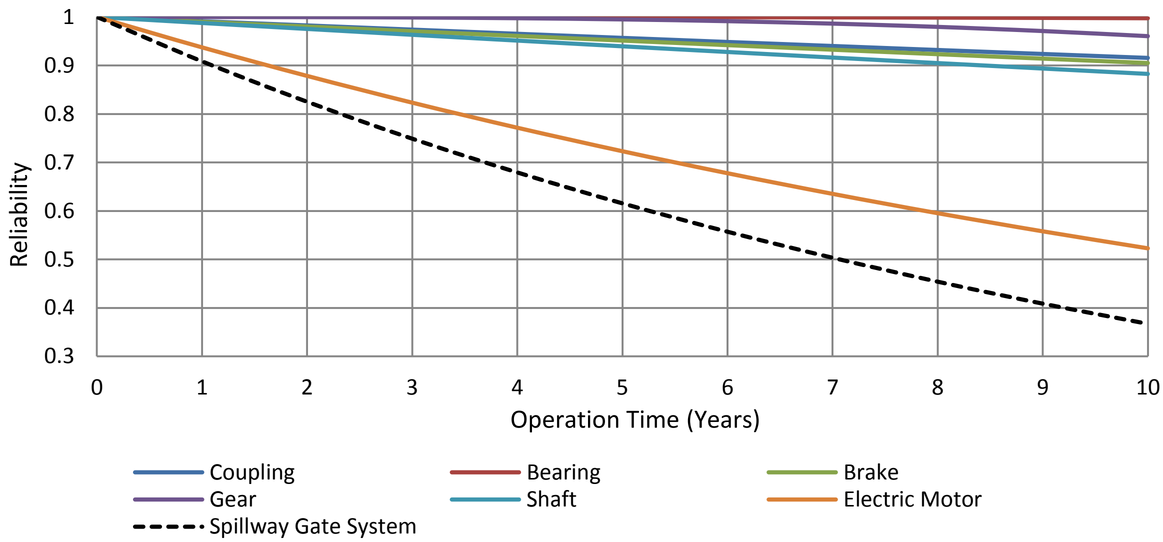

Figure 2.3 Reliability of Major Components in Spillway Radial Gate System

2.2.3 Kaplan-Meier Estimator

Lifetime data of hydropower facilities can be classified into two types: complete data (i.e. all times of failure are observed and recorded) and censored data. If equipment did not fail in the observation period till time t, then t can be considered as a lower estimate of the time to failure. This type of data is called censored data and is commonly encountered in hydropower facilities such as generating turbines and spillway gates. In this section, both the empirical reliability function for complete data sets and the Kaplan-Meier reliability estimator using censored data are discussed.

Arrange the n historical time to failure data in an ascending order:

$$t_1 < t_2 < \cdots < t_{n-1} < t_n \tag{2-10}$$

The empirical reliability function for complete data is formulated as follows:

$$R_n(t) = \begin{cases} 1 \quad (t < t_1) \\ \dfrac{n-i}{n} (t_i < t < t_{i+1}, i = 1,2, \dots, n-1) \\ 0 \quad (t \geq t_n) \end{cases} \tag{2-11}$$

If m failure events happen at the same time t_j, a simple adjustment will be required:

$$R_n(t) = \frac{n-m}{n}, (t_j \leq t < t_{j+1}) \tag{2-12}$$

The Kaplan-Meier estimation procedure is based on a sample of n items, among which k values are distinct observed time to failure ($k < n$). The reliability estimate function is given by:

$$R_n(t) = \begin{cases} 1 \quad (t < t_1) \\ \displaystyle\prod_{j=1}^{i} \frac{n_j - m_j}{n_j} \ (t_i < t < t_{i+1}, i = 1,2, \dots, k-1) \\ 0 \quad (t \geq t_k) \end{cases} \tag{2-13}$$

where n_j refers to the number of operating items right before t_j, and m_j is the number of failures at time t_j.

The Kaplan-Meier estimator is a nonparametric approach which provides robust results, but it is neither easy nor convenient to directly use such nonparametric reliability estimate results without fitting them to specific probability distributions. For example, the reliability function in Equation 2-5 can be transformed to a linear function by taking natural logarithm of its both sides, as follows:

$$\ln[-\ln R(t)] = \beta \ln t - \beta ln\alpha, (\alpha > 0, \beta > 0) \quad (2\text{-}14)$$

With results from the nonparametric analysis, linear curve fitting can be conducted using Equation 2-14. An example of such analysis is demonstrated by analyzing forced outage historical records of a generating unit in the Ruskin Powerhouse, as shown in Figure 2.4. The scattered points that represent the nonparametric reliability estimates are well aligned, and a regression analysis provides the following result:

$$y = 0.5119x - 2.2441 \text{ with } R^2 = 0.9692 \quad (2\text{-}15)$$

which indicates that Weibull distribution is an appropriate probability distribution for the reliability analysis of this hydropower facility and for similar facilities. The scale parameter α and shape parameter β can be estimated as well by the slope and the intercept of the fitted function with the y-axis.

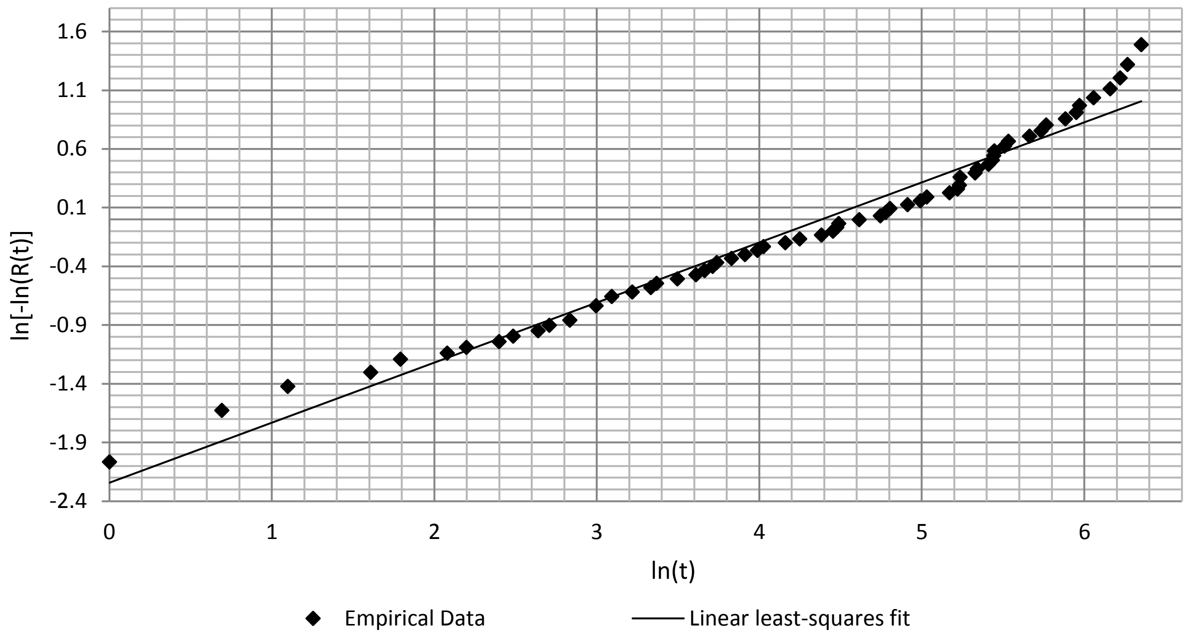

Figure 2.4 Weibull Plot of the Kaplan Meier Estimated Reliability for A Generating Turbine in Ruskin Dam

2.3 Reliability-based Hydro Operations Planning

2.3.1 Hydro System Operation Modeling

The Operations Planning Tool (OPT) is a simulation-optimization model that has been developed at BC Hydro for operations and planning of hydropower systems to meet economic, environmental and social constraints. It is formulated as a linear programming problem using AMPL (Fourer, Gay and Kernighan 2002) and is solved using CPLEX solver (IBM Corp. 2010). A graphical user interface (GUI) is currently under re-development to provide a user-friendly environment for coupling the AMPL model with CPLEX solver and to assist user-specified input. Figure 2.5 shows the OPT framework that consists of input data, optimization model and output variables including reservoir elevation, spill through different non-power release structures, daily turbine discharge, hydropower generation and energy revenue.

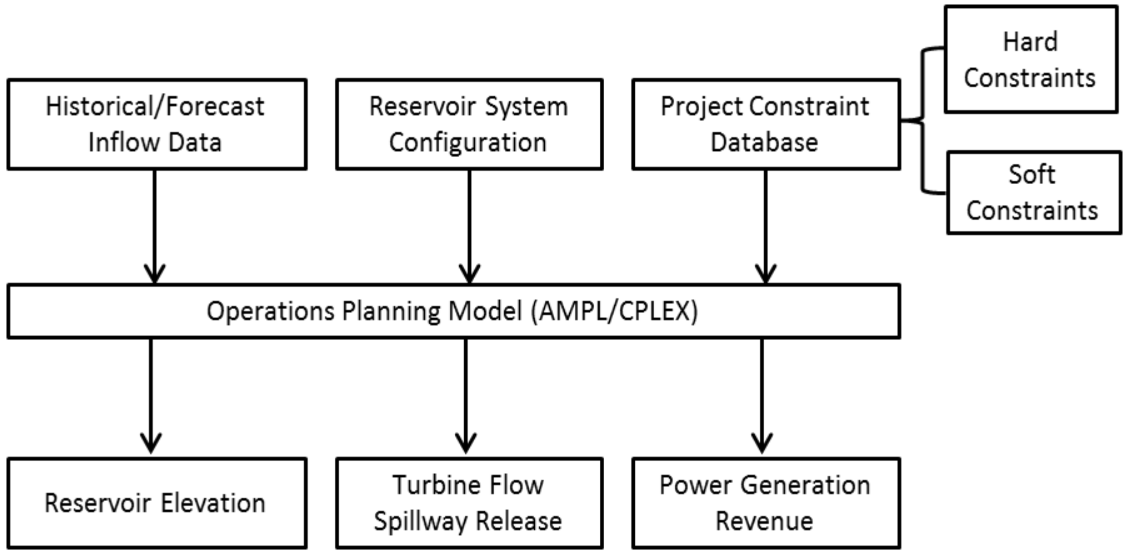

Figure 2.5 General OPT Model Framework

Hydropower operations are typically operated with a set of constraints on preferred ranges of reservoir elevations and spillway releases. These ranges can be specified and set by users and interested parties, such as operations planning engineers and stakeholders. They comply with BC Hydro operating orders to prevent overtopping or excessive overdraft of the reservoir. Water releases through spillway facilities are also constrained to certain target levels to meet environmental requirements, for instance, to maintain minimum flow rate to protect salmon habitats. Deviations outside theses ranges are undesirable and are subject to penalty functions[2] which are treated as soft constraints in the model to reflect system operating priorities. Hard constraints in the OPT are constraints that cannot be violated and consists of mass balances, storage and discharge capacities, diversion and streamflow requirements, and to address other aspects of operating requirements for specific hydropower systems. The objective function in the model is formulated as below:

[2] Formulation of the OPT model is discussed in Appendix C.

$$\text{Minimize: } \sum w_e F_E + \sum w_s F_S - \sum w_g GP \tag{2-17}$$

where w_e, w_s and w_g are the weight coefficients used to specify the relative importance of each term in the objective function based on different operation requirements; F_E and F_S are the values of the penalty functions for reservoir elevation and spillway release, respectively, G is the hydropower generation as a function of turbine discharges; and P is the electricity market price.

2.3.2 Case Study – Cheakamus Hydropower System

The Cheakamus hydropower system is used to illustrate an operations planning modeling study that incorporates reliability analysis of spillway gates. The Cheakamus River originates in the Coast Mountains in British Columbia, running northwest towards the famous ski resort of Whistler before turning south to join the Squamish River, as shown in Figure 2.6. The Cheakamus hydro system comprises a small storage reservoir forming the Daisy Lake, a power plant located on the Squamish River and a tunnel linking the Daisy Lake to the power plant. Normal operating water level in the reservoir ranges between 364.97 m and 377.95 m above mean sea level. Discharge facilities in this system include two generating units, two spillway radial gates, overflow weirs, a low level sluice gate and a hollow cone valve. Failure of spillway gates to operate on demand may result in dam overtopping incidents, which could lead to loss of life, and other economic and social consequences. This is particularly serious in the Cheakamus system where the reservoir storage volume is small and rapid changes in water level could occur in high inflow events. During the flood of October 2003, peak flow lasted for extended period and the rise in reservoir water level was 5 m within 24 hours.

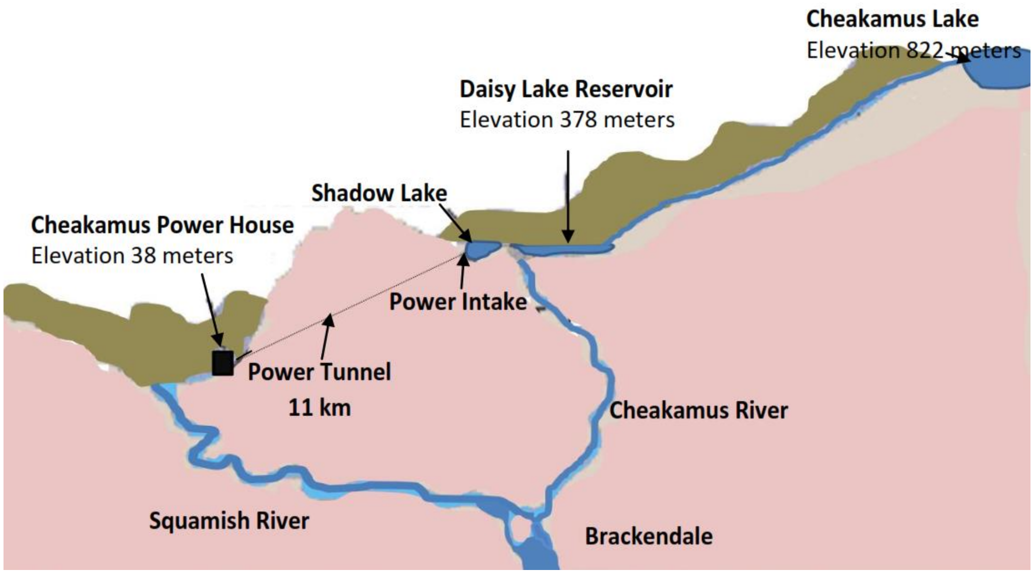

Figure 2.6 Cheakamus River System Map (BC Hydro 2005)

Using the reliability analysis approaches discussed in Section 2.2, the reliability function of spillway radial gates in the Cheakamus Dam is fitted to the Weibull distribution, as follows:

$$R(t) = \exp[-\left(\frac{t}{476}\right)^{1.3334}] \tag{2-18}$$

Monte Carlo simulation is performed to simulate the spillway gate failure based on the analytical reliability formulation in Equation 2-18. A random binary number is generated to represent the probability of an event occurring at a given time, in this case the spillway gate failure event. The repair time after each failure is also simulated using a similar approach based on the fitted lognormal distribution.

A historical high inflow scenario (1995) is used to demonstrate the case study. Hydrologic data and hydraulic data for the Cheakamus hydropower system was defined in the OPT. It is assumed that the spillway gate failure mode consists of complete failure to open on demand (i.e. spill equals zero). It is also assumed that all the facilities were maintained or repaired in the previous year, and that the Monte Carlos simulation results are independent from previous outages. Table 2.1 shows a typical simulation outcome of failure and repair time and duration of the radial gates outages for the Cheakamus system.

Table 2.1 Failure Simulation of Spillway Radial Gates in Cheakamus Dam

Gate Number	Simulation Start Time	Failure Start Time	Failure End Time
SPOG1	January 1, 1994	July 17, 1995	July 29, 1995
SPOG2	January 1, 1994	April 26, 1995	May 22, 1995

Figure 2.7 shows the reliability-based operation modeling results for the 1995 inflow year. Two cases with and without gate failure are presented. The optimal decision variables including spillway gate releases, turbine discharges and reservoir elevations are illustrated. It can be seen that the SPOG2 failure did not cause significant rise in reservoir elevation. In contrast, SPOG1 failure coincided with higher inflow and relatively high reservoir level, and resulted in significant rise of approximately 6 m in the reservoir water level. When SPOG1 failed, excessive water is released through SPOG2 to mitigate the excessive water level rise. It can be also seen that the turbine release schedule is not affected by spillway gate failures.

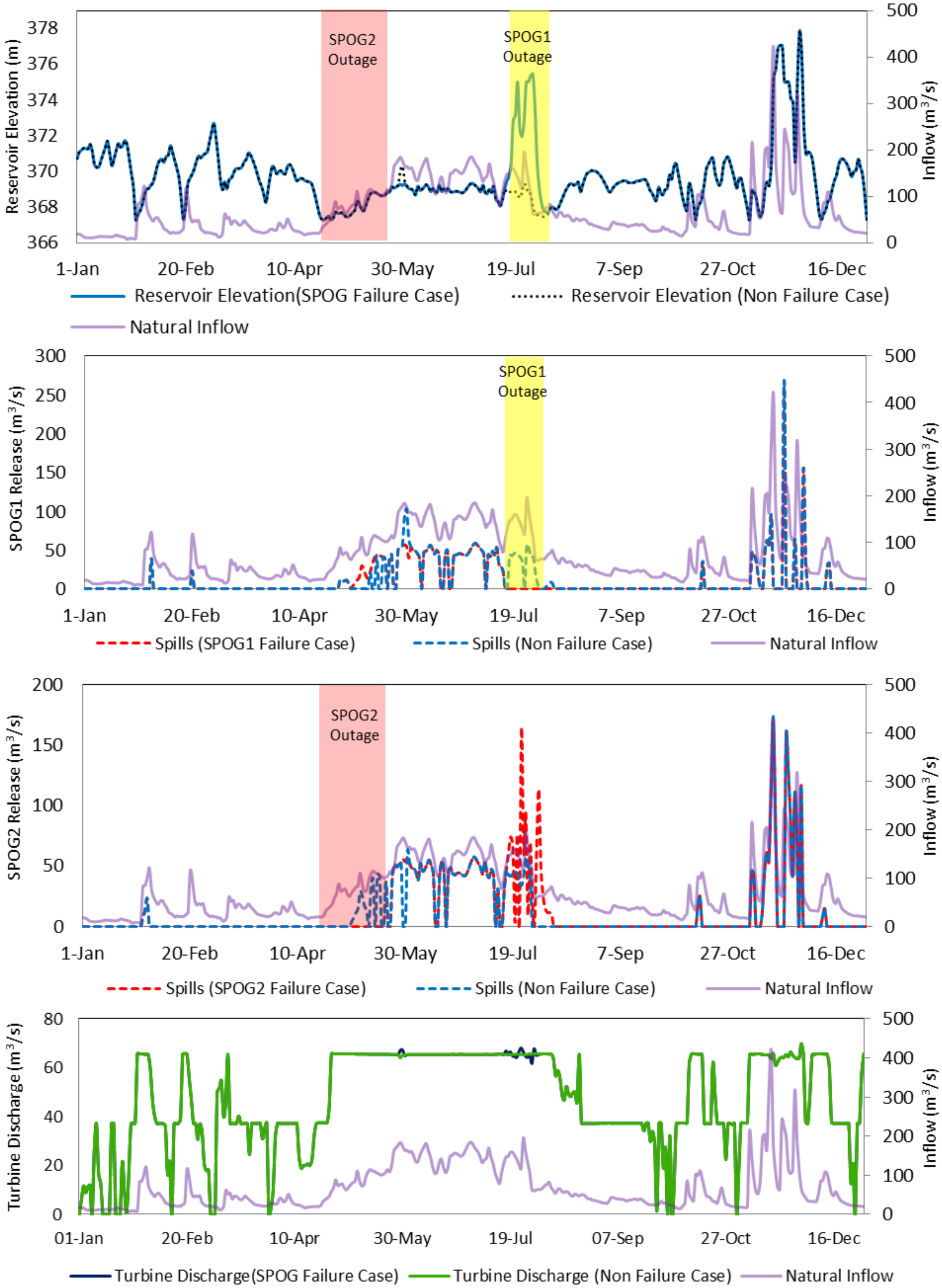

Figure 2.7 Cheakamus Hydropower System Modeling Results

2.4 Conclusions

Many existing hydropower storage facilities were built decades ago and components of these aging infrastructure facilities have higher risk of failure which could potentially increase the probability of dam safety incidents. Current approaches used to assess the risk and uncertainties in operational decision making are mainly based on qualitative assessments that may suffer from subjectivity. This paper investigated a number of reliability analysis approaches which can be used to quantify the reliability of hydropower facilities such as spillway gates and generating turbines. Time-dependent reliability functions were developed using system reliability models and reliability block diagrams. Alternatively, if historical failure data is made available, reliability functions can be derived using the Kaplan-Meier estimator and numerical Weibull distribution curve fitting techniques. Other similar types of facilities in hydropower systems can be treated using similar approaches as well.

We integrated the reliability analysis approach into a deterministic hydro system simulation-optimization model to develop a reliability-based operation framework which formally treats risk and uncertainty that is typically encountered in reservoir operations. This paper presents the framework we have developed and illustrates the application of the framework to a hydropower system in British Columbia. Preliminary modeling results and analysis revealed that it is important to conduct reliability analysis for hydropower facilities. The analysis framework we outlined in this paper can provide decision makers with information about operational risks in hydropower system operations.

Chapter 3: Reliability-based Operations Planning Modeling of Reservoir Water Release Facilities

This chapter presents a manuscript which is to be submitted to a technical journal related to water resources engineering. It provides an overview of a reliability-based modeling and analysis framework for water release facilities of hydro reservoirs.

3.1 Introduction

Failure of hydropower water release facilities could significantly impact reservoir operations and can potentially pose threats to public safety, and cause damage to properties and the environment. Spillway gate or valve failure has been one of the main causes of reported dam safety incidents (US National Research Council 1983). In July 1995, one of the spillway radial gates at Folsom Dam in California failed, owing to the flawed joints adjacent to the trunnion, causing sudden large downstream flood in the lower reaches of the American River (Todd 1999). Another catastrophic incident that resulted in the injuries of five people was the dam breach of the upper reservoir at the Taum Sauk Pumped Storage Project in Missouri in 2005. A pumping unit failed to shut down due to a sensor malfunction, causing water to overtop the embankment of the dam for 7 minutes. The overflow undermined and scoured the embankment, leading to the dam failure within that time frame (Rogers, Watkins and Chung 2010). Lewin et al. (2003) provided a number of spillway gate failure examples from around the world and investigated different approaches to ensure gate reliability at dam projects in the US and in Europe. They summarized the major failure modes of spillway gate installations, and addressed the needs for assessing the reliability of spillway gate systems to identify potential problems.

In recent years, there has been growing interest in developing and utilizing reliability methodologies to estimate the reliablity of spillway and flow-control facilities to evalute and understand potential equipment and operational failures. Yen et al. (1980) applied the concepts of reliability to the hydraulic design of conduits using the first-order second-moment (FOSM) method to determine the probability of failure. Cheng (1982) later discussed various methods to calculate the risk of dam overtopping using return period analysis, using Monte Carlo simulation and the mean-value first-order second-moment (MVFOSM) method. Stedinger et al. (1989) applied the Event Tree Analysis (ETA) to describe the random factors contributing to major floods, reservoir operations, and possible downstream damages. They evaluated the probability of dam failure and the distributions of damages and loss of life using combinations of various analytical methods and Monte Carlo simulation. Lafitte (1993) developed the Fault Tree Analysis (FTA) which identified the events that could cause failure for spillway gates as well as the associated operating equipment. Barker et al. (2003) used the FTA to analyze the mechanical and control component failures of radial and drum gates to determine the reliability of the overall system. Event tree and fault tree analyses enable the assessment of probabilities of multiple and combined failures in complex systems, but both methodologies are accurate only if all major contributors to failures are anticipated (Clemens and Simmons 1998). For complicated system failures and operators' cognitive errors, where failure proabilities of specific components are typically difficult to find, the ETA and FTA need to include subjective probablities that are usually estimated by experts (Kumanmoto and Henley 2000). Putcha and Patev (1997) applied the concept of time-dependent reliability to navigational miter gates where load and capacity are treated as random variables as a function of time. One of the newly proposed approaches is the dormant reliablity analysis for infrequently operated spillway gates, the failures of which are latent (Kalantarnia, Chouinard and Foltz 2014). However, this approach has the limtation of assuming constant failure rates which means that a used component that has not failed is as good as a new component, and it is not applicable to spillway gates that are frequently operated.

A long list of other factors make reservoir operation a complex and dynamic problem, including hydrological uncertainties, dam safety concerns, and multiple operational objectives that are often conflicting. Hydrological aspects of risk and uncertainty have been widely discussed in the literature (Bras 1990, Bedient and Huber 1992, Linsley, et al. 1992, Maidment 1992). Methods for analyzing floods provide estimation on the exceedance probability of inflows and reservoir storages during specific time. But over the years, the emphasis and accomplishment of uncertainty and reliability analysis has focused merely on hydrology in most reservoir operation studies (Labadie 2004). Uncertainties other than the natural randomness of floods and rainfalls have not been considered until recently (National Research Council 2000). The National Research Council noted that reliability performance of hydraulic systems, stage-discharge errors and geotechnical reliability are all relevant concerns for reservoir operations and flood management, and highlighted the need for a framework to understand the full range of risk and uncertainty. Since the establishment of the Harvard Water Program in the 1960s (Maass, et al. 1962), various state-of-the-art computer modeling tools have been developed in support of reservoir system management and operations planning. These models are traditionally based on predefined rule curves and are typically supplemented by the experience and judgement of the operators and decision makers of these systems. Chance constrained programming has been used to model the probability of spillway releases being within their preferred operating zones using the determininistic equivalent of the corresponding uncertain variable (ReVelle, Joeres and Kirby

1969, Simonovic and Mariño 1980, Changchit and Terrell 1993, Archila, et al. 2014). However, many authors raised concerns about the use of deterministic linear decision rules (Loucks 1970, Stedinger 1984, Strycharczyk and Stedinger 1987). It is well recognized now that reservoir operations planning models should take into account the systematic uncertainy of water release facilities to evaluate the potential risks for supporting operational decisions, which requires a formal process to incorporate reliability of these facilities in decision making.

In this paper, we outline a reliability-based modeling framework to integrate reliability analysis of water release facilities in reservoir operations planning to formally and quantitatively treat the uncertainty in an economical and reliable manner. The remaining part of this paper is organized as follows. Section 3.2 provides a general overview of the reliability-based hydro reservoir operations planning modeling framework, where the reliability analysis process to evaluate and predict the performance of water release facilities is presented. Section 3.3 presents the application of the framework to a hydropower reservoir system in British Columbia. Section 3.4 provides conclusion and recommendations for future research and development.

3.2 Reliability-based Modeling Framework

This section presents a reliability-based reservoir operation modeling framework to support decision makings in reservoir operations and planning. The model incorporates the hydrological uncertainty, and utilizes reliability analysis approaches to analyze the performance of water release facilities and to predict their failures. The modeling framework is illustrated in Figure 3.1 and it consists of several components including the input data module, reliability analysis process module, the optimization model, and model output and analysis module. Section 3.2.1 discusses the reliability analysis process we have developed to predict and simulate failure events of water release facilities in operation using statistical reliability assessment, where failure data is collected and used for the nonparametric product-limit estimate of censored failure data. This estimate is then fitted to parametric distribution models and is validated using confidence interval analysis. Section 3.2.2 presents the multi-objective optimization model developed to assist planning the operations of hydropower reservoir systems. The input data required for the optimization model such as hydrologic data and the energy price are discussed in Section 3.2.3. The output of the model is described in Section 3.2.4.

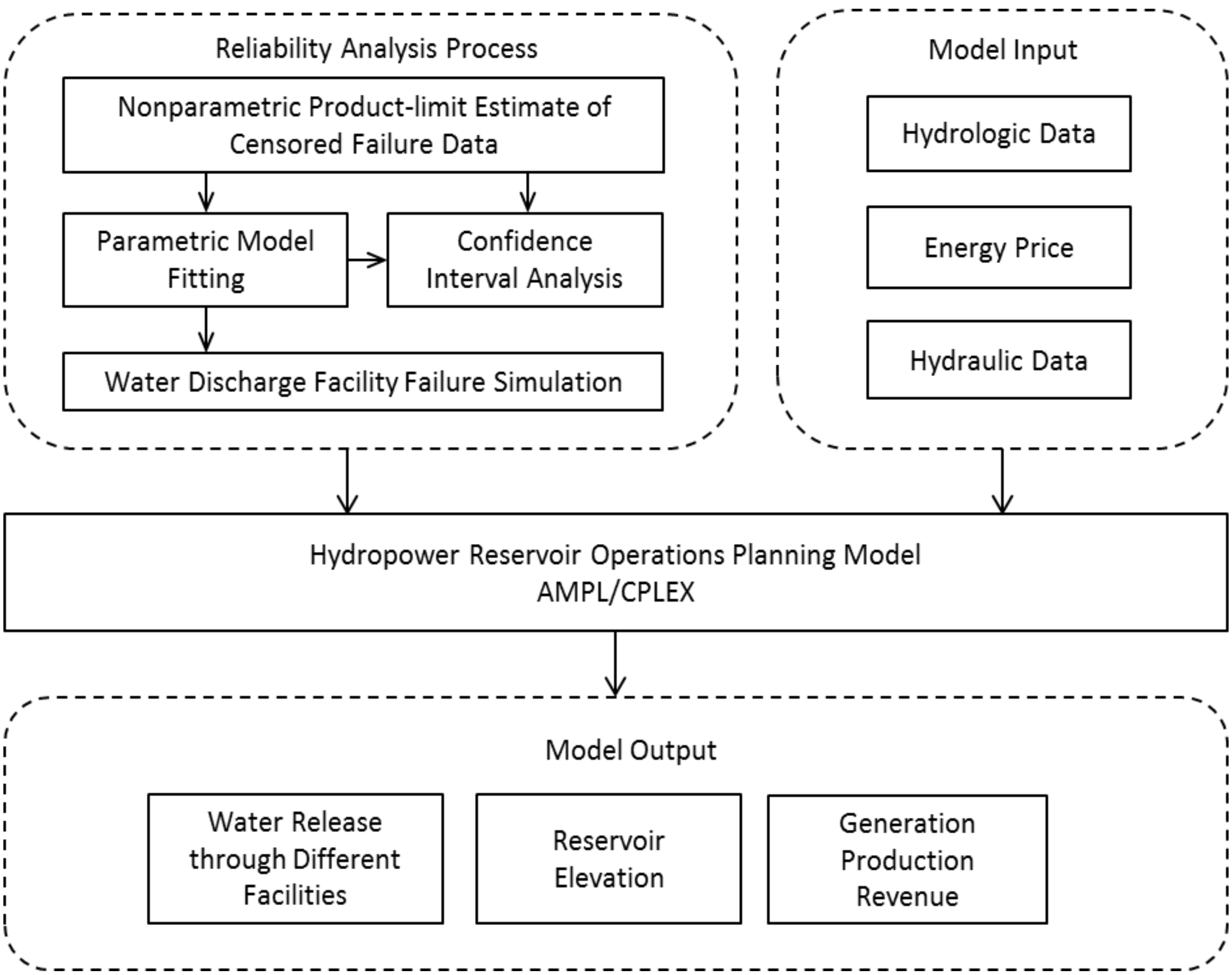

Figure 3.1 Reliability-based Reservoir Operations Planning Modeling Framework

3.2.1 Reliability Analysis Process

Reliability analysis generally has two main procedures: assessment and prediction. Assessment involves the estimation of the reliability of a component or system throughout its useful life. Prediction is the extrapolation and simulation of future failures depending on historical data. This section focuses on the reliability analysis process for reservoir water release facilities to quantitatively assess their reliability and to simulate their outages for modeling this class of uncertainty in reservoir operations. This reliability analysis process we have developed can be used to model the reliability of spillway release facilities and other systems (Zhou, et al. 2014). Section 3.2.1.1 provides a review of reliability data including failure data acquisition, data classification and estimation methodologies. Statistical procedures to assess the reliability of water release facilities are discussed in Section 3.2.1.2 through Section 3.2.1.4 and the simulation of failure and repair events of water release facilities is discussed in Section 3.2.1.5.

3.2.1.1 Review of Reliability Data

Quantitative reliability methods depend on the amount of available data to perform a valid analysis. However, reliability data regarding failures of non-power release facilities is scarce. At present, few hydropower dam owners or operators keep adequate and sufficient records on failures of non-power release facilities during their operational lifespan. Most publicly available data are qualitative and difficult to analyze mathematically. Estes et al. (2005) used the Conditional Index method to evaluate the verbal descriptions of spillway gate reliability from inspectors of these facilities. This method provided the capability to disaggregate and interpret qualitative data, but such analysis still carries limitation with certain level of subjectivity. Previous studies in this filed, though limited, can also be important data sources. For example, the U.S. Department of the Army (2006) prepared a technical manual summarizing the process of obtaining reliability data regarding power generation, power distribution and HVAC components. The U.S. Army Corps of Engineers (2001) published reliability data for the mechanical and electrical systems of navigation locks. These are publically available data sources but they are mainly applicable to specific projects of interest.

In this paper, failure data information of water release facilities was retrieved from the Commercial Management (CM) system, an enterprise database application developed and maintained by BC Hydro. The database contains information on water release facilities such as generating turbine outages, non-power spillway operation failures and unusual conditions of water conveyance. Recorded details of outages include complex failure modes of different types of facilities. The CM database includes extensive records on turbine unit outages over the past decade. However, only a finite number of failure data of spillway facilities has been recorded that contains only partial information about the failure time and duration.

Using collected failure data, the parameters of the reliability distribution functions can be estimated to formulate and predict the time-dependent reliability of components. Popular estimation techniques for analyzing the reliability of dam gates and associated operating equipment are the method of moments (Melching, Yen and Wenzel 1990), the maximum likelihood method (Guo, Szidarovszky and Niu 2013) and Bayesian inference (Smith 2006, Wilson, Anderson-Cook and Huzurbazar 2011). Johnson and Kotz (1994) reviewed the method of moments and the maximum likelihood method for estimating parameters of the Weibull distribution, a lifetime distribution which adequately describes observed failures of different types of components. However, the use of these methods is not recommended for small data samples (Murthy, Bulmer and Eccleston 2004, Lai, Murthy and Xie 2006). Therefore here we seek an estimation method that is appropriate for analyzing the reliability of water release facilities.

Researchers in the reliability analysis field classify the failure data into two types: complete data and censored data. In the complete data classification, each observation in the data set is the actual time to failure for the facility over its lifetime. Censored data arises when monitoring of a facility in order to observe the time to failure is stopped before the facility fails. This type of data is incomplete as only partial information on the failure time and duration is collected (Phillips 2003, Pham 2006). Censored data could also result from removal of facilities from service before failure or could be the result of loss of failure records due to extraneous causes (Nelson 1972, Rausand and Hoyland 2004). Kaplan and Meier (1958) developed the product-limit estimate methodology to estimate survival functions for life testing in medical treatment studies using censored data. The product-limit method is outlined in the following section to estimate the time-dependent reliability of water release facilities.

3.2.1.2 Product-limit Estimate

When the failure data is censored, we are not able to observe all the potential time to failure in the data set over the lifetime of a facility. The potential lifetime is the time a facility would be operated until failure. Given n random variables of the potential lifetime $T_1, T_2, \dots, T_n$, and n random variables of the censoring time $C_1, C_2, \dots, C_n$ which are assumed to be independent of the potential lifetimes, the observed lifetime, t_i, is presented as:

$$t_i = \min(T_i, C_i)\,, i = 1,2, \dots, n \tag{3-1}$$

Figure 3.2 illustrates a schematic of the random lifetime and censored lifetime data. The minimum of the lifetime and censored time determines whether the observation is terminated by failure or by censoring. For example, the observed lifetime of Facility 1 is the exact failure time, whereas the observed lifetime of Facility 2 and 3 is set to the censored lifetime type which produces lower estimates of the actual lifetime.

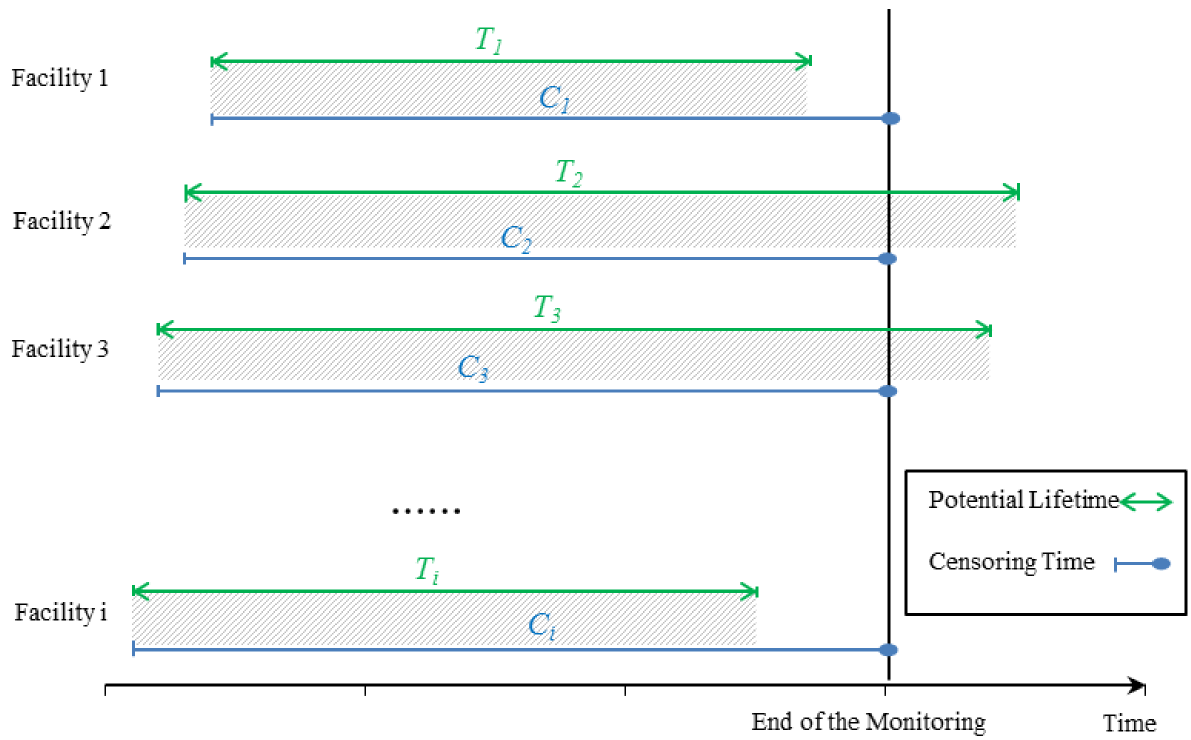

Figure 3.2 Illustration of Random Lifetime and Censored Time Data

The product-limit method for estimating the time-dependent reliability function follows three steps:

(1) Arrange the observed lifetime data by dividing it into suitably chosen time intervals $(t_0, t_1), (t_1, t_2), \dots, (t_{i-1}, t_i)$, where $t_0 = 0$.

(2) For each interval (t_i, t_{i+1}), where $i = 0,1, \dots, (I-1)$ the term $\hat{p}_i$ is computed as an estimate of the conditional probability of surviving just past time t_i, given the condition of being operative just prior to t_i as follows:

$$\hat{p}_i = \frac{n_i - m_i}{n_i} \tag{3-2}$$

where n_i represents the number of facilities operative just prior to t_i and m_i represents the number of failures at t_i.

(3) Build up the estimate of reliability function $\hat{R}(t)$ as a product of each term $\hat{p}_i$ for all intervals prior to time t:

$$\hat{R}(t) = \prod_{t_i < t} \hat{p}_i \tag{3-3}$$

Peterson (1977), Elandt-Johnson and Johnson (1980), Lawless (1982), Cox and Oakes (1984), and others further examined and justified the product-limit estimate and discussed its properties.

If the failure data is complete without censoring, the product-limit estimate coincides with the commonly used empirical reliability function (Ayyub, Kaminskiy and Moser 1998, Rausand and Hoyland 2004):

$$\hat{R}_n(t) = \begin{cases} 1 & \text{for } \ t_0 < t < t_1 \\ 1 - \dfrac{j}{n} & \text{for } \ t_j < t < t_{j+1} \ \ , i = 1,2, \dots, (n-1) \\ 0 & \text{for } \ t_n < t \end{cases} \tag{3-4}$$

where n is the number of the observations and $\hat{R}_n(t)$ decreases by $\frac{1}{n}$ just before each observed failure time.

The outage data of water release facilities was retrieved from the BC Hydro CM database and processed using the product-limit estimation method. The data represents the failure records from 2003 to 2014 for spillway sluice gates and radial gates. The start time and end time of all recorded failure events, as well as the failure causes, are aggregated and presented in Table A.1 and A.2 in Appendix A. Figure 3.3 presents the time-dependent reliability estimate of sluice and radial gates using the censored data for 9 reservoir systems in the Lower Mainland and Vancouver Island. Non-power release facilities in these two regions are more frequently operated than those in the Interior region of BC. The plot of the reliability estimate is a step function with a series of discontinuities or jumps at the observed lifetimes. It can be seen that the reliability estimate of sluice gates drops from 1 to 0.79 in the first year and it drops to 0.63 in the second year provided that the gates are still operative. Radial gates have higher reliability as compared to sluice gates within 2 years of operation. Their reliability drops from 1 to 0.85 by the end of the first year and drops to 0.68 by the end of the second year, provided that the gates are still operative. It can also be seen that the product-limit estimate for radial gates tend to have slightly lower reliability than sluice gates when they are operated for more than 3 years. The product-limit estimation method using censored data can estimate the time-dependent reliability of spillway gates explicitly when limited number of failure events has been recorded. This type of nonparametric estimate can also be used as a basis for fitting an adequate parametric reliability function (Rausand and Hoyland 2004).

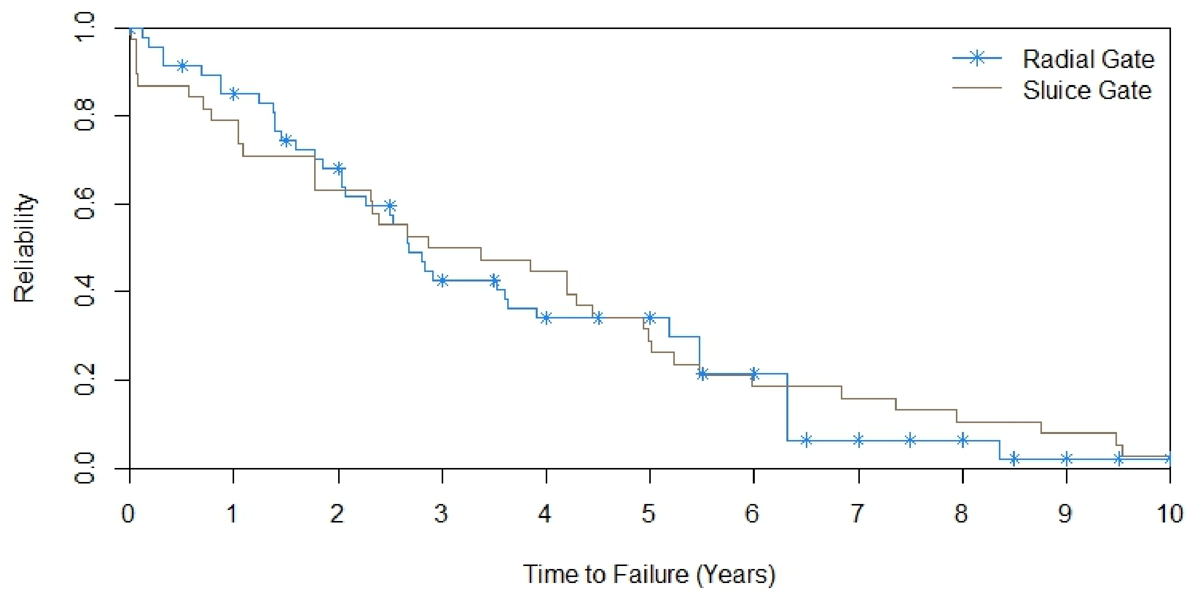

Figure 3.3 Time-dependent Reliablity Estimate of Non-power Water Release Facilties

3.2.1.3 Model Fitting Analysis

The product-limit estimate of reliability is nonparametric, which means it does not depend on the parametric features of certain probability distributions. However, it is not convenient to directly use such nonparametric reliability estimates results in operations modeling without fitting them to specific probability distributions. The Weibull probability distribution function is widely used for fitting the lifetime data; other models such as the polynomial hazard function can achieve good fits as well (Krane 1963).

Distribution parameters can be estimated either using graphical probability paper or using statistical methods. Graphical probability papers usually yield crude estimates whereas the statistical methods are more refined and can be used to obtain confidence limits for the estimates.

One of the statistical methods is the least squares estimation, in which the unknown parameters of the distribution can be linearly related through the transformation of the reliability function:

$$g[R(t)] = \theta_0 + \theta_1 l_1(t) + \cdots + \theta_k l_k(t) \tag{3-5}$$

where $l_1(t), \ldots, l_k(t)$ can be derived from the reliability function and form a linearly independent set of functions of t, and $\theta_0, \theta_1, \ldots, \theta_k$ are the regression parameters to be estimated.

For example, the reliability function of a two-parameter Weibull distribution is:

$$R(t) = 1 - F(t) = \exp[-(\frac{t}{\alpha})^{\beta}], \alpha > 0, \beta > 0 \tag{3-6}$$

where α is a scale parameter, β is the shape parameter that determines the appearance or shape of the Weibull distribution, and $F(t)$ is the cumulative distribution function. $R(t)$ can be transformed logarithmically twice, as shown in Equation 3-7:

$$\ln[-\ln[R(t)]] = \theta_0 + \theta_1 \ln(t) \tag{3-7}$$

where $\theta_0 = -\beta ln\alpha$ and $\theta_1 = \beta$.

Similar to the Weibull distribution model, the polynomial hazard function model also offers flexibility in modeling failure rates, which can adequately describe many physical failure processes, though sometimes higher degree polynomials could be problematic (Lawless 1982). The cumulative polynomial hazard function can be defined as follows:

$$H(t) = a_0 + a_1 t + \cdots + a_k t^k \tag{3-8}$$

where $a_0, a_1, \dots, a_k$ are parameters that must satisfy certain constraints to ensure that the cumulative hazard function $H(t)$ is an increasing function of $t \geq 0$. The reliability function can be expressed in terms of $H(t)$ as below:

$$R(t) = e^{-H(t)} = \exp[-(a_0 + a_1 t + \cdots + a_k t^k)] \tag{3-9}$$

A second-order polynomial exponential reliability function ($k = 2$) can be logarithmically transformed as follows:

$$\ln[R(t)] = \theta_0 + \theta_1 t + \theta_2 t^2 \tag{3-10}$$

where $\theta_i = -a_i, (i = 0,1,2)$.

The regression parameters, θ_i, can be estimated in similar fashion as those in Equation 3-5, as follows:

$$Min\colon\ J(\theta) = \frac{1}{2n}\sum_{i=1}^{n}\{y_i - [\theta_0 + \theta_1 l_1(t_i) + \cdots + \theta_k l_k(t_i)]\}^2 \tag{3-11}$$

where $y_i = \hat{R}(t_i)$ are the corresponding estimated reliability values from the censored data and n is the number of data samples. The gradient descent algorithm can be used to fit the regression parameters (Mitchell 1997). If only limited number of reliability data is available, refinements such as the regularization method can be used to address the underfitting problem, as follows:

$$Min: J(\theta) = \frac{1}{2n}\{\sum_{i=1}^{n}\{y_i - [\theta_0 + \theta_1 l_1(t_i) + \cdots + \theta_k l_k(t_i)]\}^2 + \lambda \sum_{j=1}^{k} \theta_j^2\} \tag{3-12}$$

where λ is the regularization parameter which controls the regression parameters θ_j. As the magnitude of the regression parameters increases, the regularization term will increase the penalty term in the cost function.

Figure 3.4 shows the reliability model fitting results, superimposed on the nonparametric estimated reliability function of spillway radial gates. It can be seen that both the Weibull distribution model and the polynomial hazard function model give adequate parametric estimates. The shape parameter β of the Weibull function was estimated at 1.15, which indicates that the radial gates have started to enter the wearout phase of their service life. More specifically, the gates have an increasing concave failure rate. The coefficient of determination R^2 is 0.969 for the Weibull fitting and is 0.971 for the polynomial hazard function model. This provides a strong verification and confidence that both model fitting methods are acceptable for modeling spillway gates investigated in this study.

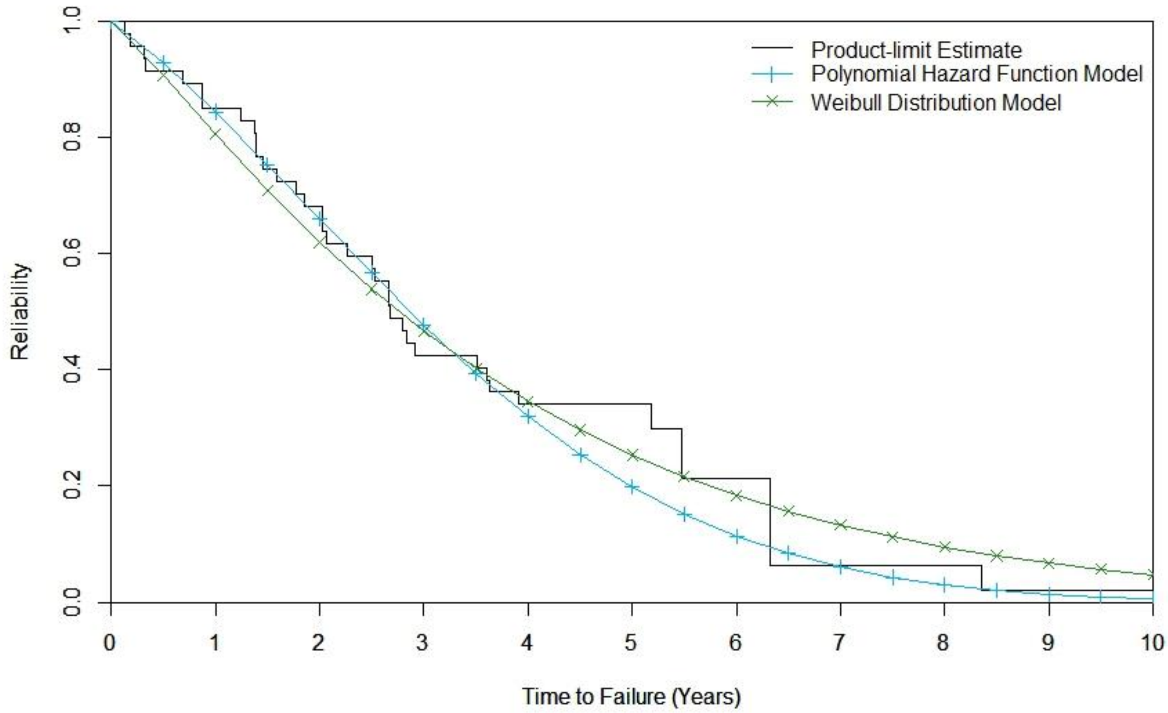

Figure 3.4 Model Fitting of the Spillway Radial Gate Reliabilty

3.2.1.4 Confidence Interval Analysis

In this section, the confidence interval of the spillway gate reliability estimate is analyzed. This type of analysis is important especially when the size of the data sample is small. The confidence interval of the product-limit estimate of reliability is given as:

$$\hat{R}(t) \pm z_{(1-\frac{\alpha}{2})}\sqrt{Var[\hat{R}(t)]} \tag{3-13}$$

where α is the significance level which is the complement of confidence interval (i.e. $\alpha = 0.05$ reflects a confidence interval of 95%), $z_{(1-\frac{\alpha}{2})}$ is the $(1-\frac{\alpha}{2})$ quantiles of the standard normal distribution. In particular, for the 95% confidence interval, $(z_{1-\frac{\alpha}{2}}) = 1.96$. The Greenwood's formula (Upton and Cook 2008) is applied to calculate the variance as follows:

$$Var\left[\hat{R}(t)\right] = \hat{R}^2(t) \sum_{t_j<t} \frac{m_j}{n_j(n_j - m_j)} \tag{3-14}$$

where n_j and m_j represent the number of facilities operative just prior t_j and the number of failures at t_j respectively, as discussed in Equation 3-2. This approach could possibly yield confidence interval values that are outside the range $[0, 1]$. For example, if analyzing the 95% confidence interval for the radial gate reliability using Equation 3-13, the upper bounds for $0 \leq t \leq 0.32$ would exceed 1 and the lower bounds for $t \geq 6.32$ would go below 0, as shown in Table 3.1. In this case, replacement of negative lower bounds by 0 and upper bounds greater than 1 by 1 is necessary. In addition, the assumption of normality, implicit in Equation 3-13, may not hold for small to moderate failure data sizes (Hosmer and Lemeshow 1999).

Table 3.1 Sample Calculations of the Confidence Interval for the Radial Gate Reliability

Time to Failure (Years)	$\hat{R}(t)$	$Var\left[\hat{R}(t)\right]$	95% Confidence Interval	
			Lower Bound	Upper Bound
0.000	1.000	0.0000	1.000	1.000
0.127	0.979	0.0004	0.937	1.020
0.186	0.957	0.0009	0.900	1.015
0.320	0.936	0.0013	0.866	1.006
0.323	0.915	0.0017	0.835	0.995
…	…	…	…	…
5.473	0.213	0.0036	0.096	0.330
6.320	0.064	0.0013	-0.006	0.134
8.356	0.021	0.0004	-0.020	0.063

An alternative approach was proposed by Kalbfleisch and Prentice (2002) to avoid these problems, by giving an asymmetric confidence interval:

$$\exp[-e^{c_1}] < R(t) < exp[-e^{c_2}] \tag{3-15}$$

where

$$c_{1,2} = \ln\left[-ln\hat{R}(t)\right] \pm z_{1-\frac{\alpha}{2}}\sqrt{Var(\ln\left[-\ln[\hat{R}(t)]\right])} \tag{3-16}$$

and the variances in Equation 3-16 can be formulated as:

$$Var(\ln\left[-\ln[\hat{R}(t)]\right]) = \frac{1}{[\ln[\hat{R}(t)]]^2}\sum_{t_j<t}\frac{m_j}{n_j(n_j - m_j)} \tag{3-17}$$

The upper and lower bounds of spillway radial gates reliability resulting from the application of this method are shown graphically in Figure 3.5. For example, the reliability of spillway gates after being operated for one year is between 0.713 and 0.926 with the likelihood of 95%, and the most likely estimate is 0.851. It can also be observed in Figure 3.5 that the Weibull reliability function remains within the 95% confidence interval. Parametric curves fitted for the upper and lower bounds are also presented. The variance, representing the uncertainty of the reliability estimate, increases in the first three years and eventually reaches a maximum of about 0.5% and then it diminishes indicating that the estimate is accurate. Several authors further described the problem of obtaining small-sample confidence intervals for reliability (Johns and Lieberman 1966, Thoman, Bain and Antle 1970, Mann and Fertig 1973).

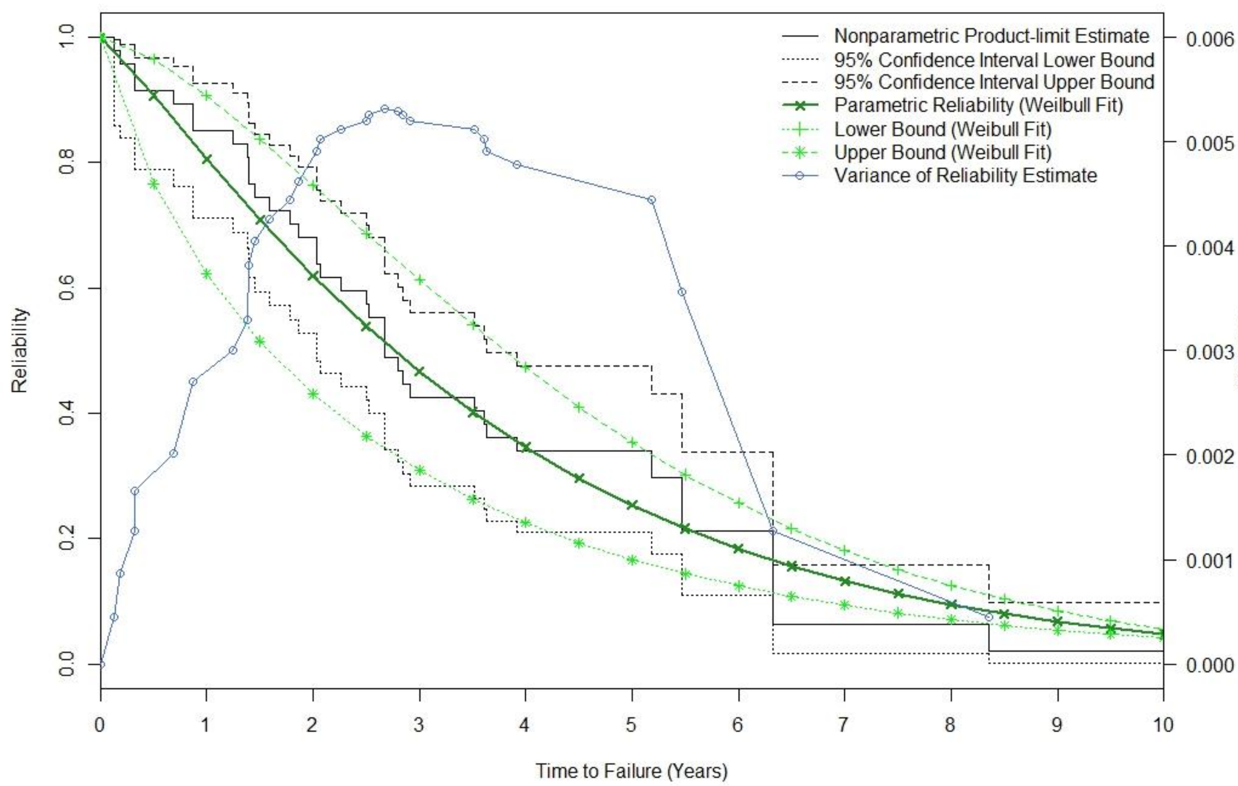

Figure 3.5 Spillway Radial Gate Reliability Estimate with 95% Confidence Intervals

3.2.1.5 Monte Carlo Simulation

When failure of a water release facility occurs, such as a spillway gate or a turbine generator, restoring it back to the normal operating condition becomes the primary task. The failure-repair process typically follows a two-phase cycle, whose duration is determined by the time to failure (TTF) and the time to repair (TTR). The TTF is the elapsed time since the last perfect repair until the next failure happens and it reflects how reliable a facility is. The TTR represents the time required to repair a failed facility. It assumes that perfect repairs are carried out, that is, once the facility has failed and a repair is completed, its function is fully restored. The lognormal distribution can be used by fitting the repair time data (O'Connor and Kleyner 2012). Figure 3.6 presents the fitted cumulative probability distribution functions of the TTR for the BC Hydro spillway gates investigated.

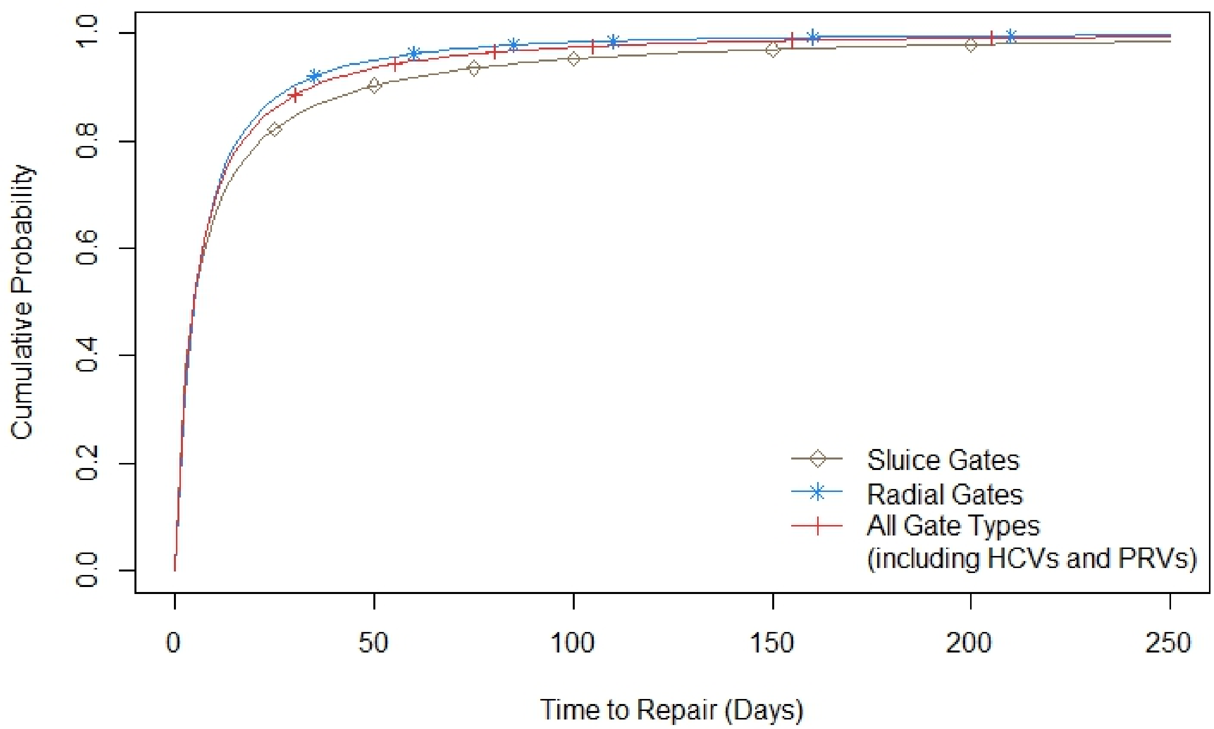

Figure 3.6 Cumulative Lognormal Distributions of Spillway Gate Repair Time

Given the time-dependent reliability function and the lognormal repair time function which are monotonic and continuous, Monte Carlo simulation can be used to predict the time of failure and repair events. The random variables of TTFs and TTRs can be generated using the inverse transform method (Tung, Yen and Melching 2006). Suppose a random variable U follows the uniform distribution over the unit interval [0,1], the following relationships hold:

$$TTF = R_t^{-1}(U) \quad (3\text{-}18)$$

$$TTR = F_t^{-1}(U) \quad (3\text{-}19)$$

where $R_t^{-1}(U)$ and $F_t^{-1}(U)$ are the inverse distributions of the fitted reliability function and the cumulative lognormal function respectively. To simulate the TTF, random variables following the uniform distribution can be generated by the pseudo-random generator (Billinton and Allan 1992). Next, Equation 3-18 and 3-19 are solved for the TTF using each of the generated uniform random variables.

Figure 3.7 shows the simulated TTFs and TTRs of the spillway radial gates. The scattered data points consist of 3,000 generated random sequences of alternating lifetimes and repair times. The marginal plots illustrate the univariate histograms and fitted probability density functions of the TTF and TTR respectively, which are independent and identically distributed. The most probable TTF for the radial gates is between the 1 year and 1.5 years, and the average simulated repair process takes 15 days. The results of the Monte Carlo simulation can be used to analyze the operational availability of the water release facilities, as described in Appendix B.

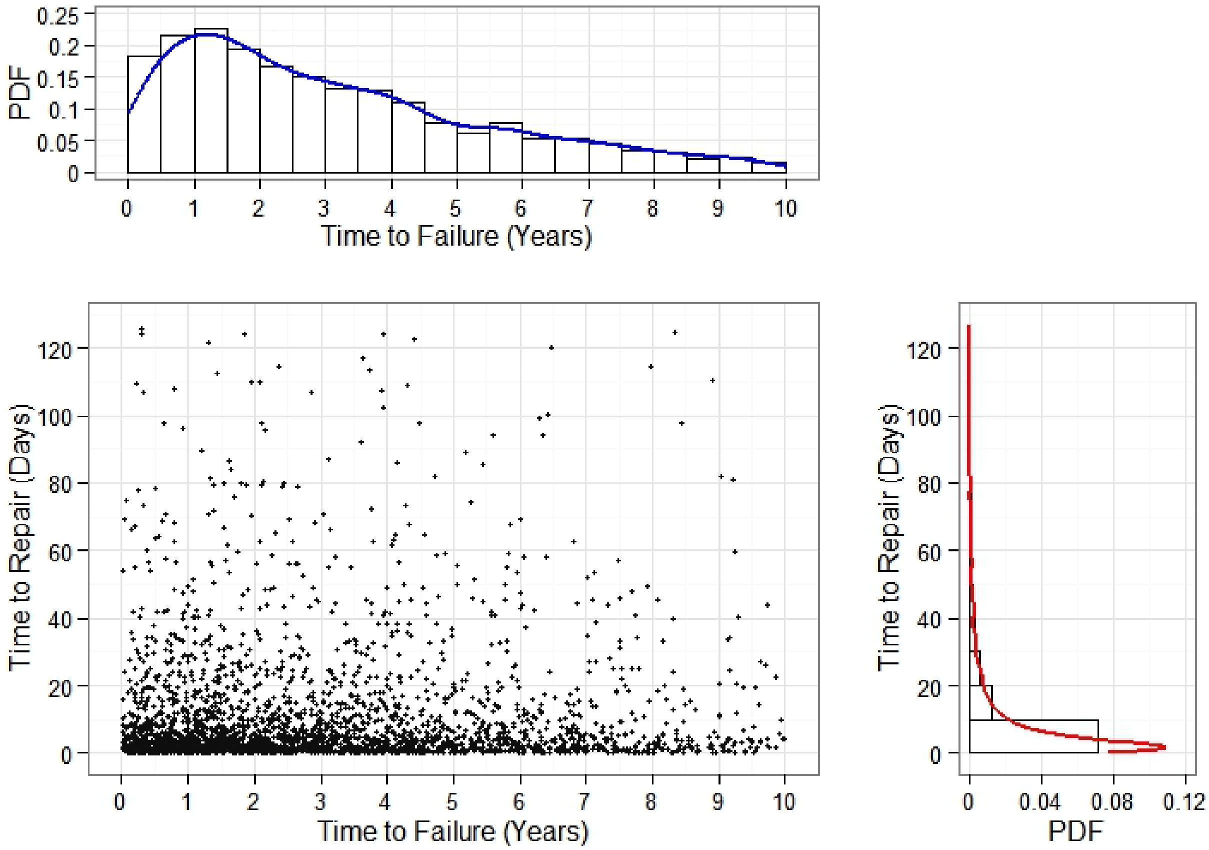

Figure 3.7 Simulated Time to Failure and Time to Repair for Spillway Radial Gates

3.2.2 Operations Planning Model

We have enhanced and used the BC Hydro Operations Planning Tool (OPT), an optimization model that is typically used by the operations planning engineers to simulate operation of hydropower generation schedules. The model objective is to maximize net income from power generation while meeting operational constraints on dam safety, fish and wildlife habitat and recreational requirements. The model can also optimize the timing and duration of plant and turbine outages. The model can also be used to prepare reservoir operating plans using inflow and market forecasts, and to evaluate the impact of reservoir operations on water releases and levels under various operating scenarios.

The operations planning model is programmed in AMPL (Fourer, Gay and Kernighan 2002), a programming language that is popular for solving complex optimization problems. The linear programming (LP) method, one of the most widely used techniques in reservoir operations (Yeh 1985, Wurbs 1991, Labadie 2004), is used to solve the large-scale optimization problem and converge to a global optimal solution. Some extensions of LP such as the mixed integer programming (MIP) and piecewise linear approximations are also used to model discrete variables and to approximate nonlinear functions. The ILOG CPLEX solver is used to solve the LP and MIP problems (IBM Corp. 2010).

The OPT model incorporates multiple and conflicting objectives to maximize hydropower generation revenues and to minimize the negative impacts of reservoir elevations and water releases that deviate from a set of operating requirements (BC Hydro 2011). To solve the multi-objective problem the weighting method is used to explicitly capture the tradeoffs among the objectives. Further details on the objective function formulation and model constraints are described in Appendix C.

3.2.3 Model Input

To run reservoir operation simulation studies, a number of model input data are required including the hydrologic data, market prices for hydropower electricity, and the hydraulic characteristics data of reservoir systems.

Hydrologic and other input data are prepared. The historical inflow records for pertinent locations of reservoir systems from BC Hydro's operational achieved data are used. The reservoir inflow sequences have been reviewed and adjusted using a data quality control process based on comparisons to nearby gaged basins with similar hydrology (Vassilev, Sreckovic and Groves 2008) covering a period of 40 years of inflow records. The hydrologic data is recorded as the mean flow rates over specified time intervals (e.g., daily) or time steps. The OPT model can adopt hourly or daily time steps during flooding events, and can use longer time steps such as a week or a month for normal hydrologic conditions.

Given the historical inflow records, stochastic simulations of hydrologic time series can be used to generate synthetic inflow data. A set of synthetic inflow sequences were generated using the SAMS system (Sveinsson, et al. 2007). The SAMS system preserves the statistical characteristics of the historical data. This set of inflow sequences were used for the hydrologic input in the OPT model and provided the model a variety of hydrologic scenarios, including those of critical conditions, such as critical and unforeseen flooding events.

The energy price is another uncertain input parameter in the OPT. Energy prices are influenced by many factors such as the electricity demand, natural gas price fluctuations, global or regional economic growth, and government policy on greenhouse gas emissions (BC Hydro 2013). It is difficult to accurately predict electricity prices because the prices are very volatile and because they do not follow certain trends. The electricity market price at the Mid-Columbia (Mid-C) region is used to calculate revenues from power generation production of the hydro reservoir systems.

Specific hydraulic data for each hydro reservoir project is used. It can be categorized by the reservoir system network data and reservoir physical characteristics. The reservoir system data contains the number and names of storage reservoirs and non-storage control points, which are interconnected by flow paths for each river system. The reservoir physical data includes the relationships between reservoir elevations and storage volumes, and the discharge capacity rating curves for generating turbines and spillway gates. The reservoir physical data provides fundamental information characterizing a reservoir system as required in modeling studies.

3.2.4 Model Output

The model output comprises the optimized values for a number of decision variables and essential data for evaluating the performance and feasibility of simulated operation scenarios. The output data is stored in a tabular format, including optimal reservoir elevations and storages, spillway releases, turbine releases, power generation, the unit commitment, and the objective function values. To avoid perfect foresight and to simulate actual system operation, the optimization problem is solved for a 5-day rolling planning horizon. Output data on ending reservoir elevation and water releases from the rolling horizon runs are used to initialize the next run.

3.3 Reservoir Operation Case Study

In this section, the reliability-based modeling framework is applied to the Daisy Lake Reservoir, a hydropower storage reservoir system in British Columbia, to illustrate the application of reliability-based modeling framework. The investigation includes numerous simulation runs and analyses of the results. Both the historical and synthetically generated inflows were used. The reservoir operating policies evaluated in the study include water releases form multiple discharge facilities and reservoir elevations under different operating scenarios and hydrologic conditions. Although the focus of the case study is on the reliability-based operations planning that considers both the reliability of water release facilities and hydrologic extremes, conventional operation studies based on historical inflows are also discussed. Section 3.3.1 provides an overview of the Daisy Lake Reservoir and the inventory of the water release facilities in the reservoir system. Section 3.3.2 presents the operations planning study results using 40 years of historical inflows. Section 3.3.3 consists of the reliability analysis applications to the spillway gate systems and simulations of the operations planning model using synthetic inflows, followed by interpretations and discussions of the model results.

3.3.1 Reservoir System Overview

The Daisy Lake reservoir is located adjacent to the Sea-to-Sky Highway, approximately 32 km north of Squamish in southwestern British Columbia, Canada. The Cheakamus Dam impounds water flowing south from the headwaters of the Cheakamus River, forming the Daisy Lake Reservoir. A power intake tunnel links the Daisy Lake Reservoir to the 157 MW powerhouse in the Squamish Valley (BC Hydro 2005). Two penstocks carry the water from the tunnel exit to the Cheakamus generating station which is discharged into the Squamish River. The maximum turbine release is 65 m^3/s. The normal operation head of the reservoir is about 340 m between the Daisy Lake Reservoir and the power generating station at the Squamish River. Figure 3.8 shows a schematic of the Cheakamus dam and reservoir system and the various types of water release facilities.

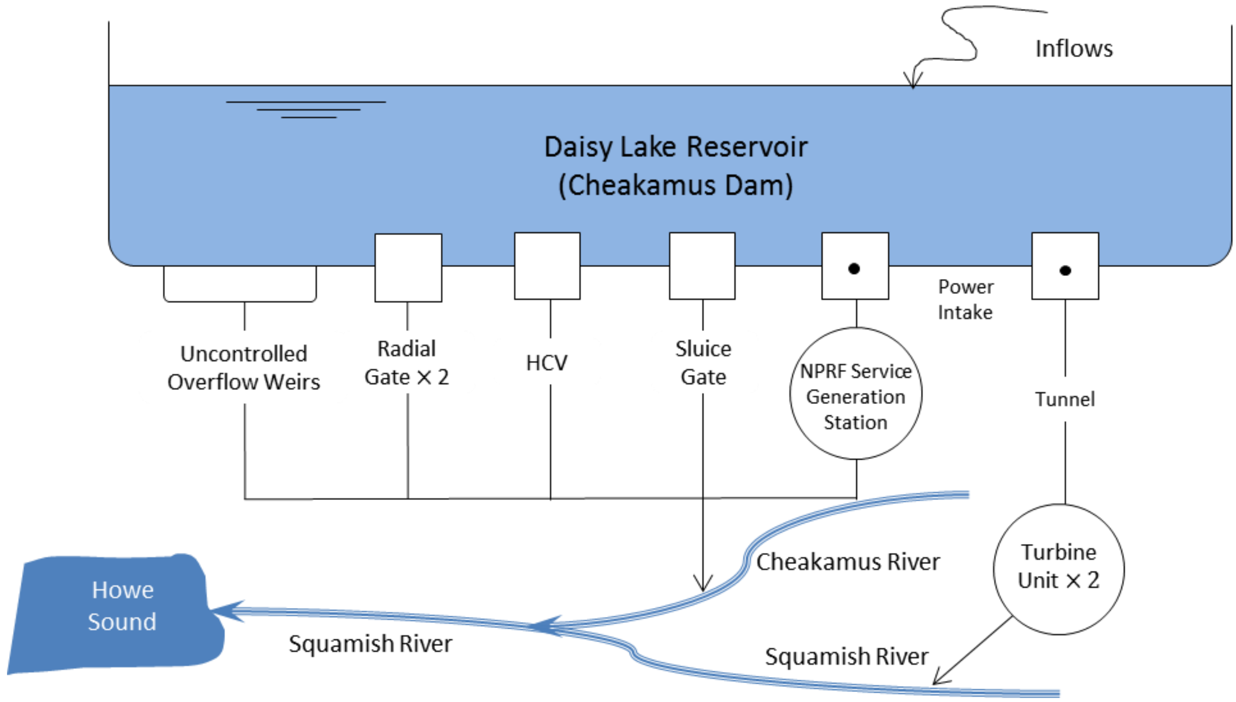

Figure 3.8 Physical Layout of the Daisy Lake Reservoir System in British Columbia

Water release facilities in the Daisy Lake Reservoir system comprise two turbine units, two spillway radial gates, one low level sluice gate, four free crest weir spillway sections on the main dam and one low level hollow cone valve (HCV) primarily used for fish flow releases. The two radial gates are operated to pass the flood flows. The control of the radial gate movement is limited to certain ramping rates to reduce the risk of downstream flood damages resulting from rapid water releases. The sluice gate is operated either fully open or fully closed, and is only opened when the radial gates reach their maximum discharge capacity. The free crest overflow weir sections supplement the discharge capacity when reservoir level reaches 378.4 m above mean sea level.

During normal operations, the Daisy Lake Reservoir has an operating range from 364.90 m to 377.95 m, a fluctuation of 13.05 m. The reservoir can store about 55 million cubic meters of water, which is only 3.5% of the average annual total inflows (BC Hydro 2005). Sudden increase in inflows due to intense precipitations or snowmelt can rapidly increase the reservoir water level in a short period of time. Other hazards such as floating debris and icing load on spillway facilities in winter, also contribute to the potential operational risks in this system.

3.3.2 Normal Operation Case Study

The following section illustrates how the OPT operations planning model has been normally used by BC Hydro operation engineers as a tool to optimize hydropower reservoir releases and explore daily operation alternatives. A daily time step is used to optimize generation schedules, reservoir releases and elevation in a typical 5-day look-ahead rolling horizon optimization interval with perfect foresight of reservoir inflows. In this study, daily inflow records for the period 1967 - 2006 are used to model normal operations of Daisy Lake Reservoir. The median, 10^{th} and 90^{th} percentiles and the daily reservoir inflows for the period of record are presented in Figure 3.9.

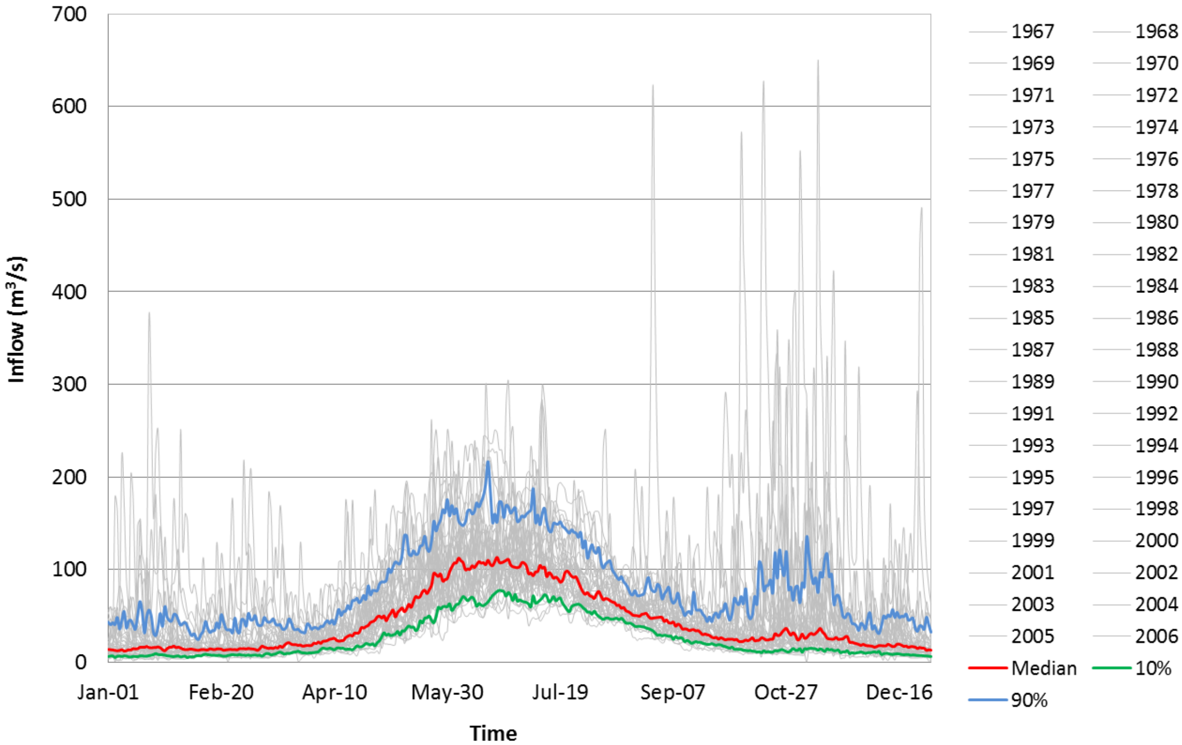

Figure 3.9 Daisy Lake Reservoir Daily Natural Inflow (1967-2006)

The optimization process is driven by the economic goal of maximizing generation productions after satisfying other multipurpose goals and constraints such as minimizing adverse effects of flood events through operation of spillway facilities, maximizing physical conditions for recreation and minimizing environmental impacts such as fish impact.

A typical reservoir operating plan is usually followed to meet target elevations at various times of the year. From 1 October to 31 December, when heavy precipitations are more likely to occur, the target reservoir level is lowered to provide additional storage volume to manage high inflow events. During the spring freshet period, usually from May to August, the natural inflow into Daisy Lake Reservoir normally surpasses the turbine release capacity; therefore, the reservoir is usually drawn down before the onset of the snowmelt in the freshet to accommodate the high inflows with minimum spillway releases to reduce future downstream flood risk. The target reservoir elevation is derived using the penalty functions which serve as operational constraints in the model. Any deviation from the target elevation is penalized according to the penalty values as represented by a piecewise linear convex function f_E. Similarly, water releases that deviate from the target flow regimes are penalized using the penalty function f_R. The minimization of penalty functions and the maximization of the value of hydropower generation constitute the objective function, as follows:

$$\text{minimize: } \{w_E \sum_{j}^{J} \sum_{t}^{T} f_E(E_{j,t}) + w_R \sum_{j}^{J} \sum_{t}^{T} \sum_{n}^{N} f_R(R_{j,n,t}) - w_G \sum_{j}^{J} \sum_{t}^{T} G_{j,t} P_t\} \qquad (3\text{-}20)$$

where $E_{j,t}$ is the reservoir elevation in reservoir j at time step t, $R_{j,n,t}$ is the non-power water release from facility n, P_t is the electricity market price, $G_{j,t}$ is the power generated, w_E, w_R and w_G are the weighting factors assigned by decision makers to the corresponding objective function term, as discussed in Appendix C.1. The formulations and features of model constraints are described in Appendix C.2. Physical and operational constraints for the Daisy Lake Reservoir are established using the system operating orders and recommendations from the Cheakamus River Water Use Plan (BC Hydro 2005).

In this study, an operation scenario is modeled running a 40-year sequence of historical inflows. Figure 3.10 illustrates the results of optimal reservoir elevations for the historical inflow scenarios and it shows that the Daisy Lake Reservoir level fluctuates seasonally within current reservoir elevation operating range from 367.45 m to 377.95 m. It can also been seen that the reservoir elevation can exceed the maximum normal level during the fall storm season (October to December) due to high inflows. This has occurred in 12 years of the entire forty-year study period. Figure 3.11 shows the optimal total water releases from the Daisy Lake Reservoir, including turbine releases and spills through non-power release facilities into the Cheakamus River. Note that this operating scenario does not include special constraints such as turbine unit maintenance scheduling and failure simulation of non-power water release facilities.

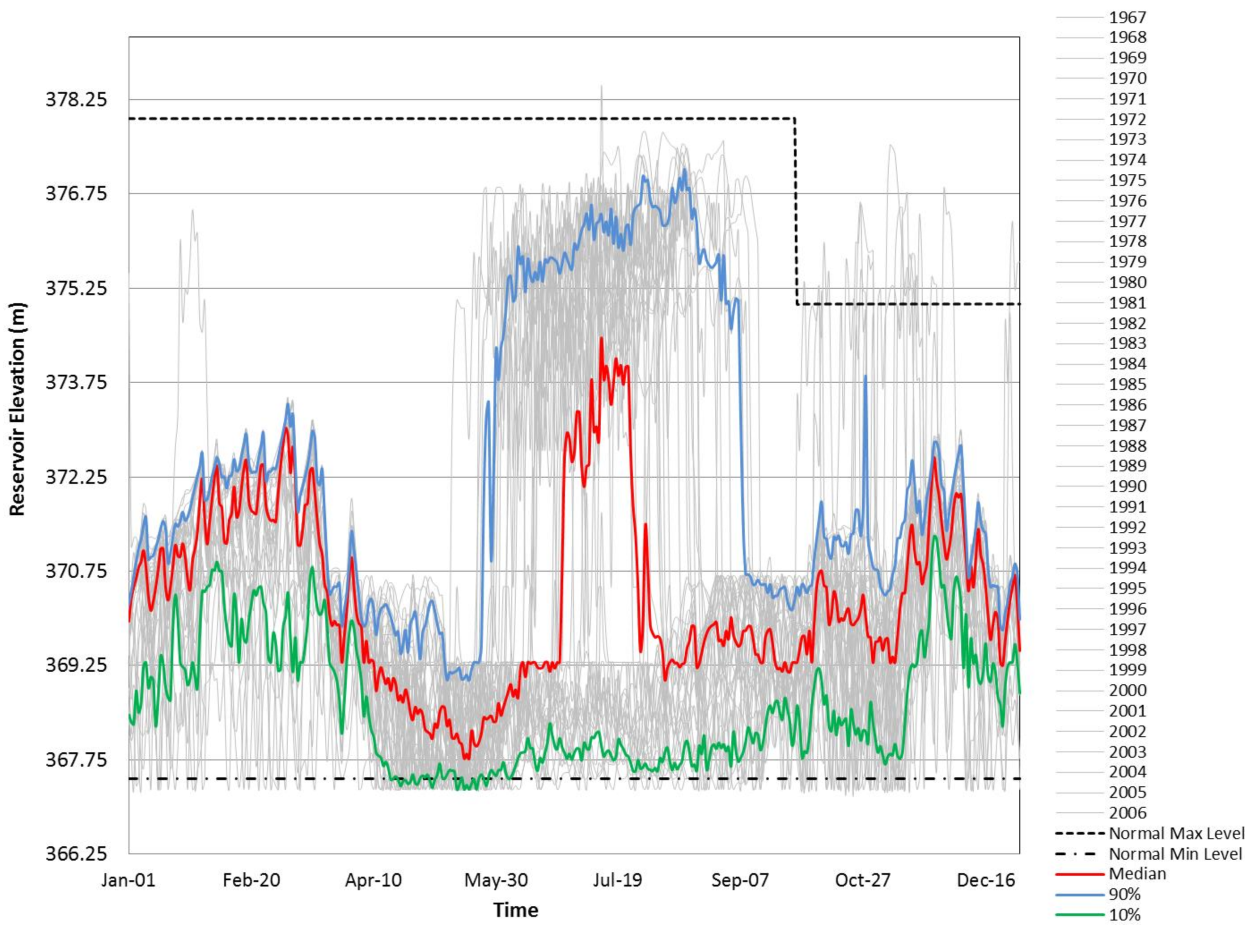

Figure 3.10 Optimal Reservoir Elevation of Daisy Lake Reservoir

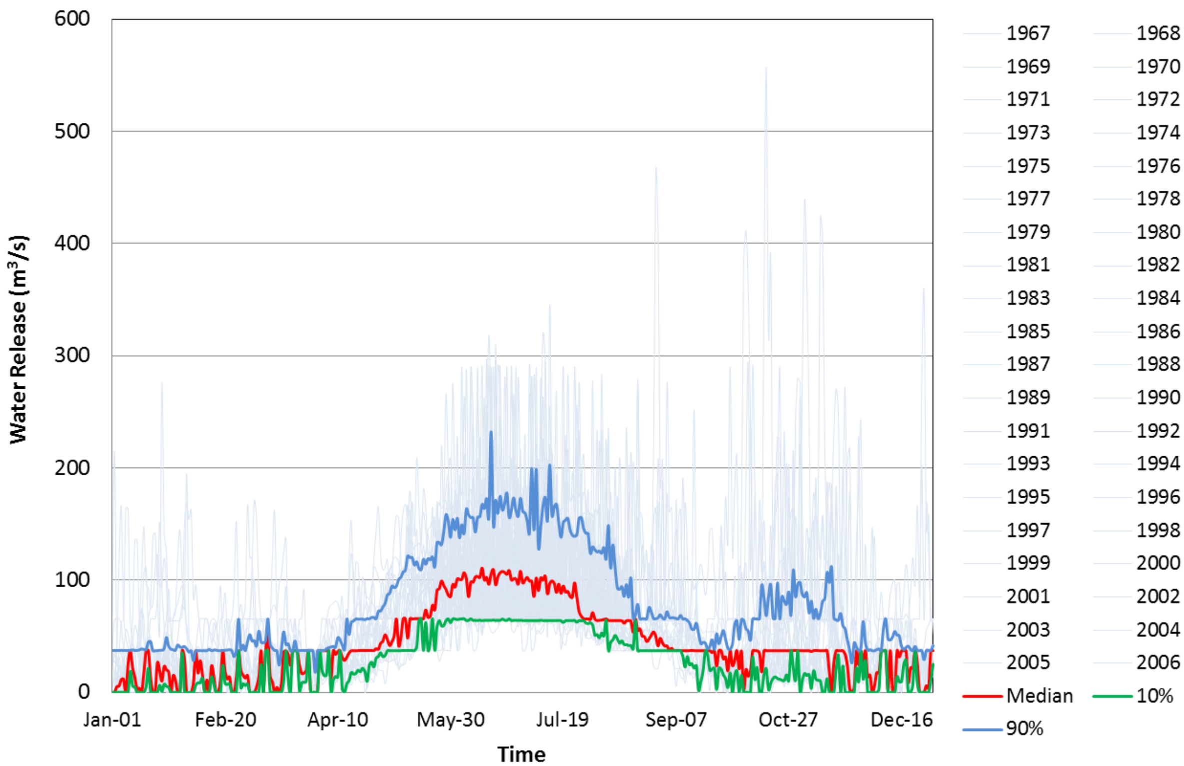

Figure 3.11 Optimal Total Water Releases from Daisy Lake Reservoir

3.3.3 Reliability-based Operation Case Study

In BC Hydro's coastal reservoir systems such as Daisy Lake Reservoir, flooding is a major concern and flood control becomes a prominent objective of reservoir operations. Traditionally, reservoir operations planners assume that water release facilities are available on demand. As discussed earlier, they typically use a set of rule curves to evacuate enough reservoir storage capacity in anticipation and prior to major high inflow events to avoid overtopping incidents (Zhao, et al. 2014). To manage reservoir operations in a reliable manner, operators and decision makers need to consider both hydrologic risk and the uncertainty of the availability of water release facilities. This section presents the reliability-based operation modeling study for the Daisy Lake Reservoir that models the reliability of spillway gates under various potential hydrologic scenarios. Time and duration of failure events and repair processes of spillway gates are simulated following the reliability analysis process described in Section 3.2.1. A number of operation scenarios are modeled by running the reservoir operations model using a number of 40-year of synthetically generated daily inflows sequences. Modeling results are analyzed and discussed, with a particular focus on reservoir elevations to assess the risk of overtopping of dam facilities in high inflow events.

A number of assumptions and simplifications are made in the reliability-based reservoir model to illustrate its functionality. The first is to assume independence between failure and repair events of water release facilities in simulations. For instance, it is assumed that failure of a spillway gate will not be affected by the operation or failure of other spillway gates in the reservoir system. Some failure events may have common causes such as remote control malfunctions or power supply outages, so it is more likely that failures of individual spillway gates overlap with each other. The radial gates in Daisy Lake Reservoir are of the same type and are exposed to the similar operating environment. It is therefore assumed that the times to failure of the two gates follow an identical lifetime distribution. The failure mode for the radial gate is the failure of the gate to operate to its open positions at prescribed time. When a gate fails to open, the release capacity of the gate is assumed to be zero. For simplicity, outages of the sluice gate, HCV and turbine units are not simulated as their discharge capacities are small compared to the radial gates. Modeling of the time needed to operate the gates to the required gate positions is assumed to be less than the length of the time step used in this study and is therefore omitted in this study.

Similar to the normal operation study discussed in Section 3.3.2, a daily time step and 5-day rolling horizon are used in this reliability-based operation study. Monte Carlo simulation is used to simulate the failure and repair events of spillway radial gates. One hundred 40-years daily inflow sequences were synthetically generated using SAMS, a stochastic simulation tool to model hydrologic time series (Sveinsson, et al. 2007). Physical and operational constraints are formulated to reflect operational constraints of the Water Use Plan (BC Hydro 2005) and to comply with the BC Hydro's system operating order for the Cheakamus system. The PMF of the Daisy Lake Reservoir is estimated to be 4,129 m^3/s and the corresponding reservoir water level is expected to reach 381.59 m (Zaman 2010). Some of the critical water elevations of Cheakamus Dam are listed in Table 3.2.

Table 3.2 Critical Water Elevations of Cheakamus Dam

Elevation (m)	Remarks
381.59	Probable Maximum Flood (PMF) Storage Level
381.42	Side Earthfill Dam Crest
380.40	Main Dam Crest
378.40	Free Crest of Overflow Weir (Uncontrolled Spillways)
377.95	Crest Elevation of SPOG1 & 2
367.28	Sill Elevation of SPOG1 & 2
364.90	Minimum Elevation Required for Generating Turbine Units

Figure 3.12 illustrates the results of the reliability-based operations study. The 100 synthetically generated inflow sequences were sorted and ranked for the highest synthetically generated annual peak (2,300 m^3/s) to the lowest. The first graph shows the highest 40-year synthetic inflow sequence generated using the periodic autoregressive moving average (PARMA) model in SAMS. Failure and repair events of both radial gates (i.e. SPOG1 and SPOG2) are simulated independently and their outages are displayed in the second graph. The failure and repair

simulation starts at time t=0 when both gates are assumed to be functioning, and it continues until the end of the 40 years sequence. In this scenario, there were 15 failures of SPOG1 and 10 failures of SPOG2 as illustrated in the second graph which also shows the total water releases through the radial gates and the uncontrolled overflow weirs. The third graph shows the optimal reservoir elevations for this inflow sequence and the preferred operating range which varies during the freshet and storm seasons as discussed earlier. It can be seen that the reservoir elevation exceeds the normal operating maximum water level 14 times in this study and the number of days in which the reservoir storage limits are exceeded range from 1 to 19. It can also be seen in Figure 3.12 that reservoir elevation reaches the PMF storage level (381.59 m) when the peak inflow of about 2,300 m^3/s simultaneously occurs with an outage of both spillway radial gates in the 95th month of this sequence. The second highest peak of about 1500 m^3/s in this sequences occurred in the 47th month and as both gates are functioning the simulation results show that the reservoir elevation reached 378.16 m which is below the crest of uncontrolled overflow weirs.

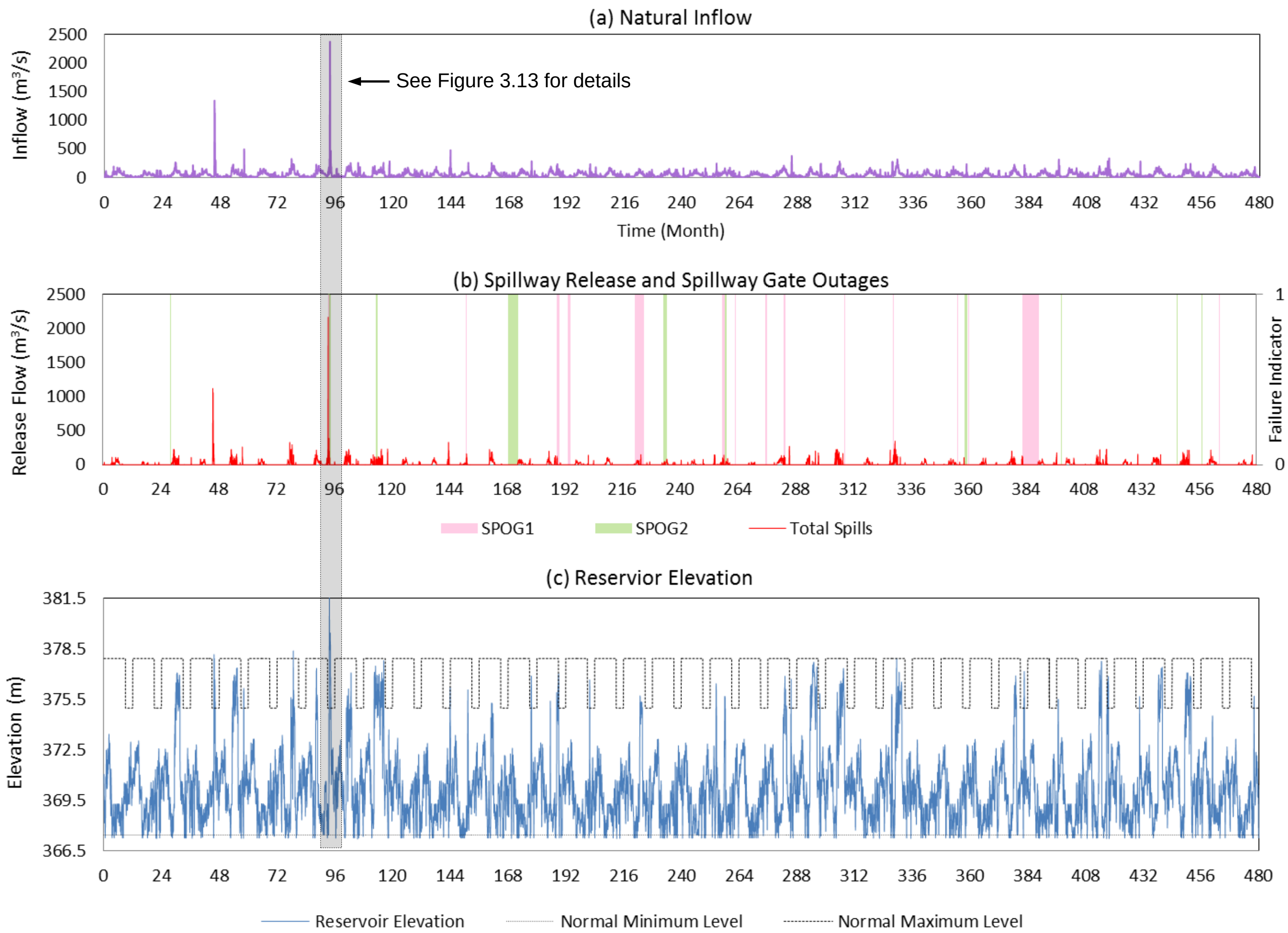

Figure 3.12 Modeling Results for Reliability-based Reservoir Operation Scenario

Figure 3.13 shows the daily results for the 95th month. The first hydrograph shows the natural inflows, total reservoir releases and spill outflows including spillway releases through radial gates and over the uncontrolled weir crest. The second graph shows the failure time and duration of the radial gates. The third graph illustrates the simulated reservoir elevations that exceed critical dam levels during the flood event extending from day 2850 to 2855 in this sequence. Reservoir elevation remains in normal operating ranges when the radial gates are functioning. When both radial gate fail (for days 2850 to 2866) turbine units and the low level outlet cannot provide sufficient discharge capacity to pass the high inflow. Reservoir elevation rises up quickly and it reaches the free crest of the overflow weirs (378.40 m). The excess inflows start to spill through uncontrolled spillways and reservoir elevation continues to increase until it reaches the main dam embankment crest and overtop it. The overtopping could cause severe damages to Cheakamus Dam and the downstream floods would inundate the adjacent highway (Zaman 2010) causing significant damages. It can also be seen that under this extreme inflow sequence the reservoir elevation does not drop and remains above the overflow weir crest level until one of the gates (SPOG2) is restored.

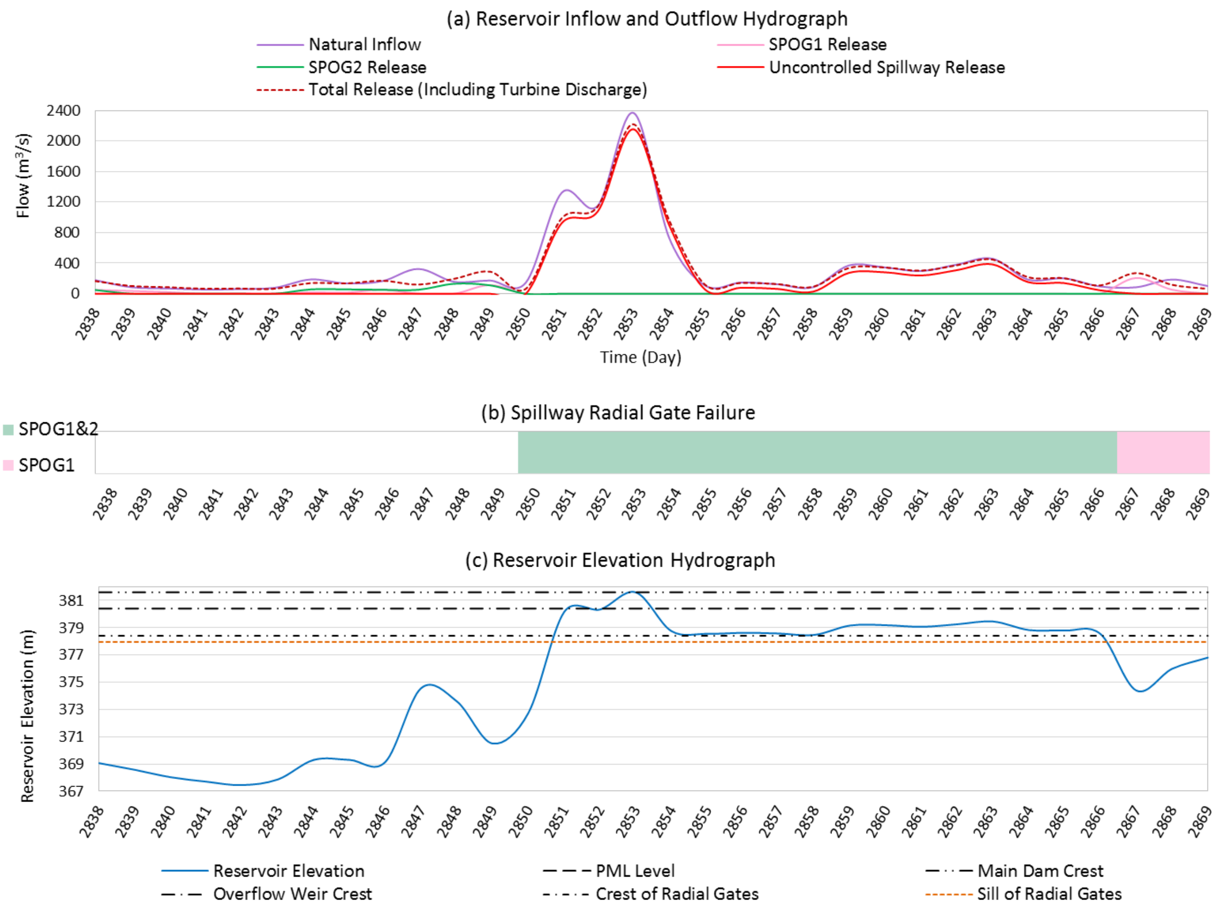

Figure 3.13 Reservoir Releases and Elevation during High Inflow with Simultaneous Gate Failures

The probability of attaining flood safety margin is an important measure for a reliability-based operation modeling analysis (Zhao, et al. 2014). Figure 3.14 illustrates a set of reservoir elevation exceedance curves under different operating scenarios. Table 3.3 summarizes the number of the simulated radial gates failures and range of time to repair the gates for the corresponding operations scenario modeled in the case study. These gate outage scenarios were randomly chosen from a series of failure and repair simulation samples. The exceedance curves were calculated for both normal operation using historical inflows and for reliability-based operating alternatives, with and without radial gate outages for the highest 5% of the synthetic inflow sequences. The solid colored lines represent the operating scenarios that do not consider spillway gate failures, whereas the dashed lines represent the same scenarios but with gate failure and repair simulations. Under normal operating conditions the exceedance probability of the reservoir elevation exceeding the overflow weir crest (378.4 m) is 0.00013 while the exceedance probability of reservoir elevation exceeding the same level is considerably higher under the reliability-based operation. For example for Gate Failure Scenario 1, the likelihood of reservoir elevation exceeding 378.4 m is 0.0012, which is nearly an order of magnitude higher than the normal operation case.

Table 3.3 Summary of the Number of Simulated Radial Gates Failures and Range of Time to Repair

Operating Scenario	SPOG1		SPOG2	
	No. of Failures	Range of TTR (days)	No. of Failures	Range of TTR (days)
Gate Failure Operation (Historical Inflow Scenario)	13	2-99	8	1-118
Gate Failure Scenario 1	15	1-205	10	2-118
Gate Failure Scenario 2	16	1-20	12	1-104
Gate Failure Scenario 3	11	1-105	8	1-77
Gate Failure Scenario 4	12	1-183	9	2-205
Gate Failure Scenario 5	12	1-319	15	1-146

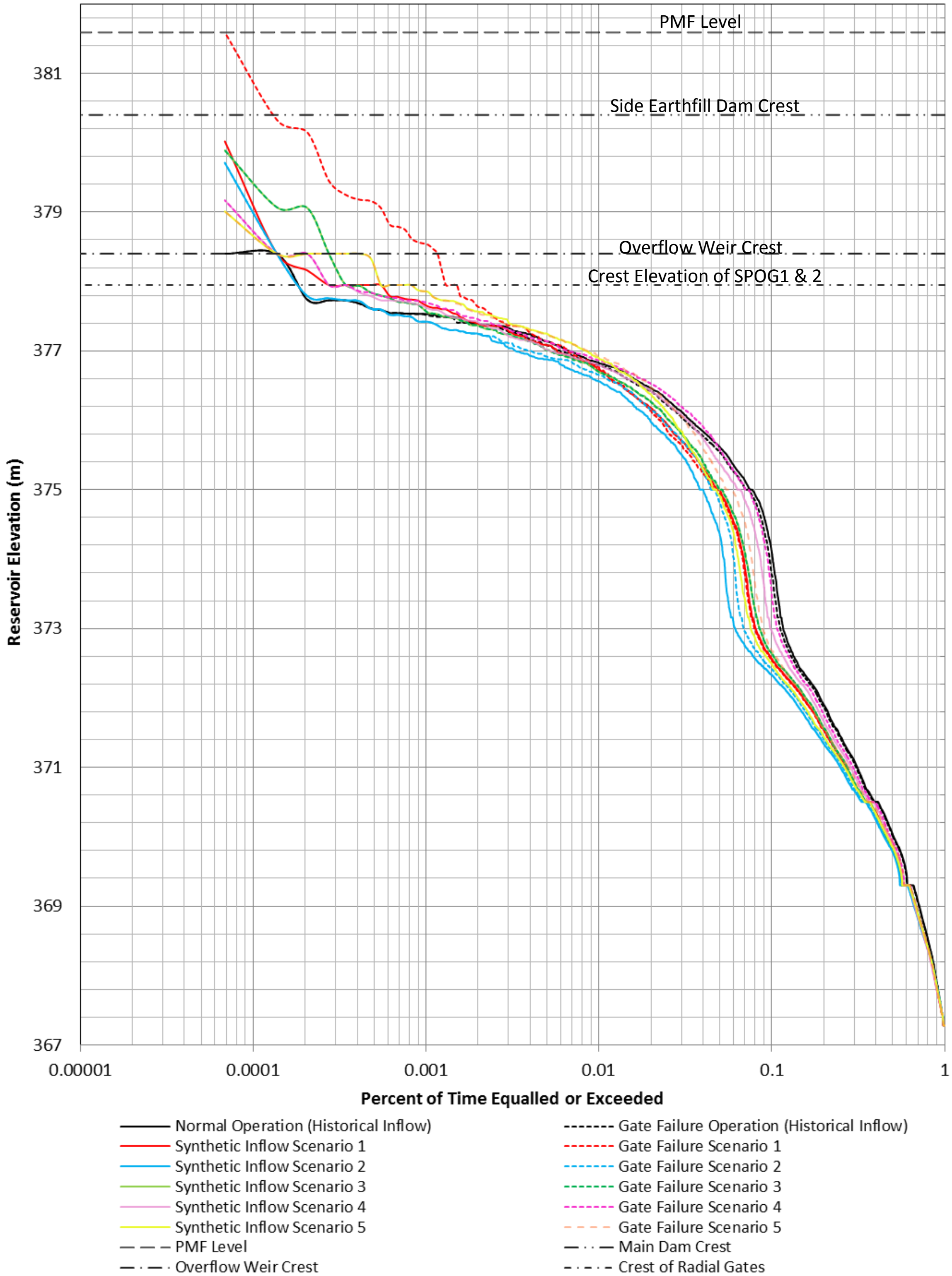

Figure 3.14 Reservoir Elevation Exceedance Curves for Normal and Reliability-Based Operations Using Historical and Synthetically Generated Inflow Scenarios With and Without Radial Gate Failure Simulations

The results of this case study show that spillway gate outages that coincide with peak inflow events can cause reservoir elevations to peak up to the PMF storage level even at considerably lower peak flows than the PMF level. Furthermore, a reliability-based operation analysis can demonstrate that dam overtopping is more likely to be caused by a simultaneous occurrence of high inflow events and spillway gate failures than by just an analysis that only considers extreme inflow events. It can be therefore concluded that reservoir operations planning should not only consider hydrologic risk but also incorporate uncertainties of other variables such as the reliability of water release facilities. Comparison of reservoir elevation exceedance curves of the operating scenarios analyzed in this study shows that high reservoir levels are more likely to occur when the failure time and duration of the radial gates outages are modeled and this highlights the need to consider the uncertainty surrounding gate failure in the analysis of reservoir operations under uncertainty.

Although a single study may not cover the extreme diversity of reservoir operation problems, the focus in this study is to illustrate, in some detail, how reservoir operations and variables such as reservoir elevation and spillway release are affected by unexpected spillway gate failures. The hope is that the case study can provide helpful information to improve reservoir operations planning by integration of a reliability-based operations analysis into daily reservoir operations. Practical and useful studies can be done to prevent dam overtopping incidents from happening, such as adapting new operating rules considering the reliability of gates, increasing discharge capacity for some facilities, or enhancing and optimizing periodic inspections for these facilities.

3.4 Conclusion

Current practice of deterministic reservoir operation modeling has the limitation to understand and evaluate uncertainty which exists in water release facilities. The reliability-based operation modeling framework presented in this paper seeks to improve hydro reservoir operations by incorporating a reliability analysis process for water release facilities.

The reliability analysis process consists of statistical reliability assessment and failure simulation and it can be extended to assess the availability of spillway facilities (See Appendix B). The statistical reliability assessment we have adopted in this research uses the nonparametric product-limit estimation method which is applicable for the current condition given that only limited failure data is available in the utility industry regarding non-power water release facilities. Adequate probability distributions are fitted to estimate the reliability of these facilities and are validated using confidence interval analysis. The failure and repair process of water release facilities is simulated using Monte Carlo simulation for many 40-year inflow sequences.

A multiobjective operations planning model has been developed and used to run various reservoir operating scenarios. A specific hydro reservoir system in British Columbia is selected and modeling results of both the normal operation and reliability-based operation are illustrated. The reservoir operation scenarios presented in the case study attempt to reevaluate the existing operating plans for reservoir elevations and related water release policies. This research demonstrates the importance of collecting water release facility failure information to assess the reliability of these facilities for operations planning and for dam safety assessments.

Chapter 4: Conclusions

The investigation and development of the reliability-based hydro reservoir operations planning model achieved all the research goals listed in Chapter 1. The modeling framework developed and presented in this thesis enhances current practice in reservoir operation modeling by accounting for uncertainty on the reliability performance of water release facilities and hydrological risks.

4.1 Summary and Conclusion

The ability to evaluate the reliability of a water release facility is important for understanding its expected performance over time and can support operation planning engineers to quantitatively assess uncertainty and risks in reservoir operation. A number of reliability methods with respect to hydropower facilities were investigated and used to develop a reliability-based modeling framework that can be used in reservoir operations studies. Reliability block diagrams were prepared and system reliability models were used to analyze the reliability of individual mechanical and electrical components as well as the overall system reliability. A more comprehensive reliability analysis process was developed in Chapter 3 based on censored failure data. The product-limit estimation method was applied to study the time-dependent reliability of different types of spillway gates and hydropower turbines, and the results were validated by confidence interval analysis. Parametric model fitting techniques were subsequently used to fit probability distribution functions such as the Weibull distribution and polynomial hazard functions. Failure and repair times of water release facilities were simulated using Monte Carlo simulation, which provided random variables to capture the uncertainty of availability for hydro reservoir systems facilities.

The OPT simulation-optimization model was enhanced to assist planning hydro operations and to evaluate reservoir elevations and water releases under various operating scenarios. To accommodate for the conflicting goals in operation, a multi-objective optimization problem was formulated and solved using mixed integer linear programming techniques, where variables such as reservoir storages, turbine discharges and spillway releases are subject to various physical and operational constraints.

The application of reliability analysis for water release facilities was successfully integrated into the OPT to create a modeling framework that treats risk and uncertainty quantitatively. The Cheakamus hydro system was selected to illustrate application of the reliability-based model which incorporates reliability assessment and failure simulations of radial and sluice spillway gates. The planning horizon was set to a 5-day rolling horizon interval to simulate actual system operation with no perfect foresight. The model simulated random gate failure and repair events, and produced results for numerous operating scenarios using historical and synthetically generated inflows. Model result analysis focused on reservoir elevation to assess the risk of dam overtopping during high inflow events. Reservoir elevation exceedance probability under different operating scenarios was analyzed to measure the potential risk that could be encountered in reservoir operations. It was demonstrated that dam overtopping is more likely to occur due to a simultaneous occurrence of high inflow events and spillway gate failures than being caused by an extreme inflow event such as the PMF. It can be concluded that reservoir operations planning should not only consider hydrologic risk but also incorporate other uncertain variables such as the availability of water release facilities. The study highlights the need for the use of reliability analysis approaches described in this thesis.

4.2 Future Work

4.2.1 Reliability Data Collection

The biggest challenge in this study was the lack of sufficiently large amount of failure data of hydropower facilities, particularly for critical facilities such as spillway gates. Currently, few hydropower dam owners and utility companies keep adequate and sufficient records on failures of water release facilities. This deficiency limits the development of quantitative reliability studies as they depend on the amount of available data to perform valid analyses (O'Connor and Kleyner 2012, Kalantarnia, Chouinard and Foltz 2014). In this research we adopted the product-limit estimation method to alleviate such limitation, but it should be recognized that in the long run it will be beneficial for the operations and maintenance personnel to systematically collect and document such failures. Ansell and Phillips (1994) suggested constructing a reliability database that removes ambiguity, clarifying objectives and that contains full and sufficient information on such components and systems. The reliability analysis process we have developed can be updated to attain higher levels of accuracy as more failure data is progressively recorded.

4.2.2 Operations Planning Model Enhancement

Further development of the OPT model can be investigated to enhance the reliability-based operations modeling framework, as listed below:

- Extreme flood simulation studies are needed to evaluate dam safety issues in reservoir operation for situations where the reservoir inflow peak is greater than the maximum spillway gate capacity. In the modeling studies we carried out, synthetic inflow data was generated to create a variety of hydrologic scenarios using stochastic simulations of hydrologic time series. The main philosophy behind synthetic data generation is that the generated inflow samples preserve statistical properties of historical inflows (Salas, et al. 1980). As a result, each generated inflow series is likely to occur following historical inflow patterns which extends historically available sequences. But the statistical techniques may not be accurate anymore since the "stationarity" assumption that reservoir systems fluctuate with an unchanged variability is no longer valid due to climate change (Milly, et al. 2008). Other methods to simulate extreme floods should be investigated, such as using rainfall-runoff models with synthetically generated rainfall sequences. The U.S. Bureau of Reclamation (2003) outlined methods to develop probabilistic extreme flood hydrographs, one of which used the rainfall-runoff model with an estimate of extreme precipitation and calibrated the model to a peak discharge frequency curve with hydrologic data.

- The Daisy Lake reservoir operation in the case study was generally modeled in daily time steps. Future reliability-based operations planning studies can use coarse granularity such as weekly or monthly time steps to simulate reservoir operations under normal hydrologic conditions, and can switch to finer granularity such as hourly or even smaller time steps for critical periods during peak inflow periods or during the outage period of water release facilities.
- Penalty functions can quantify user-defined preferences for different reservoir elevation and flow release ranges, but defining penalty values is a difficult task which requires simulations of numerous operating scenarios, particularly during high inflow events. Alternative methods to replace the use of penalty functions can be investigated in the future.

- The reliability-based operation model can be further applied to multi-reservoir systems to measure the operational risk and uncertainties of hydro facilities in cascaded systems.

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Appendices

Appendix A

This appendix presents the failure records of spillway gates for the product-limit estimate in the reliability analysis process described in Chapter 3. According to the BC Hydro CM database, recording and electronic archiving of gate failures started at on February 1, 2003. The data on failure and repair events was collected until November 18, 2014. The tabular data in this appendix includes the failure start time and end time, and the failure causes for the sluice and radial gates in 9 hydropower reservoir systems in Lower Mainland and in Vancouver Island.

Table A.1 Spillway Sluice Gate Failure Records (2003-2014)

Project	Facility	Failure Start Time	Failure End Time	Failure Causes or Reasons
CMC	SPOG1	23:53, 23 Jan 2008	13:22, 30 Jan 2008	Failed to operate via SCADA
CMC	SPOG1	10:48, 09 Nov 2008	16:53, 28 Nov 2008	Gate unable to lower
CMC	SPOG2	06:15, 14 Apr 2007	11:08, 17 Apr 2007	Failed to operate via SCADA
CMC	SPOG2	01:42, 27 Feb 2010	09:30, 01 Mar 2010	Defective equipment
CMC	SPOG2	01:05, 23 Mar 2010	10:39, 23 Mar 2010	Unknown cause
CMC	SPOG2	23:30, 29 Mar 2010	13:48, 09 Apr 2010	Gate pulsed several times and stopped moving
CMC	SPOG2	15:15, 02 May 2010	16:09, 03 May 2010	Blown fuses
CMC	SPOG2	23:28, 01 Jun 2010	16:00, 02 Jun 2010	No respond to remote controls
CMC	SPOG2	22:20, 15 Jun 2010	14:17, 16 Jun 2010	Blown fuses
CMC	SPOG2	06:00, 07 Jul 2010	08:15, 07 Jul 2010	Blown fuses
CMS	LLOG1	16:00, 17 Aug 2012	18:26, 04 Nov 2013	Defective equipment
ELK	LLOG1	17:05, 02 Oct 2005	09:45, 03 Oct 2005	Faulty A/D converter
ELK	LLOG1	08:14, 26 Dec 2010	12:51, 27 Dec 2010	Snow and freezing rain, blown motor overload fuses
ELK	LLOG1	00:00, 24 Jul 2011	16:41, 12 Oct 2011	Control and telemetry Invalid
ELK	LLOG1	00:30, 03 Mar 2014	13:43, 04 Mar 2014	Equipment damaged by ice
JHT	SPOG1	04:30, 12 Nov 2004	12:27, 12 Nov 2004	Unknown cause
JHT	SPOG2	04:30, 12 Nov 2004	12:27, 12 Nov 2004	Unknown cause
JHT	SPOG2	20:00, 14 Dec 2005	11:55, 17 Feb 2006	Blown tranformer in the control circuit
JHT	SPOG3	04:30, 12 Nov 2004	12:27, 12 Nov 2004	Unknown cause
JHT	SPOG3	14:49, 03 May 2010	03:53, 07 Sep 2010	No oil in gearbox
SEV	SPOG1	20:45, 30 May 2005	22:00, 30 May 2005	Slack cable
SEV	SPOG2	15:10, 02 Dec 2009	13:44, 09 Dec 2009	Defective equipment
SEV	SPOG3	11:44, 16 May 2007	16:00, 20 Jul 2007	Defective equipment
SEV	SPOG3	07:11, 25 Jul 2012	08:36, 25 Jul 2012	Unknown cause
SEV	SPOG4	02:13, 10 Jun 2010	14:13, 10 Jun 2010	Telemtered value jumping
BRR	SPOG2	13:54, 07 Dec 2006	16:49, 11 Dec 2006	Electrical control problem

Table A.2 Spillway Radial Gate Failure Records (2003-2014)

Project	Facility	Failure Start Time	Failure End Time	Failure Cause or Reasons
CMS	SPOG1	11:10, 31 Dec 2006	14:46, 16 Jan 2007	Oil heater failed
CMS	SPOG1	14:11, 30 Jun 2008	00:00, 15 Jul 2008	Gate mis-alignment
CMS	SPOG1	00:05, 20 Oct 2010	07:26, 30 Oct 2010	Operation isolation
CMS	SPOG1	09:51, 25 Feb 2011	13:54, 26 Feb 2011	Oil heater failed
CMS	SPOG1	20:24, 13 Apr 2011	20:55, 14 Apr 2011	Remote control problem
CMS	SPOG1	15:35, 21 Jun 2011	15:42, 03 Jul 2011	Defective Equipment
CMS	SPOG1	04:00, 16 May 2012	12:00, 18 May 2012	Station service generator outage
CMS	SPOG1	13:29, 27 Feb 2014	14:57, 12 Mar 2014	Main motor out of service
CMS	SPOG2	17:27, 23 Feb 2005	13:51, 03 May 2005	Defective transducer
CMS	SPOG2	23:34, 18 Sep 2006	11:13, 20 Sep 2006	Defective control equipment
CMS	SPOG2	9:53, 15 Jan 2007	11:58, 15 Jan 2007	Contorls locked out
CMS	SPOG2	12:25, 17 Nov 2009	14:40, 18 Nov 2009	Unknown cause
CMS	SPOG2	15:35, 21 Jun 2011	15:42, 03 Jul 2011	Defective equipment
CMS	SPOG2	04:00, 16 May 2012	12:00, 18 May 2012	Station service generator outage
ELK	SPOG1	17:05, 02 Oct 2005	09:45, 03 Oct 2005	Faulty A/D Converter
ELK	SPOG1	17:39, 10 Dec 2010	15:36, 11 Apr 2011	Broken hoist cable
ELK	SPOG2	17:05, 02 Oct 2005	09:45, 03 Oct 2005	Faulty A/D Converter
ELK	SPOG2	17:39, 10 Dec 2010	14:39, 31 Mar 2011	Broken hoist cable
COM	SPOG1	22:24, 10 Jun 2011	15:23, 16 Jun 2011	False Alarm
COM	SPOG1	21:00, 27 Jun 2013	08:13, 28 Jun 2013	Sticky Relay
COM	SPOG2	22:24, 10 Jun 2011	15:23, 16 Jun 2011	False Alarm
COM	SPOG2	21:00, 27 Jun 2013	08:13, 28 Jun 2013	Sticky Relay
RUS	SPOG1	10:05, 28 May 2009	16:18, 29 May 2009	Ongoing replacement
RUS	SPOG1	14:05, 31 Jan 2012	17:39, 31 Jan 2012	Affected by construction crew drilling
RUS	SPOG2	10:05, 28 May 2009	16:18, 29 May 2009	Ongoing replacement
RUS	SPOG3	10:05, 28 May 2009	16:18, 29 May 2009	Ongoing replacement
RUS	SPOG3	13:00, 08 Dec 2011	11:49, 20 Dec 2011	A large boulder impeded the gate
RUS	SPOG4	10:05, 28 May 2009	16:18, 29 May 2009	Ongoing replacement
RUS	SPOG4	11:37, 08 Apr 2011	14:00, 13 May 2011	Defective Equipment
RUS	SPOG5	10:05, 28 May 2009	16:18, 29 May 2009	Ongoing replacement
RUS	SPOG6	10:05, 28 May 2009	16:18, 29 May 2009	Ongoing replacement
RUS	SPOG7	10:05, 28 May 2009	16:18, 29 May 2009	Ongoing replacement
SFL	SPOG2	13:05, 12 Aug 2013	14:28, 20 Aug 2013	User interface not working

Appendix B

Availability is another key measure for the performance of the reservoir water release facilities. It is defined as the probability of finding the component in the operating state at some time t (Billinton and Allan 1992), which means that either the component has not failed till time t or it has already been repaired after failure so that it is fully operational again at time t. Availability considers both the reliability and maintainability properties of a repairable release facility. For example, the high reliability of a sluice gate does not simply imply the high availability. If the repair time is prolonged, the availability of the gate will reduce. In other words, the availability indicates the likelihood of being able to repair or maintain a facility.

Figure B.1 illustrates the comparison of the instantaneous availability between repairable and irreparable facilities. When no repairs are being carried out, the instantaneous availability reduces to the reliability function. For repairable facilities, the instantaneous availability incorporates the maintainability information, and it can be formulated using the renewal theory (Elsayed 2012). The operative state of a facility at time t is assured, either because it has not failed till time t with the reliability $R(t)$, or because it has been functioning properly since the last repair which occurred at time $(0 < u < t)$. Hence, the instantaneous availability is expressed as:

$$A(t) = R(t) + \int_0^t R(t-u)f(u)du \qquad \text{(B-1)}$$

where u is the time when the last repair occurred and the facility has continued to function since that time, and $f(u)$ is the probability density function of repair time.

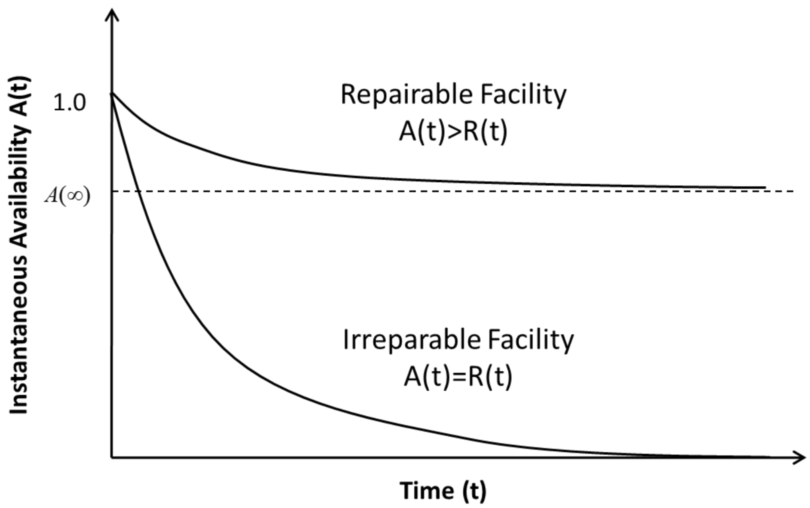

Figure B.1 Availability of Repairable and Irreparable Facilities

Since the instantaneous availability is not easy to evaluate, the steady state availability is more commonly used (Gámiz, et al. 2011). The steady state availability gives the long-term operational performance of a repairable system and is mathematically defined as the limit of the instantaneous availability function as time approaches infinity. It can be estimated as

$$\lim_{t \to \infty} A(t) = \frac{\sum_{i=1}^{N} TTF_i}{\sum_{i=1}^{N} (TTF_i + TTR_i)} \qquad \text{(B-2)}$$

where (TTF_i, TTR_i) are the alternating sequences of time to failure and time to repair being simulated, and N is the number of samples. The availability of spillway radial gates converges to 0.979 as the sampling number N approaches 10^6. It can be thought that after a reasonable long period of time spillway gate availability is almost invariant with time. The estimated steady state availability can be used to calculate forced outage rate of spillway gates and can provide a guide for the operation engineer to tackle other relevant problems (Billinton and Allan 1992). In practical cases, the useful life of a water release facility is much shorter than the time when availability reaches a steady value. Figure B. illustrates the availability which resulted from the simulation of sequences of operating-repair cycles for spillway radial gates. It can be seen that in the early phase of simulation there is considerable difference between simulated values. The amplitude of oscillations becomes smaller as simulation time increases, and after 60 years the availability of radial gates reaches close to the steady state value.

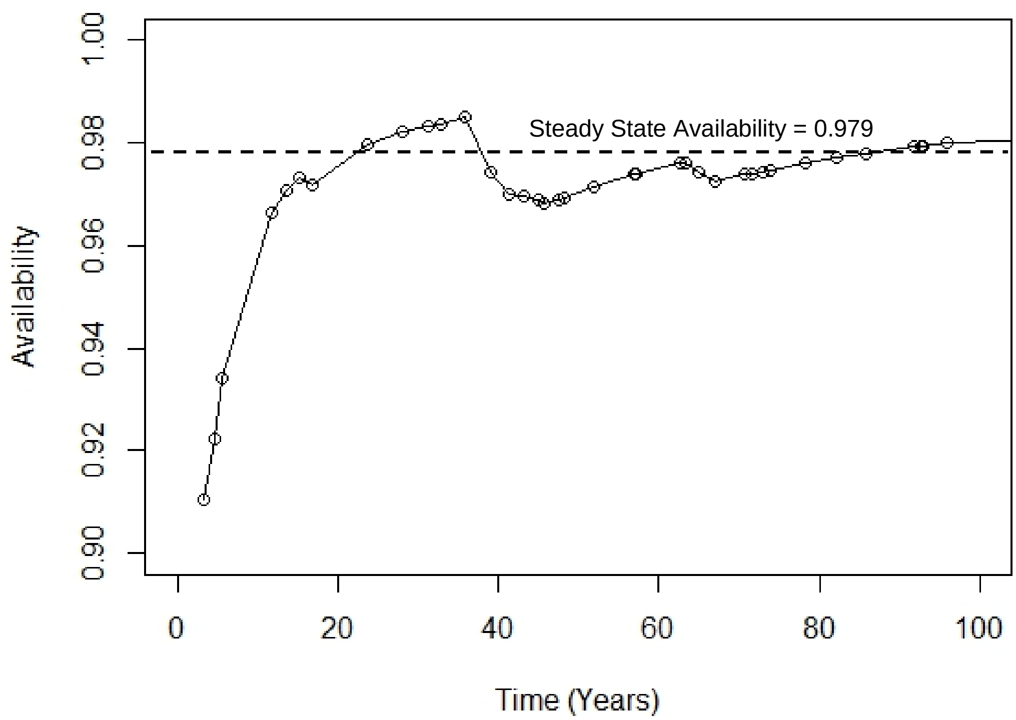

Figure B.2 Availability Simulation of A Spillway Radial Gate

Appendix C

This appendix highlights some of the elements and features of the BC Hydro OPT optimization model developed for hydropower reservoir operations. Generally, an optimization problem can be formulated as an objective function subject to a number of constraints. The objective function and constraints are represented by mathematical expressions as functions of the decision variables. The solution to an optimization problem is to find the global optimum of the objective function in a given domain, by varying the values of the corresponding decision variables. The reservoir operations planning model incorporate a variety of decision variables, which mainly include storage volumes, water releases through spillway gates and generating turbines, and power generations. Section C.1 presents the formulation of the objective function and Section C.2 outlines the model constraints consisting of the mass balances, storage and discharge capacities, and equations to model other aspects of hydropower reservoir systems operations.

Hydropower reservoir operation is typically a large-scale, nonlinear and nonconvex problem. The nonlinearity is due to the intrinsic nature of the generating units whose power generation is a nonlinear function of discharge rate and head (Chang, et al. 2001). The non-convexity is often caused by the physical characteristics of non-power water release facilities. For example, the rating curves representing the relationship between reservoir storages and spillway releases for most reservoirs are typically not convex (BC Hydro 2005).

Among many optimization techniques, the linear programming (LP) method is the simplest and most widely used to solve the complex problem of reservoir operations. The nonlinearities of the problem can be accurately incorporated by using piecewise linear approximation (Shawwash, Siu and Russel 2000). The LP method has been applied to model the operations of multi-purpose reservoirs involving conflicting criteria such as flood control, recreation, and preservation of fish habitat (Labadie 2004). The weighting method is used in LP to explicitly capture the tradeoffs between conflicting and non-commensurate objectives, by assigning weights to objectives based on their relative priorities.

Sometimes the reservoir operation problem requires some of the decision variables to be integer values. Typically, the integer variables are either one or zero to model the "on" and "off" status of generating turbine units and failures of water release facilities. When the objective function and constraints are linearly formulated with integer and non-integer decision variables, the optimization technique is called mixed integer linear programming (MILP). The MILP technique extends the capability of LP, representing the nonlinear and discrete nature of reservoir operations planning. It is usually solved using the branch and bound algorithm. One advantage of this algorithm is that it can be terminated early to save computational time, as long as a feasible solution is found and when the solution is approaching the optimum. The MILP technique can be applied to model the maintenance and outage scheduling of generating turbine units (Archila 2015).

The operations planning model is formulated using AMPL (Fourer, Gay and Kernighan 2002) and the CPLEX solver is used to solve for the decision variables to maximize the objective function. CPLEX has many directives and parameters that allow users to customize the way the branch and bound algorithm and linear programming algorithms are used to solve the problem.

C.1 Objective Function

The optimization model needs to identify multiple objectives such as to maximize the value of the hydropower electricity production and to minimize the adverse environmental impacts. To accommodate these objectives, a grand additive objective function is formulated by multiplying each objective function term by a weighting factor. The objective function is formulated to maximize the returns from energy productions and to minimize the deviations from the operational constraints. Deviations outside of the preferred operating ranges are not desirable and are penalized using a number of penalty functions. The mathematical formulation of the objective function is presented as:

$$\min \ \{w_1 \sum_{j}^{J} \sum_{t}^{T} f_V(V_{j,t}) + w_2 \sum_{j}^{J} \sum_{t}^{T} \sum_{n}^{N} f_R(R_{j,n,t}) - w_3 \sum_{j}^{J} \sum_{t}^{T} \sum_{z}^{t} G_{j,t,z} P_{t,z}\} \qquad \text{(C-1)}$$

where $V_{j,t}$ (reservoir storage) and $R_{j,n,t}$ (spillway release from facility n) are the decision variables in reservoir system j at time step t; $P_{t,z}$ is the electricity market price at time t that corresponds to sub-time steps z representing different price zones such as the peak hours called heavy load hours (HLH) and the off-peak hours called light load hours (LLH); $G_{j,t,z}$ is the hydropower generation production in hydropower reservoir system j in sub-time step z at time t; w_i is the weighting factor for each term of the objective function.

The first two terms in the objective function minimize the deviations of reservoir storages and spill releases from the preferred operational ranges, where $f_V(V_{j,t})$ represents the penalty function for the reservoir storage and $f_R(R_{j,n,t})$ stands for the penalty function for the spill releases. The penalty functions are used to prescribe desired operating ranges. Through the use of these penalty functions in the objective function, the model can derive water release regimes which minimize the net penalties of the reservoir system. Figure C.1 shows an example of a piecewise linear penalty function for the reservoir elevation in Daisy Lake Reservoir. The most preferred elevation range is between 367.45 m and 377.95 m with no penalty. The higher the penalty value is in a penalty zone, the less likely the model will decide to optimize the reservoir elevation in that zone. The penalty functions are date-dependent and can vary throughout the year.

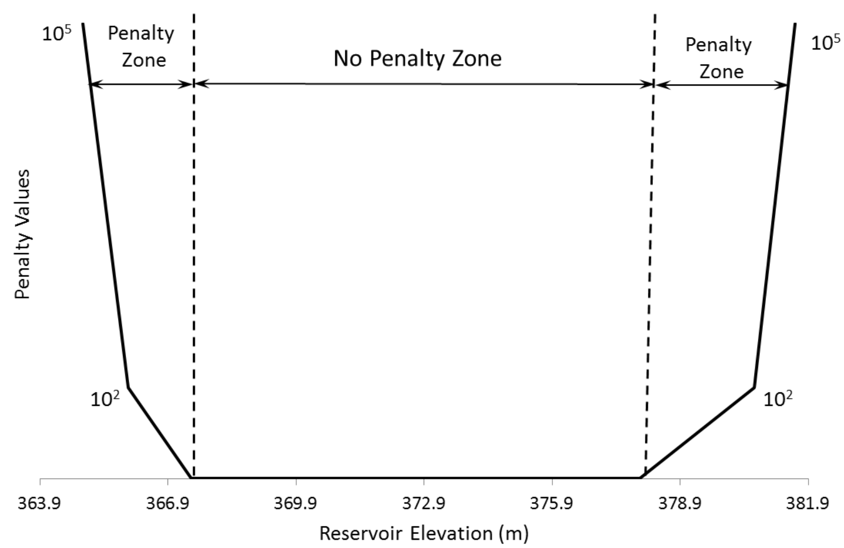

Figure C.1 Piecewise Linear Penalty Function for Daisy Lake Reservoir Elevation

The third term in the objective function aims to maximize the returns from the hydropower productions with optimal turbine discharge policies. The third term is formulated in the objective function by minimizing its negative value.

C.2 Model Constraints

The model constraints are divided into two groups: soft constraints and hard constraints. The constraints that represent desirable conditions and can be violated when necessary are defined as soft constraints. The penalty functions in the objective function are the soft constraints which prescribe preferred operating ranges and can be violated at the cost of penalties. The penalty functions were developed by the Water Use Plan consultative committees through simulations of many operation alternatives and water management scenarios (Vassilev, Sreckovic and Groves 2008). The other type of constraints is the hard constraints which cannot be violated, including physical constraints such as reservoir volumes and the reservoir storage continuity equation as well as operational constraints such as water license limits and dam safety limits. Table C.1 presents the major constraints developed in the optimization model. The remaining part of this section provides a few examples of model constraints: the non-power release constraints, continuity equation and hydropower generation limits.

Table C.1 Major Constraints in the Optimization Model

Hard Constraints	Soft Constraints	Additional Constraints
• Continuity Equation • Non-power Release Constraint • Upper/Lower Bounds for Generation and Turbine Flows • Minimum/Maximum Storage • Minimum/Maximum Spill • Water License	• Penalties for Deviating the Normal Operation Elevations • Penalties for Undesirable Spillway Releases	• Spillway Gate Failure Prediction • Generating Turbine Unit Maintenance and Outage Scheduling • Zero Turbine Efficiencies

Non-power Release Constraints

Non-power water release facilities in dams can be classified by the type of hydraulic control. The two types are the uncontrolled or free-flow spillways, and the controlled or gated spillways. The constraint of an uncontrolled spillway is expressed in the model as:

$$R_{j,n,t} = C_{j,n}[E_j(V_{j,t})] \tag{C-2}$$

where $R_{j,n,t}$ denotes the uncontrolled release through outflow work n in reservoir j at time step t, and $E_j(V_{j,t})$ stands for the reservoir elevation as a function of the storage volume, and $C_{j,n}[E_j(V_{j,t})]$ is the rating curve function of the release facility. Rating curves are used to compute the outflows of a water release facility, which present the relationship between water releases, gate opening positions if applicable, and reservoir elevations. Figure C.2 shows the discharge capacity rating curve of an uncontrolled spillway. The strategy for modeling the uncontrolled spillway releases is typically determined using the values on the rating curve function as a function of reservoir water levels.

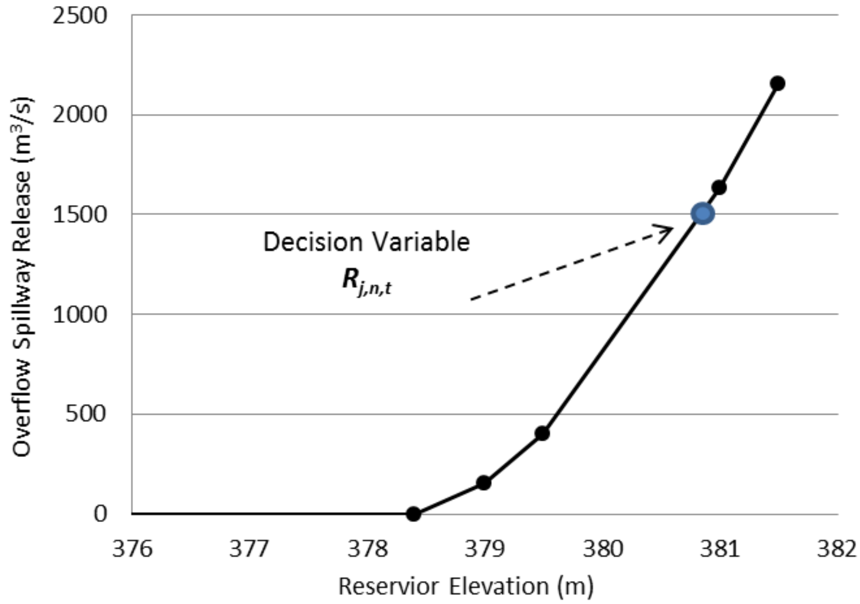

Figure C.2 Rating Curve for Free Crest Weirs on Cheakamus Dam

The discharge rating curves for the controlled or gated spillway are usually a group of curves based on different gate opening positions. Figure C.3 illustrates the rating curves for different opening locations of a spillway gate. The controlled spillway release constraint is formulated using the rating curve which has the largest discharge capacity at the fully open position, as below:

$$R_{j,n,t} \leq C_{j,n}[E_j(V_{j,t})] \tag{C-3}$$

where $R_{j,n,t}$ denotes the controlled spillway release from facility n in reservoir j at time step t, and $E_j(V_{j,t})$ stands for the reservoir elevation as a function of the storage volume, and

$C_{j,n}[E_j(V_{j,t})]$ is the rating curve function in the group which has the maximum water release capacity.

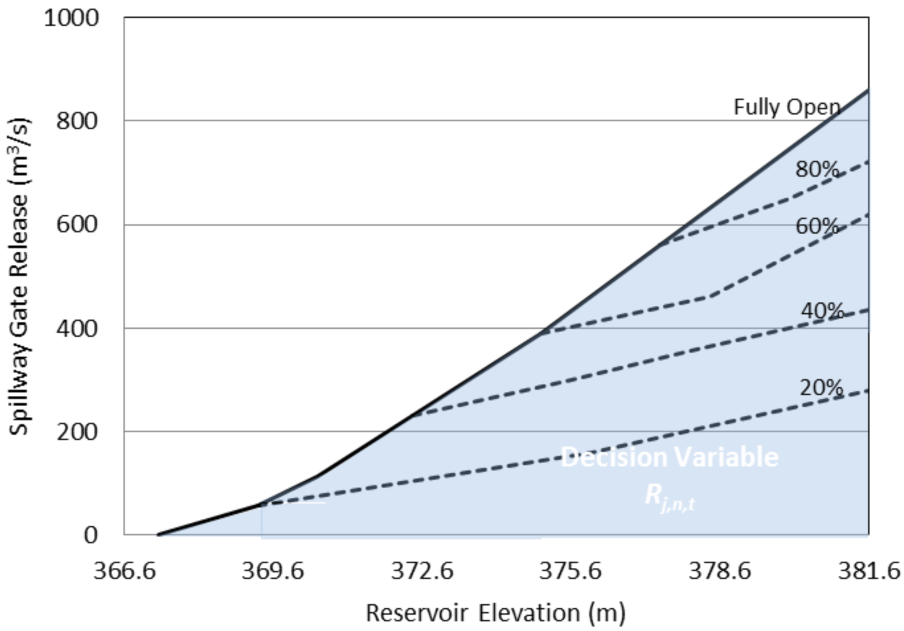

Figure C.3 Rating Curve for the Spillway Radial Gate in Cheakamus Dam

Continuity Equation

The continuity or conservation of volume equation for a reservoir system is mathematically expressed as:

$$V_{j,t} = V_{j,t-1} + I_{j,t} - Q_{j,t} - \sum_{n}^{N} R_{j,n,t} + \sum_{k}^{K} L_{kj}^{Q} Q_{k,t} + \sum_{k}^{K} \sum_{n}^{N_k} L_{kj}^{R} R_{k,n,t} \tag{C-4}$$

where $V_{j,t}$ and $V_{j,t-1}$ denote the storage volume in reservoir j at time step t and the previous time step $t-1$, respectively; $I_{j,t}$ denotes the natural inflow at time t including streams flowing into reservoir j and precipitation falling on the reservoir surface; $Q_{j,t}$ denotes the total turbine releases in the reservoir system j at time t; $R_{j,n,t}$ denotes the spillway release from the *n*-th non-power release facility in reservoir j at time step t and N represents the total number of the facilities. L_{kj}^{Q} and L_{kj}^{R} are binary parameters that represent the hydraulic connections between reservoir j and any upstream reservoir k. If $L_{kj}^{Q} = 1$, reservoir j will receive turbine releases from reservoir k; if $L_{kj}^{R} = 1$, reservoir j will receive spillway releases from N_k non-power release facilities in reservoir k. If the binary parameter is zero, there is no physical connection between the hydraulic facilities. It is assumed that evaporation and other losses from the reservoir are negligible from the perspective of operation modeling.

Hydropower Generation Constraint

Hydropower Generation from hydro reservoir j at time t is constrained by the minimum and maximum physical and operational limits, $G_{j,t}^{Min}$ and $G_{j,t}^{Max}$, formulated as:

$$G_{j,t}^{Min} \leq G_{j,t} \leq G_{j,t}^{Max} \tag{C-5}$$

Two alternative approaches are used to calculate the maximum rate at which the powerhouse can produce electricity, which are the installed capacity estimation (Loucks, et al. 2005, Chin 2006) and Generation Production Functions (Shawwash, Siu and Russel 2000). Power generation can be calculated using the traditional installed capacity estimation method:

$$G_{j,t} = \gamma Q_{j,t} \eta (E_{j,t} - E_0) \tag{C-6}$$

where γ is the specific weight of water (9.79 kN/m^3), $Q_{j,t}$ is the turbine release at time step t, η is the turbine efficiency which is usually in the range of 0.80 to 0.90, $E_{j,t}$ is the reservoir elevation at time step t and E_0 is the tailwater elevation. The Generation Production Functions (GPF) are a family of piecewise linear curves that accurately describe the maximum hydropower generation for a given set of reservoir elevation, turbine release and unit availability. The GPFs are generated based on the assumption of optimal unit commitment using the Static Plant Unit Commitment (SPUC) database (Shawwash, Siu and Russel 2000). The hydropower generation constraint can be expressed in terms of the GPF:

$$G_{j,t} \leq f_{GP}(Q_{j,t}, E_{j,t}, U_{j,t}) \tag{C-7}$$

where f_{GP} denotes the generation production function, $Q_{j,t}$ and $E_{j,t}$ are decision variables which represent the turbine release and reservoir elevation respectively, and $U_{j,t}$ denotes the unit availability in plant *j* at time *t*. In maintenance scheduling problems, the combination of available generating units can be formulated using of a set of binary variables which can restrict the selection of the GPF subject to certain unit combinations (Archila 2015).