Applying the Virtual Structure of a Risk-Informed Decision Making Framework for Operating Small Hydropower Reservoirs during High Inflow Events, Case Study: Cheakamus River System

by

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Abstract

Operating hydropower reservoirs with small storage capacity is a challenging task due to the fact that in a watershed system there usually exist multiple stakeholders with different and conflicting preferences and values. Consequently the process of planning for reservoir operation must be carried out with consideration of several, usually competing, objectives. This process becomes even more challenging during a high inflow or flooding event for three main reasons. First, the objective of minimizing adverse consequences of such an event is added to the set of objectives that the operator must deal with. Second, inflow forecast uncertainty-driven risks are highly intensified due to the high sensitivity of the outcomes to inflow forecasts. And third, the available time for making a decision is very short while comprehensive analysis is a necessity in order to make an informed decision regarding the best operational alternative. Under these circumstances, the best approach to confront this challenge could be developing a Risk-Informed Decision Making (RIDM) framework that provides operation planning engineers with a solid and pre-designed guideline to deal with the task of identifying the best operational alternative in an efficient and timely manner.

The current study is an attempt to apply the virtual structure of a RIDM framework for the Cheakamus River system in British Columbia. The framework is a coherent assembly of a number of methods and tools we have either developed or utilized from the existing widely used methods and techniques in practice. The product of our work is an example of the necessary tools that need to be used to develop recommendations for operating Daisy Lake reservoir during a high inflow event in a manner that all the operational objectives are served in the best possible way. This is done while taking into account making trade-offs among competing objectives. We illustrate the practical applicability and merits of the framework through applying it to a historical high inflow period in October 2003. The outcome is near real-time decisions with less dependency on only planners' judgement and more dependency on thorough and systematic analysis with consideration of human judgement and possible risk tolerances.

Table of Contents

List of Tables

List of Figures

Acknowledgements

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Chapter 1: Introduction

1.1 Background

BC Hydro and Power Authority is Canada's third largest electric utility with serving about 1.8 million residential customers by providing 95 percent of the population with their electricity demand in the province of British Columbia (BC). BC Hydro is mandated to provide reliable power, at low cost, for generations; and its mission is set to provide integrated energy solutions to customers in an environmentally and socially responsible manner. Each year BC Hydro generates over 43,000 gigawatt hours of electricity (BC Hydro website, 2012). An interconnected system of over 73,000 kilometres of transmission and distribution lines is used to deliver this power. Besides hydroelectric power plants, BC Hydro operates the 950 MW Burrard Generation Station near Vancouver (BC Hydro website, 2012; BC Hydro Annual Report, 2011). Burrard is a conventional thermal plant fuelled by natural gas and has a capability of 7,050 gigawatt hours per year. BC Hydro also operates two combustion turbine generation stations. The primary purpose of Fort Nelson and Prince Rupert generating stations is to provide reserve capacity and short-term energy during transmission interruptions (see Review of BC Hydro, 2011; BC Hydro Annual Report, 2005; The Journey to Sustainability: Triple Bottom Line Report, 2001; BC Hydro Annual Report, 2011, and BC Hydro website, 2012).

Just like many other regions of the world, climate change is a challenging issue for British Columbia. In a few decades, BC might be exposed to the risk of catastrophic floods and droughts. There are cases where above normal snow packs in many areas of BC can cause floods. Furthermore, the spring freshet from melting snow packs are probable to result in floods in low lying areas. In river basins with more or less regulated flows, in some years, above average snow pack levels, early spring warm temperatures, and heavy rains may cause more widespread flooding (Zaman et al., 2010).

At the risk of flooding and high inflow events in BC, this study is an attempt to use the virtual structure of a Risk-Informed Decision Making (RIDM) framework and applying it to the Cheakamus River for Operation Planning Engineers (OPEs) to assist them with the challenging task of reservoir operation during such events.

1.2 Problem Description

Maximizing clean energy production with the use of a hydropower reservoir benefits everybody but in any watershed system, there are multiple stakeholders that clean energy might not necessarily be their main concern. Therefore, in order to reach consensus, multiple objectives must be taken into account; and this makes the task of planning for reservoir operation a complex and crucial task. If the reservoir is also being used for flood control, this task becomes even much more challenging due to the fact that the objective of minimizing flood damages is added to the set of objectives. This exponentially increases the risks involved in the decision making process while the available time for making a decision is very short during flooding or high inflow events. Normally, several operational alternatives exist that each has its own advantages and disadvantages. Choosing one of these alternatives requires thorough consideration of all the potential risks, which stem from unavoidable uncertainties such as inflow forecast uncertainties.

Under these circumstances and difficulties (complexity of the problem, the need for a thorough analysis of the risks and alternatives, and time shortage), the best and maybe the only acceptable solution would be pre-developing an all-inclusive Risk Informed Decision Making (RIDM) framework to help decision makers in the process of decision making in the face of a flooding or high inflow event.

1.3 Goal of This Research

The purpose of this study is use of the virtual structure of an existing RIDM framework that provides operation planning engineers with a solid and pre-designed guideline to deal with the task of identifying the best operational alternative during high inflow events in an efficient and timely manner. We illustrate the practical applicability of the framework with applying it to a river system that has suffered from major flooding events in the past: Cheakamus River system in British Columbia.

The Cheakamus basin is a major tributary of Squamish River. The Squamish River has experienced several major floods in the past century such as flooding events in 1921, 1940, 1955, 1968, 1975, 1980-1984, 1989-1991, and 2003. These floods have caused millions of dollars of damage and indirect loss (Journeay, 2005).

On the Cheakamus River, in the Sea to Sky Corridor of southwestern BC just south of Whistler and immediately north of Garibaldi, there is Daisy Lake reservoir. Due to the small size of Daisy Lake reservoir, in the event of a multiple day high inflow period similar to October 2003, the Operation Planning Engineers (OPEs) do not have so much control over the system. Consequently, it is vital that the OPEs have a pre-developed guideline to help them cope with such events. At BC Hydro, such guidelines have been developed for different river systems containing operational requirements at different times of the year. For Cheakamus River system, the related Generation Operating Order (BC Hydro, 2011) can be used to find the operational guidelines for operating Daisy Lake reservoir in October. In our study, we try to evaluate the quality of these recommendations. Moreover, we would like to highlight the fact that during high inflow events, due to the small size of Daisy Lake reservoir, the consequences of a high inflow event could be highly affected by the empty storage in the reservoir at the start of the high inflow event rather than by the operational policies during the high inflow period.

Accordingly, the focus of our research is on the available empty storage in the reservoir at the start of the high inflow period and the developed alternatives differ from each other with regard to this. However, we also pay attention to the operational policies for each alternative during the high inflow period. In the end, the overall goal of our research is applying the general structure for an RIDM framework during high inflow events to the case study of Cheakamus River system and developing some of the required components, and using the framework to evaluate the degree of wellness of the recommended target maximum level for the reservoir in October as outlined in Cheakamus Project Generation Operating Order or GOO (BC Hydro, 2011).

1.4 Organization of This Research

The study is classified into five chapters. The current chapter shortly describes the background of the problem, the motivation to conduct the research, and the objectives of the research. In the next chapter, the existing literature on the seven areas related to this research is reviewed. This includes flood management, RIDM frameworks, inflow forecast and scenario generation methods, optimization and simulation methods, streamflow impact curves, Multi-Criteria Decision Making (MCDM), and the application of MCDM in Water Resources Planning and Management (WRPM). In the third chapter, the methodology to implement the RIDM framework for reservoir operation during high inflow events is described. Chapter 4 is a presentation of the results of applying the framework to Cheakamus River system with a discussion of the results at the end of the chapter. A short summary and conclusions of the research are presented in chapter 5.

Chapter 2: Literature Review

The risk-informed decision making framework for reservoir operation during high inflow events used in this study consists of several components. Accordingly, the literature survey of the study includes multiple sections to cover a comprehensive review of the literature related to each of the components of the framework. First of all, flood management concept and literature is introduced. The second section of the literature review is an introduction to a number of RIDM frameworks developed by major organizations across the world, especially North America, for internal and/or external use. In the third section some inflow forecast and scenario generation methods are reviewed. Next section focuses on optimization and simulation methods for reservoir operation. Streamflow impact curves are the center of attention in the fifth section. Next, multi-criteria decision making methods are studied. Finally, the role and applications of MCDM in water resources planning and management brings an end to the literature review.

2.1 Flood Management

Flood management is a multi-faceted task in order to minimize the adverse consequences of floods. This usually is carried out with manipulating and making changes to a watershed system. While these changes may reduce the unfavorable impacts of a flood, they themselves might cause other long and/or short term problems for the system. This happens due to the fact that minimizing flood damages is only one of the multiple goals in a watershed system. Therefore, flood management must be an integrated process within the context of Integrated Water Resources Management (IWRM) in cooperation and coordination with all the other active planning and management segments in a watershed system. The Global Water Partnership (2000) defines IWRM as:

“a process which promotes the coordinated management and development of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.”

This recognizes that a single intervention affects the entire system. The concept of Integrated Flood Management (IFM) was introduced in the Integrated Flood Management Concept

Paper by World Meteorological Organization (2009) as the best approach to confront the challenge of floods and defined as:

“Integrated Flood Management is a process promoting an integrated – rather than fragmented – approach to flood management. It integrates land and water resources development in a river basin, within the context of IWRM, and aims at maximizing the net benefits from the use of floodplains and minimizing loss of life from flooding.”

A schematic presentation of an IFM model is shown in figure 1. In the paper it is explained that “It has to be recognized that the objective in IFM is not only to reduce the losses from floods but also to maximize the efficient use of flood plains with the awareness of flood risk – particularly where land resources are limited. In other words, while reducing loss of life should remain the top priority, the objective of flood loss reduction should be secondary to the overall goal of optimum use of flood plains. In turn, increases in flood losses can be consistent with an increase in the efficient use of flood plains in particular and the river basin in general” (World Meteorological Organization, 2009). As this implies, IFM is a multi-objective approach that has to be conducted with thorough consideration of all the existing objectives in a floodplain.

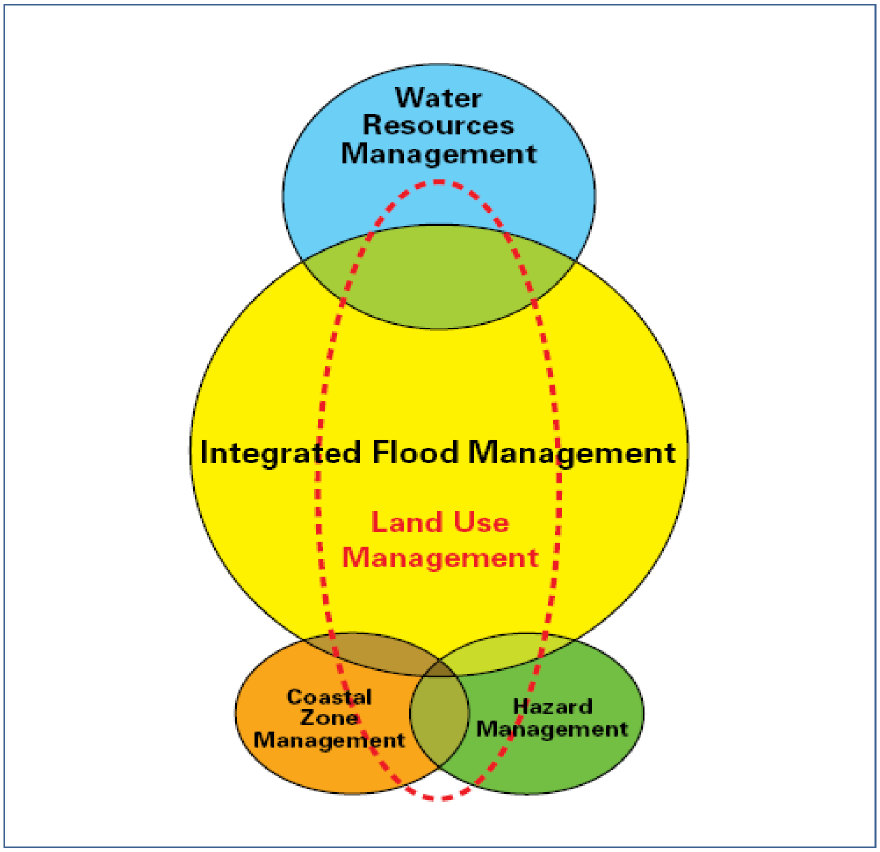


Figure 1: IFM model (World Meteorological Organization, 2009)

As a very good example of flood management in a country such as the Netherlands where two thirds of the country is exposed to the risk of flooding, a paper has been published on flood management options in the Netherlands by Silva et al. (2004). The paper is an effort to evaluate different flood management options in the Rhine River flood plain in the Netherlands to increase the flood protection level from protection against a 15000 cms flood to protection against a 16000 cms flood. The design flood along Rhine has a return period of 1250 years. As a result of two major floods in 1993 and 1995, the magnitude of the design flood has increased from 15000 cms to 16000 cms. This new level of protection has to be reached by 2015. The paper focuses on several options other than increasing the height of the dikes as many people in this crowded country already feel too boxed in and have made it clear they do not want the dikes heights increased.

A fascinating approach to stakeholder involvement in flood management has been conducted by Van Der Werff (2004) where the author analyzes the stakeholders' response to the construction of a bypass, the Green River, between the rivers Rhine and IJssel as part of the future management of the Rhine River Basin. Postmodernity, modernity and premodernity patterns of acting and thinking are used in the paper to analyze the stakeholders' defence of stakes.

Flood management measures impact the entire watershed system and sometimes are very costly. Therefore, thinking about the behavior and changes of the system in the future as a result of these measures is indispensable to the success of flood management projects. The concept of "Panarchy" (Gunderson and Holling, 2002) helps us think about the source and role of change in systems especially adaptive systems. In flood management, this assists us in thinking about sustainability, flexibility, and resilience when trying to develop flood management measures. As an example, a research has been carried out on resilience in the context of flood risk management by De Bruijn (2005).

To sum up this section, it is worth mentioning stochastic models which are developed for the purpose of describing floods. Although developing such models is not the focus of this study, as an interesting example the study by Todorovic and Zelenhasic (1970) can be mentioned where they develop a probabilistic model to describe and analyze flood phenomenon through the use of the theory of extreme values. They apply their model to 72 years of recorded data of the Susquehanna River at Wilkes-Barre, Pennsylvania. The results of the model show a fair agreement with the observed distribution function of the maximum flood peak exceedance.

2.2 RIDM Frameworks

Some of the major corporations in the world today work on developing and modifying RIDM frameworks for helping them in making important decisions and some others recruit specialists to develop such frameworks for them.

National Aeronautics and Space Administration (NASA) is an example of the former. Before the introduction of RIDM in December 2008 as a complement to NASA Continuous Risk Management (CRM), NASA risk management process used to be only based on CRM which focuses on risk management during implementation. Now risk management in NASA comprises of both CRM and RIDM. The reason for RIDM process was to overcome some of the primary issues that had hindered NASA programs in the past, including (NASA Risk-Informed Decision Making Handbook, 2010):

“1) The “mismatch” between stakeholder expectations and the “true” resources required to address the risks to achieve those expectations.

2) The miscomprehension of the risk that a decision-maker is accepting when making commitments to stakeholders.

3) The miscommunication in considering the respective risks associated with competing alternatives.”

NASA published version 1.0 of their RIDM handbook in 2010.

United States Army Corps of Engineers (USACE) is another major organization that has been developing and utilizing RIDM frameworks. As an example, The Louisiana Coastal Protection and Restoration final technical report (2009) developed by USACE goes beyond traditional cost-benefit analysis methods and uses risk-informed decision framework to evaluate alternative solutions. The approach is an attempt to identify comprehensive coast-wide plans that diminish the risk of flooding caused by storm surge and coastal degradation. This is done while taking account of a full range of risks to people, cultural heritage, environment, property and economy as well as infrastructure, construction, operations, and maintenance costs.

As a fascinating and comprehensive approach to risk-informed decision making in the field of nuclear energy, which is exposed to various significant risks, Lyubarskiy et al. (2011) explain the general Integrated RIDM (IRIDM) framework developed by International Atomic Energy Agency (IAEA) in INSAG-25 report (IAEA, 2010). They also explain the draft technical document (TECDOC) entitled "Integrated Risk Informed Decision Making Guidance" (IAEA, 2011), which is a detailed practical guidance on implementing the IRIDM process. Similar to the framework we utilize in our study, the main goal of the IRIDM framework for nuclear safety is to ensure that decision making process is an optimized process while the requirements for safe operation of the nuclear power plant are met. The framework is illustrated in figure 2. The process starts with clearly defining the issue being considered. Then, all the relevant regulatory and utility considerations are determined and used to identify the potential options or alternatives to resolve the issue. Next, evaluation of the identified alternatives is performed with the use of the key elements in the IRIDM process. These elements include standards and good practices, operational experience, deterministic considerations, probabilistic considerations, organizational considerations, security considerations, and other considerations. In fact, these key elements are the criteria used to evaluate the performance of each alternative. The importance of each element depends on the particular issue and alternative being considered. Consideration of each key element might require different inputs and the decision made should integrate different inputs for each key element and achieve a suitable balance among the various considerations. A detailed method for integration of different inputs is provided in the TECDOC. After a decision has been made, the selected alternative will be implemented and its consequences are monitored. Therefore, corrective actions can be taken and if necessary, alternatives can be redefined and the decision making process can be reiterated.

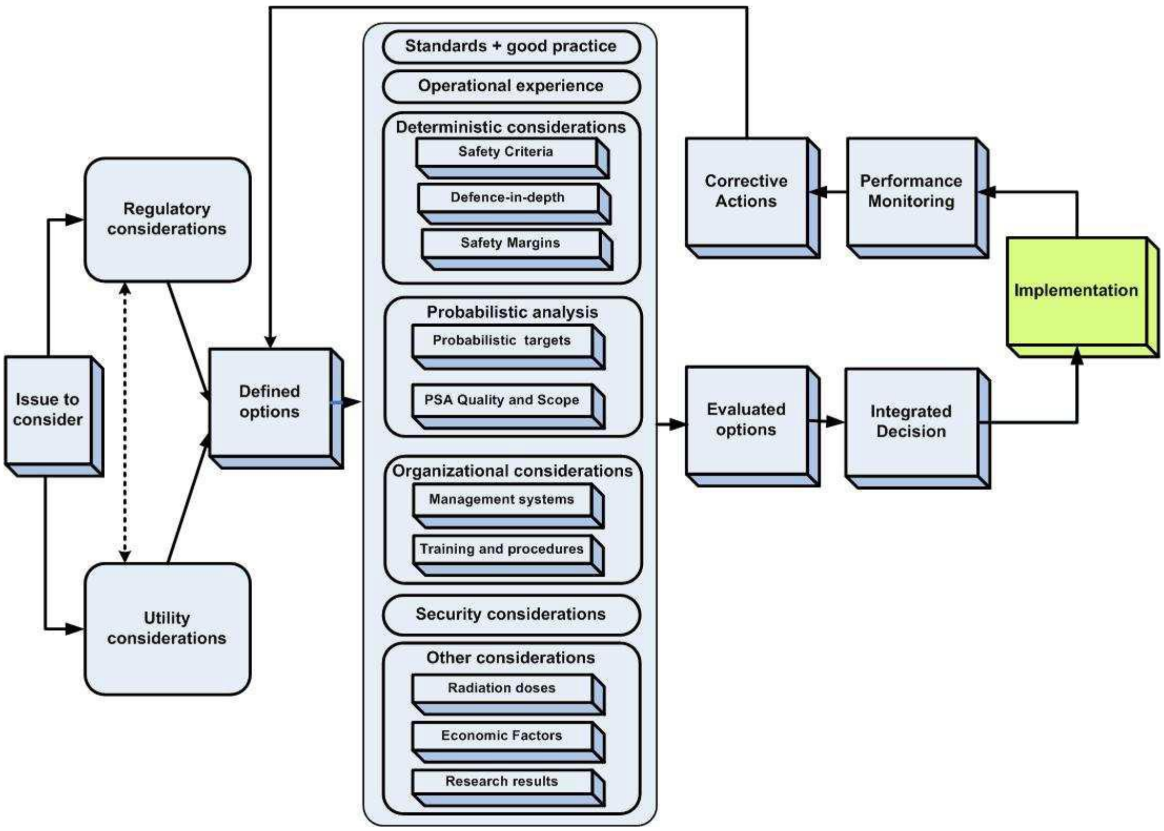


Figure 2: Basic Framework and Key Elements of IRIDM (Lyubarskiy et al., 2011)

As an example for the case where specialists are recruited to work on RIDM frameworks, Corporate Risk Associates (CRA) Ltd can be mentioned. They provide service for several clients such as British Energy, Thames Water (the UK's largest water and wastewater services company), and Kuwait National Petroleum Company. The CRA team members have used many of the probabilistic safety and reliability analysis techniques, such as fault tree analysis, event tree analysis, failure modes and effects analysis, reliability block diagrams, cause-consequence analysis, Monte-Carlo simulation, and human factors assessment, to help clients with cost effective risk management solutions. The clients come from different industries such as nuclear power, railway, and oil/gas. The CRA have also developed extensive experience by offering nuclear Probabilistic Safety Analysis (PSA) and human factors assessment to the UK's nuclear power stations (Corporate Risk Associates website, 2009).

2.3 Inflow Forecast and Scenario Generation Methods

Forecasting future events with certainty is obviously an impossible task. Uncertainty and the corresponding risks are always an impartible concern in decision making regarding future events. Accordingly, decision making for flood management is exposed to the risks arising from uncertain future inflows. The easiest way to deal with this problem, which has been used in practice many times, is only using a set of deterministic future inflows. Although this simplifies the problem, disastrous consequences are probable in this type of problem solving and have happened in the past as a result of this type of problem simplification. Generating several inflow scenarios with their corresponding probability of occurrence is another way of dealing with uncertainties.

Hydrological and hydraulic models and also purely statistical methods based on historical data have been developed to perform the task of forecasting future inflows. U.B.C. Watershed Model by M. C. Quick and A. Pipes (1977) is an example of the former that originally was developed for forecasting daily streamflow on the Fraser River system in British Columbia. The model has also been adopted for inflow forecasting of some other river systems (M.C. Quick and A. Pipes, 1977).

Zaman (2010) utilized a fitted volume distribution method to generate a probability distribution function for inflows into Daisy Lake reservoir on Cheakamus River in British Columbia. This was done with the use of the Log Pearson Type III distribution function and the EasyFit – Distribution Fitting Software (MathWave website, 2010 as cited in Zaman, 2010, p. 26). The process started with acquiring four five-day inflow forecast sequences with the approximate exceedance probabilities of 10%, 25%, 50%, and 75% from the H&TS Department at BC Hydro, which utilize the UBC watershed model (UBCWM, Quick, 1995 as cited in Zaman, 2010, p. 2) with some modifications and adaptations for their streamflow forecasts. Then, the volume curve-fitted function and the shape of the inflow forecast were used to generate five-day inflow forecast sequences with the exceedance probabilities ranging from 2.5% to 99.5%.

Among statistical methods that have been used for the task of inflow forecasting, time series models can be named that have been widely being used in the past decades. Autoregressive (AR), Autoregressive-Moving Average (ARMA), and Autoregressive Integrated Moving Average (ARIMA) are a number of these techniques with numerous applications in different areas of practice and research (see Salas et al., 1980). Some techniques have been proposed on how to decide whether AR or ARMA is the better technique for modeling a time series, such as investigating the auto-correlation and partial auto-correlation of historical data. In some cases ARIMA is an alternate way of modeling a time series with fewer parameters than ARMA, which is a positive point considering the uncertainty in the estimation of these parameters (Salas et al., 1980). Salas and his colleagues wrote a book on modeling of hydrological time series in 1980 and thoroughly explained these modeling methods.

Artificial Neural Networks have also formed a considerable portion of the inflow forecast studies in recent years. Ajith Abraham (2005) in Chapter 129 of Handbook of Measuring System Design (edited by Peter H. Sydenham and Richard Thorn, 2005) explains:

“Artificial neural networks (ANN) have been developed as generalizations of mathematical models of biological nervous systems. A first wave of interest in neural networks (also known as connectionist models or parallel distributed processing) emerged after the introduction of simplified neurons by McCulloch and Pitts (1943).

The basic processing elements of neural networks are called artificial neurons, or simply neurons or nodes. In a simplified mathematical model of the neuron, the effects of the synapses are represented by connection weights that modulate the effect of the associated input signals, and the nonlinear characteristic exhibited by neurons is represented by a transfer function. The neuron impulse is then computed as the weighted sum of the input signals, transformed by the transfer function. The learning capability of an artificial neuron is achieved by adjusting the weights in accordance to the chosen learning algorithm.”

The ASCE Task Committee on Application of Artificial Neural Networks in Hydrology published two valuable papers in 2000, one on the preliminary concepts of ANNs (ASCE Task Committee on Application of Artificial Neural Networks in Hydrology, 2000a) and another on hydrologic applications of ANNs (ASCE Task Committee on Application of Artificial Neural Networks in Hydrology, 2000b).

Another statistical method for scenario generation, which is also used in our study, is called Moment Matching. Moment Matching as its name implies is a method to generate scenarios that reproduce the desirable moments and correlations of the original (historical) data. Hoyland et al. (2003) proposed an efficient algorithm for moment matching scenario generation and created a code based on the algorithm. The algorithm and the pertaining code enable generating scenarios with desirable levels of probability. Kaut (2003) published some updates on the algorithm to make it more efficient. Kaut and Lium (2007) also published a paper on generalizing the algorithm so that in the cases where the marginal distributions are known, they can be described directly instead of describing them using their moments.

There are several other inflow forecast and scenario generation approaches and methods that a comprehensive survey of these approaches is beyond the goals of this study. As an invaluable source of newer works on this topic the proceedings of the Canadian Water Resources Association conference (2011) can be mentioned. Here we try to explain two of the presentations in this conference that were focused on flood forecast.

Johansson et al. (2011) presented the spring flood forecast method used for the Lule River in Sweden with the use of the HBV rainfall-runoff model. The Lule River basin rises in northern Sweden and flows southeast for 460 km before reaching the Gulf of Bothnia at Lulea. The basin has an area of 24,240 square kilometers and its average discharge at outlet is 498 cms. There exist 15 hydropower stations in the basin with an annual average production of about 14 TWh and the generation capacity of 4466 MW. In the basin, at least 50% of the precipitation falls as snow and approximately 60% of the annual runoff occurs during the snow melt season from May to July.

Due to the existence of several large reservoirs in the basin, the planning and optimization of the power system is highly affected by the estimates of spring flood volume and the initial start point of the melting period. Starting in January, inflows to the major reservoirs for the period until the end of August are generated weekly. In order to do this, the HBV model is run with historic time series of climate data (precipitation and temperature) since 1961. As an example, in 2011 the model was run for 50 different time series and created an ensemble of 50 inflow forecasts. Figure 3 shows the simulations for February to July and figure 4 displays the probable runoff volume over the forecast period. The forecasts are used as inputs into mid and long term production planning systems.

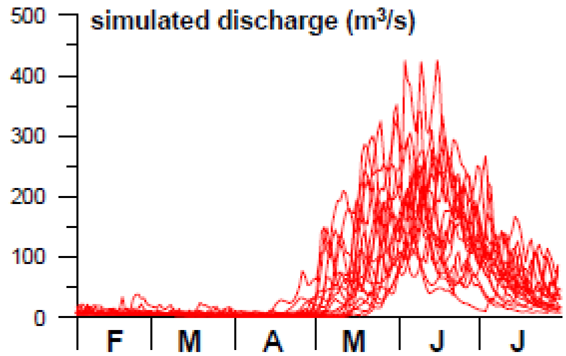


Figure 3: Simulated discharges (Johansson et al., 2011)

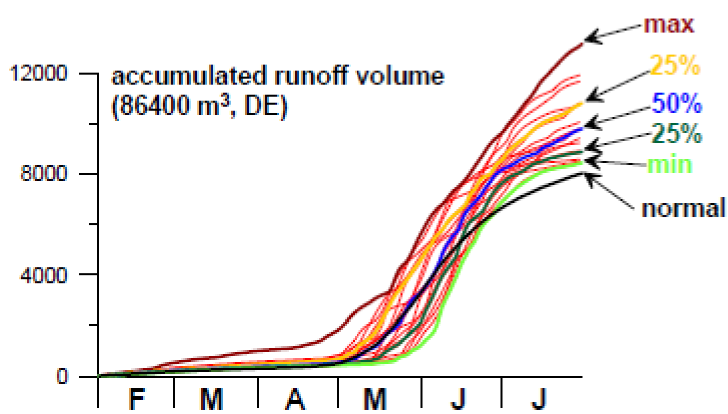


Figure 4: Probable runoff volume (Johansson et al., 2011)

Where the forecasts are made late in the melt season, the accuracy of the hydrological model and its capability to estimate the current snow pack are the significant factors. For the early forecasts, in January and February, the expected weather development in late winter and early spring is more important and relevant. The authors explained that an ongoing research project was being carried out intending to identify a reduced ensemble of historic years that were more likely to represent the current forecast period. This was done with linking the current year to historic years that were climatologically analogous to current year.

Khan et al. (2011) presented the near real-time flood level forecast modeling for the lower Fraser River during freshet 2011. Fraser River has experienced two known major flooding events in 1894 and 1948. The 1894 event, which is the largest flood in Fraser River at least in the past 162 years, did not cause so much damage as the development was limited at the time. On the other hand, the 1948 flooding event caused extensive damage even though it was not as large as the 1894 event.

The Fraser River's first flood profile was developed in 1969. In 2000/2001, a 1-D Mike 11 hydraulic model was developed for 69 km of the river's channel from Laidlaw to Mission. In 2006, another 1-D Mike 11 model was developed for 85.4 km of the channel length from Mission to Ocean. The two models were merged in 2007/2008 creating a model for 154 km of the channel length. In 2011, the model was being updated for the channel from Hope to Mission.

Fraser River's hydraulic model was used for near real time forecasting in 2007 for the first time. The model was also used in 2008 and 2009. In 2011, the snow reports were above normal in the upper, middle, and lower Fraser River, and the model was used to provide 5-day peak water level forecasts to the public, municipalities, and agencies for their flood emergency planning. Downstream boundary conditions were acquired from the predicted tidal levels at Point Atkinson and Sand Heads; and 5-day forecasted flows at Hope, Harrison Lake inlet, and Harrison Lake were used for upstream boundary conditions. The forecasted and observed water levels showed good agreement with slight over-prediction for upstream of Agassiz Bridge.

2.4 Optimization and Simulation Methods for Reservoir Operation

Reservoir operation is a complicated task usually in order to satisfy multiple competing objectives in the best possible way. It is a fact that reservoir operation is a manipulation to a watershed system and how a reservoir is operated impacts the entire watershed system. It is also a fact that normally in a watershed system there exist several stakeholders with different values and preferences. Consequently, in order to define the objectives for a reservoir operation plan, all the stakeholders in the watershed system and their values and preferences must be taken into account. The difference and conflict between stakeholders' values and preferences result in competing objectives. Therefore, planning for reservoir operation turns into a process which cannot be implemented in a very successful way only with the use of human judgement.

Simulation and optimization techniques have been widely used to assist planners in developing short and long term reservoir operation plans. Since in the current study an optimization model is developed and used, the focus of this section will be on optimization models rather than simulation models. Ziad Shawwash (2000) developed a decision support system for BC Hydro and Power Authority (BC Hydro) including six components for helping them in operating their system. “A major part of this work involved the development and implementation of a practical and detailed large-scale optimization model that determines the optimal tradeoff between the long-term value of water and the returns from spot trading transactions in real-time operations” (Shawwash, 2000). Alaa Eatzaz Abdalla (2007) presented a new method for optimal operation of a large-scale hydro-power system. The method enables efficient handling of large-scale reservoir operation problems. The author applied his method to the main reservoirs of BC Hydro system of reservoirs on Peace and Columbia Rivers. Hamideh Abolghasemi Riseh (2008) developed an optimization model with the use of Linear Programming to optimize the operation of the Kootenay River System in British Columbia. Joel Evans (2009) used a hydraulic simulation and electrical energy generation optimization model to explore the possible incremental value that curtailment of wind power might contribute in a market context. In order to mitigate the impacts of wind integration in a large-scale hydro-power system, Humberto Rivas (2010) presented two optimization models, including a long term mixed-integer optimization model and a short term stochastic linear optimization model, to assess the feasibility of installing a pumped-storage hydro system for expanding an existing hydro-power system. Nazanin Shabani (2009) implemented a Reinforcement Learning optimization algorithm to increase the time and computational efficiency in planning for reservoir operation.

2.5 Streamflow Impact Curves

The outputs of optimization models are normally the values of the variables and objective function of the model. These variables might represent different items which by themselves may not necessarily be applicable to evaluate the performance of an alternative on all the objectives. Therefore, sometimes it is necessary to define the relationship between a variable in the optimization model, such as streamflow or water level at different locations downstream of a reservoir, and the performance on an objective. There have been studies to develop curves to define this type of relationships; for instance, as displayed in figure 5, Faheem Sadeque (2010) developed a curve to show the relationship between residential property damage and Cheakamus River discharge measured by Gauge 08GA043 which belongs to Water Survey of Canada (Water Survey of Canada website, 2012). Sazid Zaman (2010) also presents two curves to show the relationship between outflows at Brackendale area (a small residential area near Gauge 08GA043) and flood damage and fish habitat impact units. Ali Naghibi (2011) worked on defining the immediate and long term fisheries impacts of extreme flooding events and developed curves to show this with the use of different peak flows for Campbell River on Vancouver Island in British Columbia.

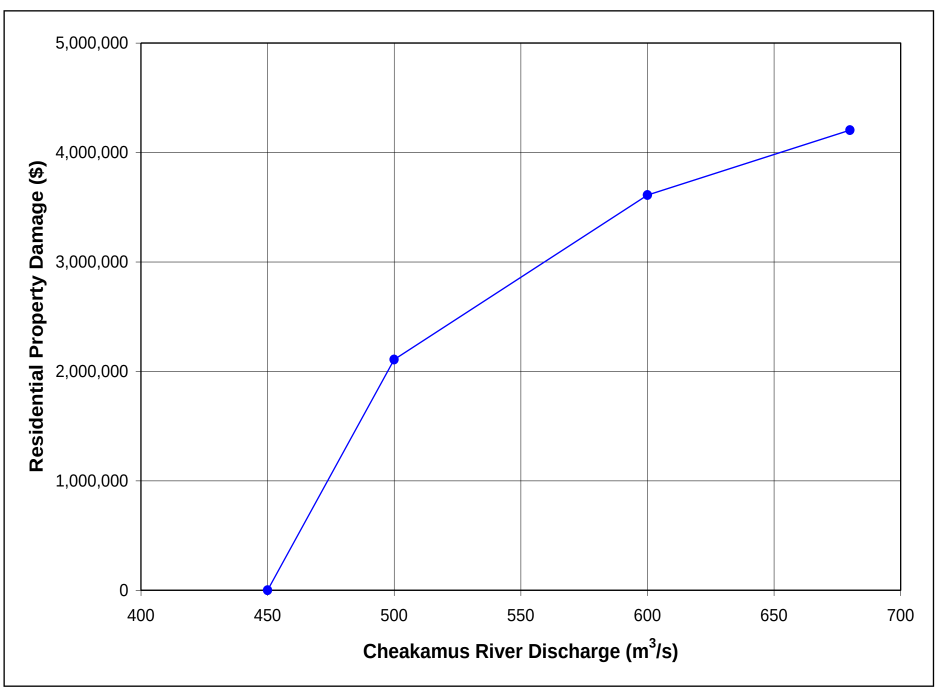


Figure 5: Property Damage Curve for the Cheakamus River (Sadeque, 2010)

2.6 Multi-Criteria Decision Making (MCDM)

Decision Making could be defined as a process in which a decision maker makes a specific choice among several existing choices. Multi-Criteria Decision Making (MCDM) as its name suggests pertains to a decision making situation where the decision maker considers multiple criteria in order to make a choice. Benjamin Franklin is allegedly the earliest known person to create a simple method to solve this type of problems. As a result of the rapid growth of operations research during and after World War II, MCDM has been a significant area of research and numerous methods have been invented to help decision makers face the challenge of MCDM problems. Moreover, numerous researchers have been contributing to great advances in the field (see MCDM Society website). As an invaluable book on MCDM, Smart Choices: A Practical Guide to Making Better Decisions (Hammond, Keeney, and Raiffa; 1999) can be named. Moreover, for a thorough description of MCDM history and other information and resources related to MCDM, MCDM Society website can be considered. Alipour et al. (2010) worked on developing a new method for solving MCDM problems with the use of fuzzy numbers, which enable more flexibility in taking account of uncertainties. With a simple search into literature, the variety of approaches and techniques to solve MCDM problems will be revealed.

MCDM techniques can be very helpful in solving water related problems due to the fact that most of the large-scale water related decisions impact multiple active components in a watershed system. One of the applications of MCDM in water resources planning and management is in planning for reservoir operation. In fact, MCDM is somehow an impartible component of a risk-informed decision making framework for reservoir operation during floods.

2.7 Role and Applications of MCDM in Water Resources Planning and Management

Wallenius et al. (2008) identified energy and water resources as one of the significant areas of science that uses MCDM to solve problems with 3.9 percent of all the publications in MCDM since 1970 until the end of June 2007. As a review of some of MCDM methods, Figueira et al. (2005a) can be mentioned; and as an interesting review of major MCDM techniques that have been used in water resources science, the review paper by Hajkowicz and Collins (2007) can be mentioned. The authors reviewed and classified these techniques as follows:

1. Multi-criteria value functions.
2. Outranking approaches, such as PROMETHEE (Brans et al. 1986) and ELECTRE (Figueira et al. 2005b).
3. Distance to ideal point methods, such as compromise programming (Zeleny 1973; Abrishamchi et al. 2005) and TOPSIS3 (Lai et al. 1994).
4. Pairwise comparisons, such as Analytic Hierarchy Process (AHP; Saaty 1987), the Analytic Network Process (ANP; Saaty 2005), and MACBETH (Bana e Costa et al. 2005).
5. Fuzzy set analysis, such as the fuzzy MCDM method by Alipour et al. (2010).
6. Tailored methods.

They also classified MCDM applications in water resources:

1. Catchment management, such as Chang et al. (1997) where the authors utilize MCDM techniques for evaluation of land management strategies in a catchment in Tweng–Wen reservoir watershed in Taiwan.
2. Ground water management, such as Almasri and Kaluarachchi (2005) where MCDM is used to analyze different alternatives for groundwater nitrate contamination management in the Sumas–Blaine aquifer in Washington State, US.
3. Infrastructure selection, such as the work by Eder et al. (1997) with the use of MCDM for analysis of twelve water supply infrastructure alternatives, including major infrastructure such as hydroelectric power schemes, in the Austrian part of the Danube River.

4. Project appraisal, such as the work by Al-Rashdan et al. (1999) to rank a number of environmental quality modification projects for Jordan River.

5. Water allocation, such as the use of MCDM by Agrell et al. (1998) for informed decision-making regarding water release from the Shellmouth Reservoir in south-west Manitoba, Canada.

6. Water policy and supply planning, such as the use of MCDM by Joubert et al. (2003) to assess the policies of water demand and supply management in Cape Town, South Africa.

7. Water quality management, such as the study by Lee and Chang (2005) where they use MCDM to plan for water quality management in the Tou–Chen River Basin in northern Taiwan.

8. Marine protected area management, such as Fernandes et al. (1999) who use MCDM for evaluation of coral reef management alternatives in the Caribbean.

Chapter 3: Risk-Informed Decision Analysis Framework and Modeling Methodology

The methodology used in this study to use a general structure for reservoir operation risk informed decision making framework is explained in this chapter. Furthermore, the methodology to apply the framework to the case study of Cheakamus River system including the techniques we used to develop the necessary components is discussed in this chapter. This starts with explaining the inflow scenario generation technique, Moment Matching; and continues with describing the optimization model. Subsequently, risk-assessment method is described; and then we explain the development of streamflow impact curves. Finally, the chapter ends with explaining the multi-criteria decision making software package.

3.1 Risk-Informed Decision Making Framework

The approach in our study is developing an optimization model that is a single-objective model for power generation, and considering the other objectives through analyzing the water level impacts at downstream area. In fact, the performance of each operational alternative on all the objectives of the study, except power generation, is dependent on the maximum water level in the residential area downstream of the reservoir. Therefore, in this study we discretize the reservoir storage at the start of the high inflow period from its minimum to its normal maximum to be sure we have covered all the potential operational alternatives, and then run the optimization model to maximize revenues. However, in the model there exist constraints to make sure that no flood damage is one of the restrictions while trying to maximize revenues. If the model fails to generate outputs, it shows that some flood damage is inevitable. Therefore, flood damage allowance is relaxed gradually until the model runs with no problem. In this way we can be sure that we are maximizing revenues while objectives such as minimizing flood, environmental, and public image damages have also been considered in the process.

The RIDM framework used in this study consists of a number of elements. Figure 6 is a presentation of the framework and its elements.

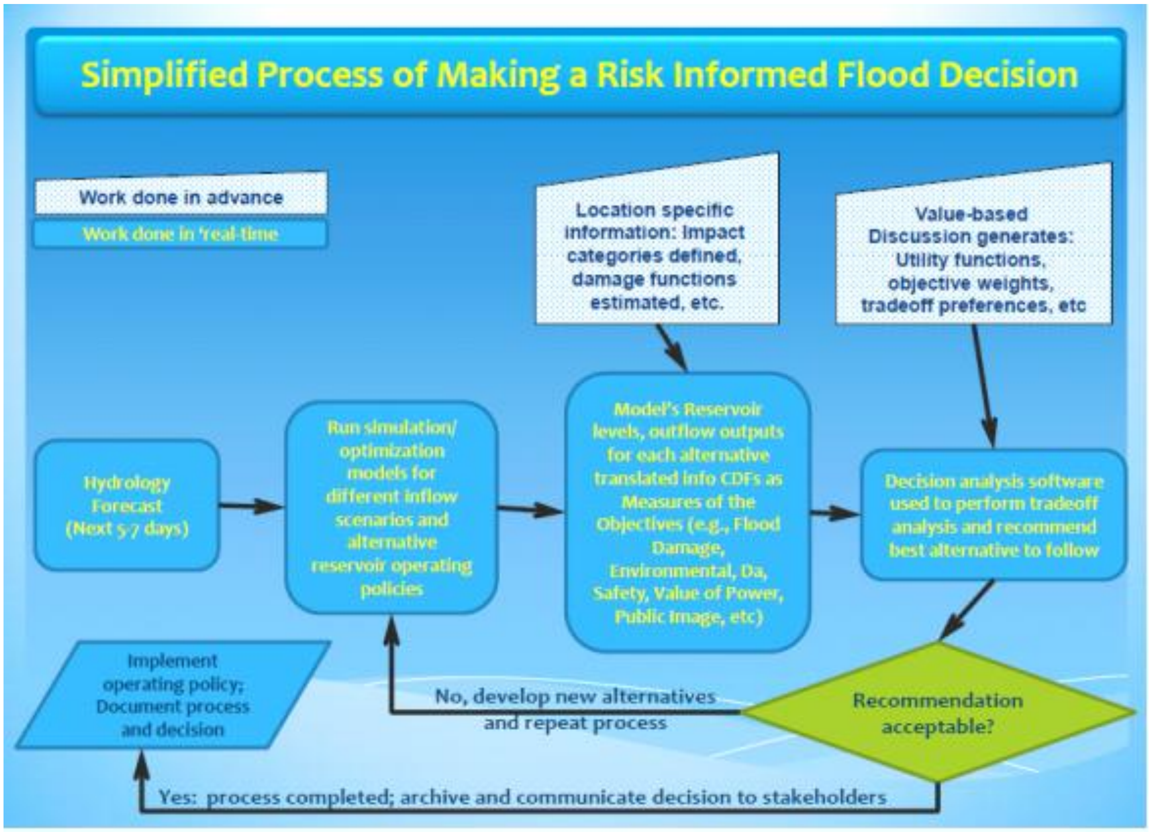


Figure 6: RIDM framework for reservoir operation during high inflow events (see Zaman, 2010)

The process starts with hydrology forecast and scenario generation for the high inflow period, which usually could be five to seven days. Afterwards, the generated scenarios are input into simulation and/or optimization models and the models are run for the entire inflow scenarios and alternatives. Alternatives are different ways of operating a reservoir that based on the related case study might be developed in different ways. Optimization and/or simulation models usually are not general and differ from each other for different case studies. The outputs of optimization and/or simulation models are usually a distribution function for the value of the objective function(s) of the model and also a number of distribution functions for the values of variables. Note that these distribution functions are separately generated for each alternative. The variables might represent different items which by themselves may not necessarily be applicable to evaluate the performance of an alternative on all the objectives. The key variables for the reservoir operation problem could be reservoir levels, outflows, water levels at different downstream locations, etc.

In order to evaluate the performance of an alternative on all the objectives of the problem, we need to translate the distribution functions of variables values into distribution functions of alternatives performance on different objectives. In order to do this, impact categories, damage functions, etc., can be developed to define the relationship between the values of variables and the performance of alternatives.

The generated distribution functions for the performance of alternatives are used as part of the inputs into MCDM software package. Depending on which software package is chosen and how we decide to handle the distribution functions, there are two different methods of generating the MCDM inputs. The first method is employing a software package that holds the capability of handling a distribution function as its input so that we can input the distribution functions to the software package with no change. The second method, as recommended in NASA's Risk-Informed Decision Making Handbook (2010) is acquiring the stakeholders' desirable level of risk-taking on each objective and extracting the corresponding performance of each alternative from their performance distribution functions. These are called performance commitments. As explained in the handbook: “a performance commitment is the performance measure value, at a given risk tolerance level for that performance measure, acceptable to the decision-maker for the alternative that was selected”. Figure 7 represents a performance commitment for performance measure X.

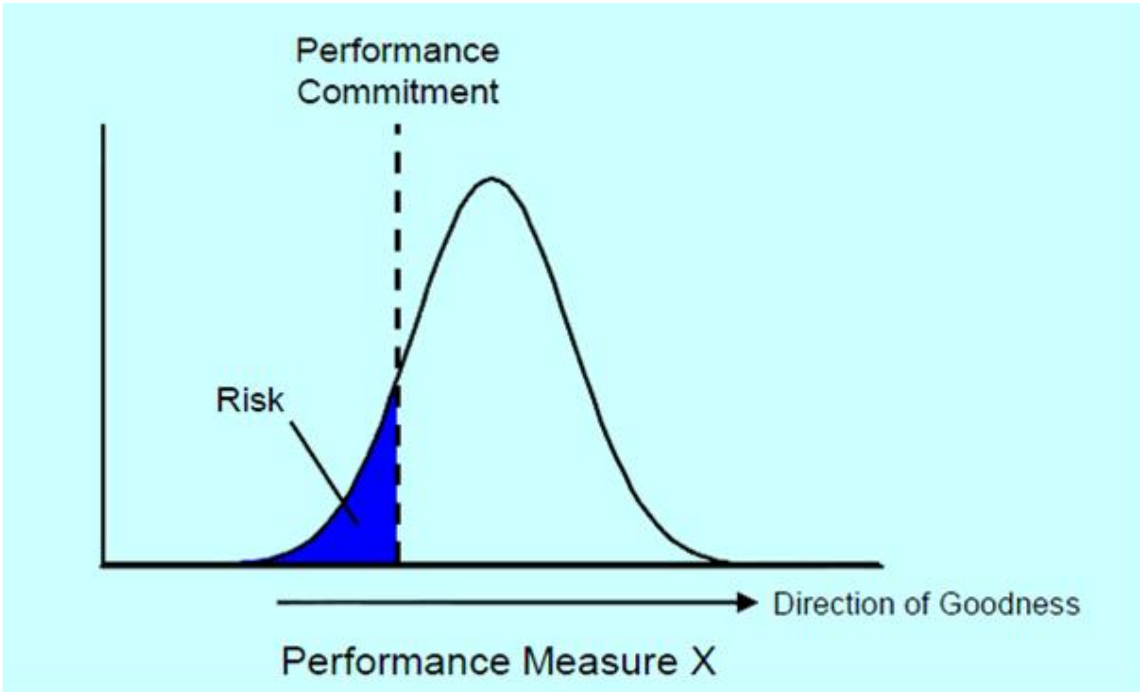


Figure 7: Performance commitment for performance measure X (NASA's Risk-Informed Decision Making Handbook, 2010)

Relative importance of the objectives forms another part of the inputs to the MCDM software package. There are different methods to define the relative importance of objectives such as utility functions, objectives weights, trade-off preferences, even swaps, etc. MCDM software packages usually provide one or a limited number of ways for defining the relative importance of objectives. What is important in choosing an MCDM software package is its compatibility with the technique we have found appropriate for defining our problem. In other words, we should not sacrifice our preferred way of defining the problem, which corresponds to a specific way of generating the inputs of the MCDM software package, only because the available software package is not capable of handling the inputs in the way we have chosen to define them. If we do so, it may affect the results of the decision making process.

Another significant point about working with MCDM software packages is consistency. In the market, there exist a number of different software packages for solving MCDM problems such as Expert Choice, Logical Decisions for Windows, WINPRE, etc. Each of these software packages might have a specific and different method(s) for inserting the inputs. Moreover, some of these software packages might be developed based on the same MCDM technique. For instance, Analytical Hierarchy Process (Saaty, 1987) has been used in some of the existing MCDM software packages in the market. In terms of consistency, where two different software packages with different MCDM techniques are used to solve a unique problem, having different outputs (ranking of alternatives) is acceptable and does not necessarily breach the consistency. This is due to the fact that there is no best or better when comparing MCDM techniques. The breach of consistency can happen where two different software packages that have been developed on the same MCDM technique result in two different solutions for the same problem. This usually shows that the different ways of inputting data to these software packages have affected the user so that the inputs are not consistent. Zaman (2010) examined several MCDM software packages and chose the Logical Decisions for Windows to use in the case study of Cheakamus River. The software packages were classified into two categories, computer-installed and web-based, and listed as follows:

Computer-Installed (non-web-enabled or local software):

- Logical Decisions for Windows (LDW website, 2010);
- Criterium Plus (Criterium Plus website, 2010);
- HiView (HiView website, 2010);
- GoldSim (GoldSim website, 2010);
- Equity3 (Equity3 website, 2010);
- WINPRE (WINPRE website, 2010).

Web-based (web-enabled and shared):

- Web-HIPRE (Web-HIPRE website, 2010);
- Opinions-Online (Opinions-Online website, 2010);
- 1000Minds (1000Minds website, 2010).

After all the required inputs of the MCDM software package are generated, the software is run and the output will be a ranking of the alternatives. The alternative ranked as first is the recommended alternative to implement for the purpose of reservoir operation.

As can be seen in Figure 6, the necessary work in order to make a recommendation has been classified into two categories: work done in advance and work done in real time. As shown in white, for our research and case study, the work that is done in advance includes development of impact curves and the relative importance of objectives. Moreover, we also need to develop or determine and acquire the inflow forecast method, optimization and/or simulation model(s), and the decision analysis software package in advance so that the real time work can be conducted as efficient as possible.

In the following sections of this chapter, each of the components of the RIDM framework of our study will be explained.

3.1.1 Inflow Forecast and Scenario Generation

Inflow forecast is the major source of uncertainty and risk in the problem of reservoir operation during high inflow events. In the literature, there exist a large number of studies on forecasting future inflows with the use of historical inflow data. The purpose of these studies is capturing the characteristics of natural inflows in the best possible way and using it to forecast future inflows that are close to reality. The experiences in the past show that the available technologies are still very far from a point where we can utilize them to issue one single very near reality inflow forecast. Therefore, generating a large number of possible future inflows with their corresponding probabilities of occurrence seems to be a good approach to reduce the uncertainty-driven risks.

At BC Hydro, five to seven-day inflow forecast sequences with the approximate exceedance probabilities of 25%, 50%, and 75% are issued in the morning of each working day during a high inflow event with the use of an adapted and modified version of UBC watershed model (Quick and Pipes, 1977). For the high inflow event of October 2003 in Cheakamus River, comparison between natural inflows and BC Hydro inflow forecasts shows that the forecasts underestimated the magnitude of the inflows. To better investigate this event, Zaman (2010) requested another inflow forecast sequence with the approximate probability of exceedance of 10%. He then fitted a Log Pearson Type III distribution function to these four inflow forecast sequences and generated 195 inflow scenarios. Apparently, increasing the number of inflow scenarios from 4 to 195 has a significant impact on reducing the uncertainties. However, fitting a Log Pearson Type III distribution function is an approximation of the inflow scenarios generated by UBC watershed model that they themselves are approximations of reality and natural inflows. Moreover, for the high inflow event of October 2003, the generated inflow scenarios by UBC watershed model underestimated the actual event and consequently the inflow scenarios generated by Zaman (2010), which were generated through fitting a Log Pearson Type III distribution function to the UBC watershed model generated scenarios, still hold this inaccuracy.

In our study, we used a statistical method known as Moment Matching and the algorithm developed by Hoyland et al. (2003) to generate 100 inflow scenarios for the period of October 17 to October 21, which was the high inflow period in 2003. The method is based on generating inflow scenarios that hold the same statistical characteristics as historical data. In our study, this was conducted through calculating the first four statistical moments and also the correlation coefficients between historical data, and then generating scenarios that reproduce these moments and correlations. Note that with the use of Moment Matching, we cover the entire set of possible future inflows with their probabilities of occurrence and do not limit our investigation to only high inflow events. This is because the experiences in the past show that both underestimation and overestimation have happened in BC Hydro inflow forecasts.

The preparation steps for generating inflow scenarios in our study were calculating the historical moments of inflows into Daisy Lake reservoir and also inflows downstream of the reservoir to Brackendale gauge. In order to do this, the historical inflow data into Daisy Lake reservoir were acquired at BC Hydro (Figures 8 to 12) and the first four statistical moments and correlation coefficients were calculated for the period of October 17 to October 21 (the high inflow period in 2003) as shown in tables 1 and 2.

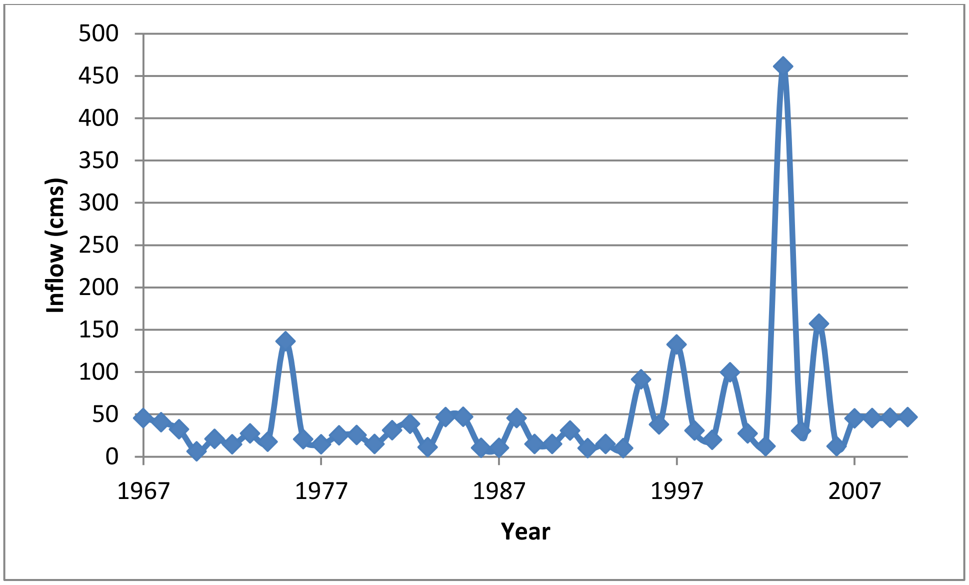


Figure 8: Inflows into Daisy Lake reservoir on October 17

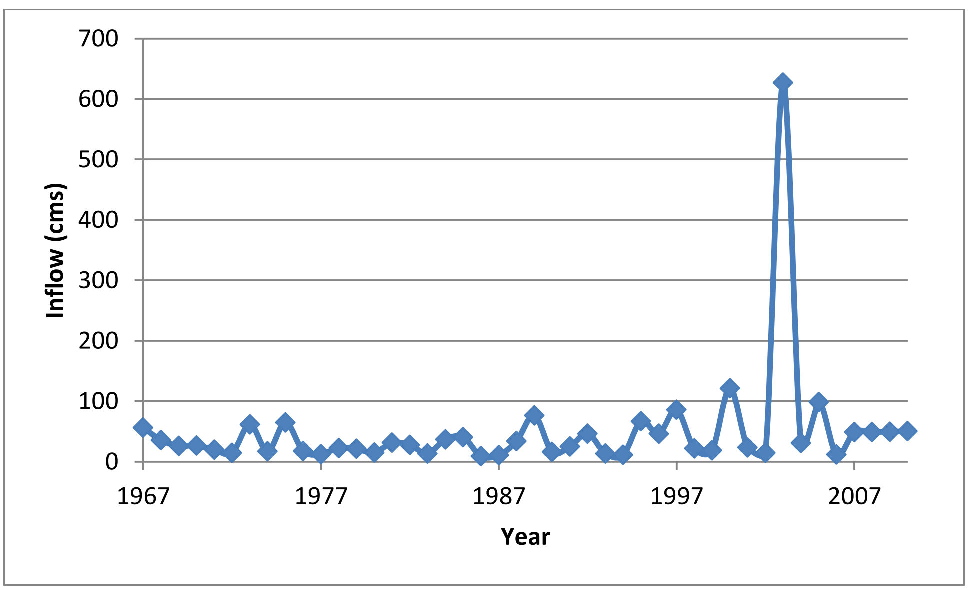


Figure 9: Inflows into Daisy Lake reservoir on October 18

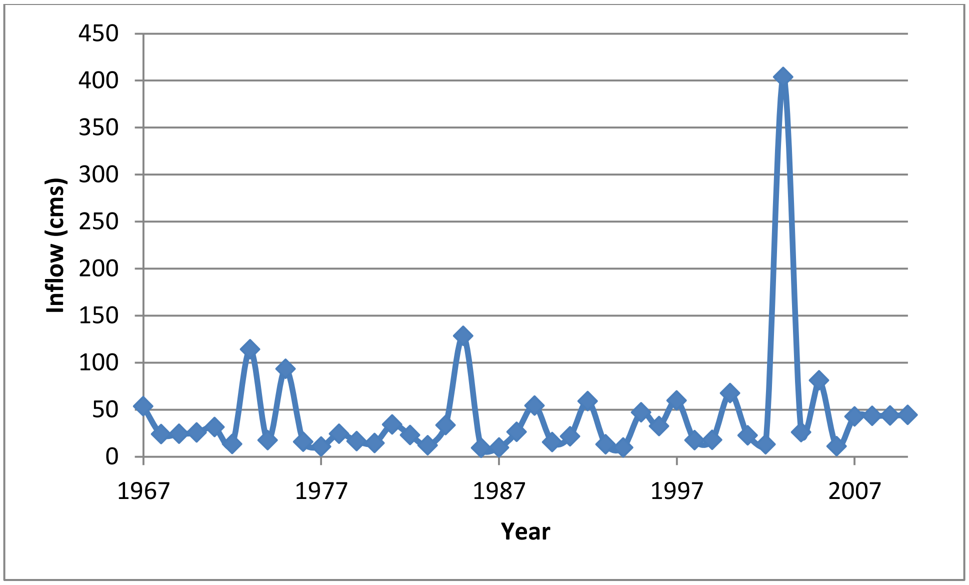


Figure 10: Inflows into Daisy Lake reservoir on October 19

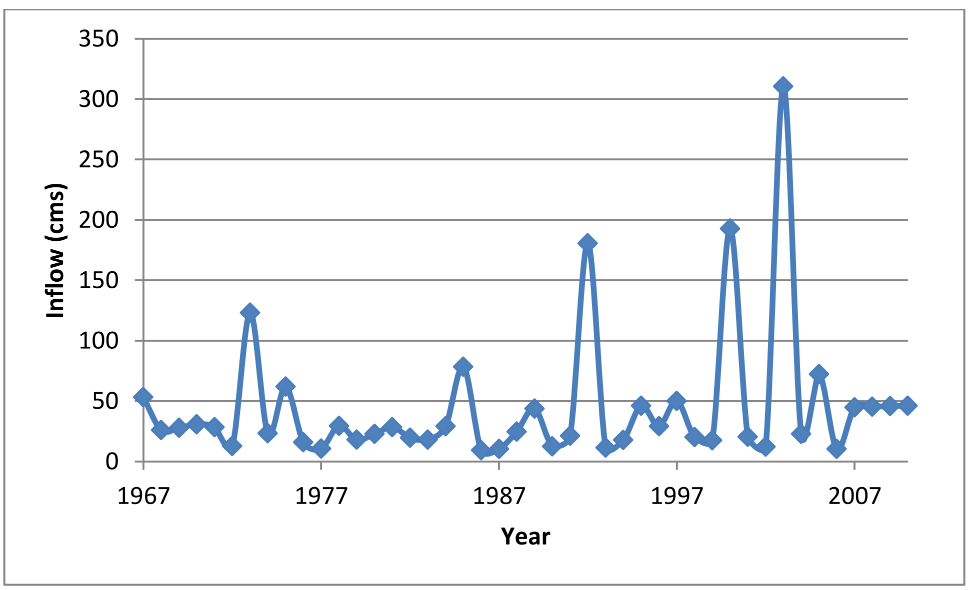


Figure 11: Inflows into Daisy Lake reservoir on October 20

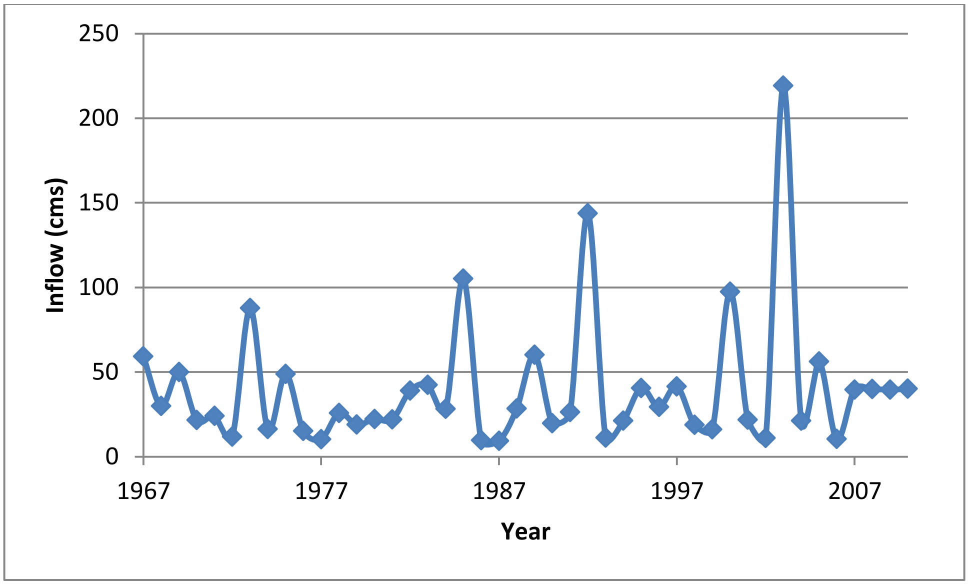


Figure 12: Inflows into Daisy Lake reservoir on October 21

Table 1: Statistical moments of historical Daisy Lake reservoir inflows

Date	Mean	Standard Deviation	Skewness	Kurtosis
17-Oct	47.00	72.62	4.65	25.30
18-Oct	49.12	92.67	5.90	37.23
19-Oct	43.12	62.04	4.85	27.46
20-Oct	44.87	56.75	3.26	11.86
21-Oct	39.76	39.24	2.90	10.24

Table 2: Correlation coefficients between historical Daisy Lake reservoir inflows

Date	17-Oct	18-Oct	19-Oct	20-Oct	21-Oct
17-Oct	1.00	0.95	0.91	0.76	0.73
18-Oct	0.95	1.00	0.95	0.83	0.80
19-Oct	0.91	0.95	1.00	0.86	0.88
20-Oct	0.76	0.83	0.86	1.00	0.95
21-Oct	0.73	0.80	0.88	0.95	1.00

Moreover, historical inflows downstream of the reservoir to Brackendale gauge were acquired with the use of the recorded measurements by Water Survey of Canada and also the recorded spills from Daisy Lake reservoir at BC Hydro. Due to the fact that the available recorded spills were only from 1984, the data used in our study for calculating the first four statistical moments and correlation coefficients between downstream inflows were from 1984 as well. The inflows are presented in figures 13 to 17 and the moments and correlation coefficients are respectively presented in tables 3 and 4.

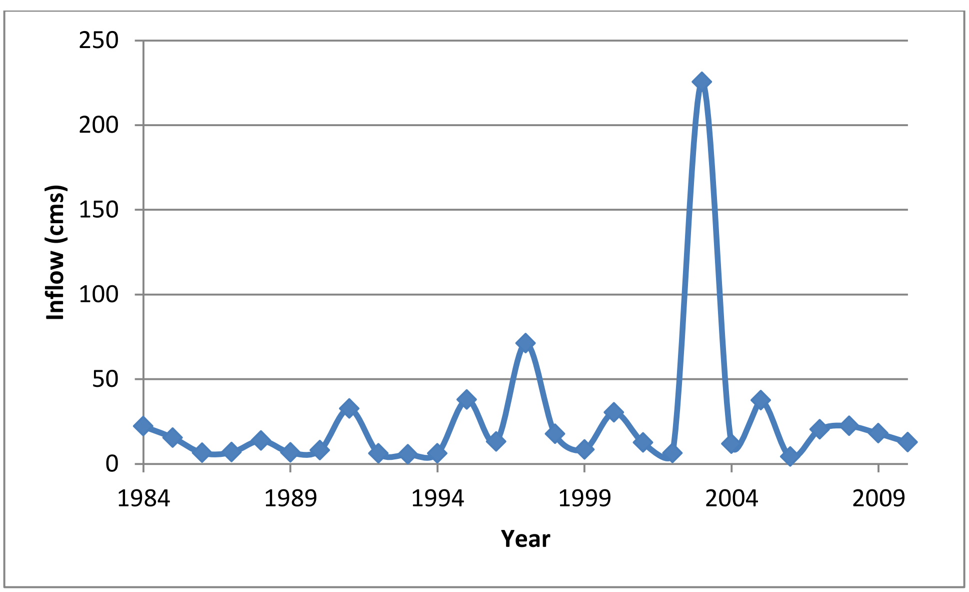


Figure 13: Inflows downstream of Daisy Lake reservoir on October 17

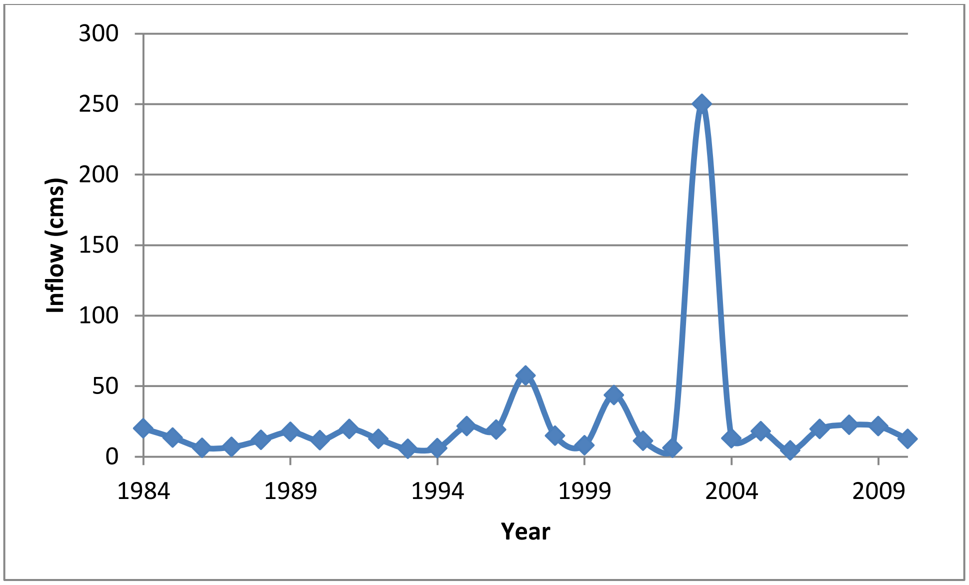


Figure 14: Inflows downstream of Daisy Lake reservoir on October 18

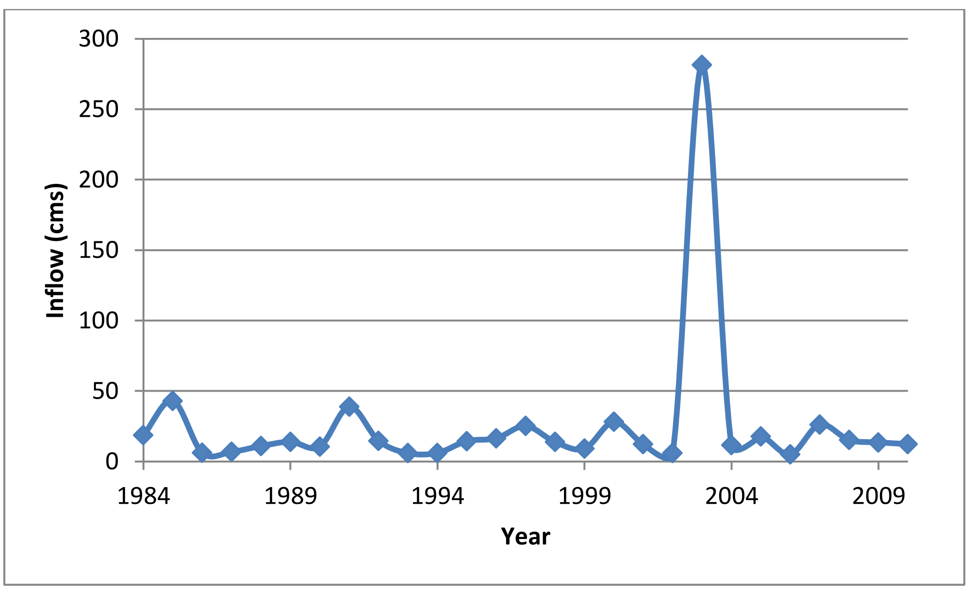


Figure 15: Inflows downstream of Daisy Lake reservoir on October 19

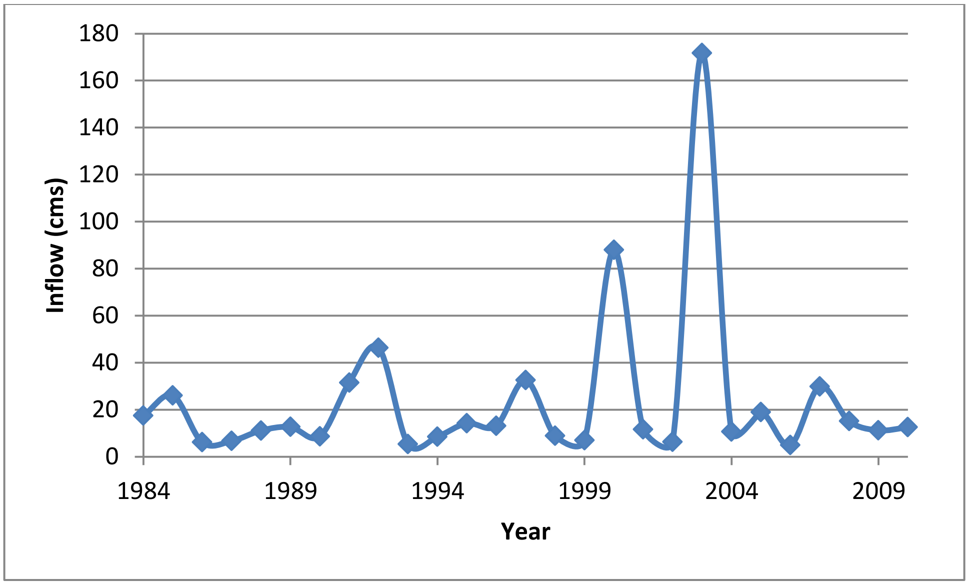


Figure 16: Inflows downstream of Daisy Lake reservoir on October 20

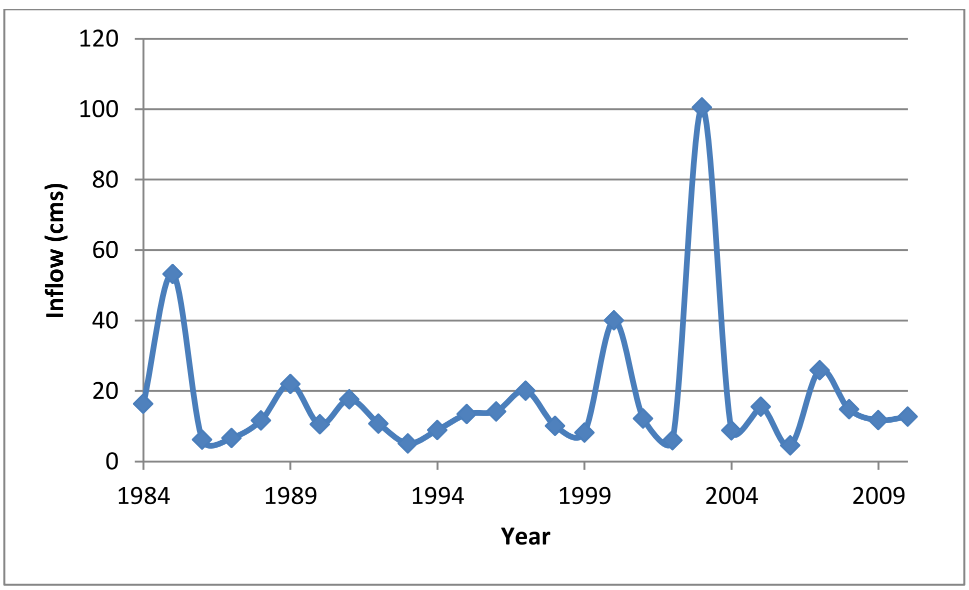


Figure 17: Inflows downstream of Daisy Lake reservoir on October 21

Table 3: Statistical moments of historical inflows downstream of Daisy Lake reservoir

Statistical Moment	Mean	SD	Skewness	Kurtosis
17-Oct	25.10	42.58	4.34	20.43
18-Oct	24.95	46.42	4.72	23.42
19-Oct	25.29	52.08	4.93	25.01
20-Oct	23.56	34.25	3.59	14.23
21-Oct	18.05	19.62	3.30	12.37

Table 4: Correlation coefficients between historical inflows downstream of Daisy Lake reservoir

Date	17-Oct	18-Oct	19-Oct	20-Oct	21-Oct
17-Oct	1.00	0.98	0.96	0.88	0.85
18-Oct	0.98	1.00	0.98	0.92	0.88
19-Oct	0.96	0.98	1.00	0.91	0.91
20-Oct	0.88	0.92	0.91	1.00	0.90
21-Oct	0.85	0.88	0.91	0.90	1.00

3.1.2 Optimization Model

Analyzing different alternatives' performance over the entire set of objectives was carried out with developing an optimization model. The purpose of the optimization model is providing the Operation Planning Engineers (OPEs) with necessary information for analyzing the performance of each operational alternative on each objective and under each inflow scenario. The objectives of our study on Cheakamus River system include:

- Maximizing hydropower revenue generation at Cheakamus generating station

- Minimizing adverse environmental impacts such as fish habitat impact
- Minimizing adverse public image impacts such as negative media coverage
- Minimizing flood damages such as flood damage to residential properties

The optimization model was developed based on the Generation Operating Order (GOO) for Cheakamus Project. Cheakamus Project GOO is a document at BC Hydro that defines the operating requirements specifically for the Cheakamus project. Many of these requirements have been taken from pertaining water licenses and the Cheakamus River Water Use Plan (WUP). Cheakamus River WUP (BC Hydro, 2005) is a document developed on behalf of the Consultative Committee for the Cheakamus River Water Use Plan. This document possesses the essence of Integrated Water Resources Management in Cheakamus River system. A comprehensive explanation of this document is beyond the scope of our study.

Our optimization model is a single-objective model to maximize the power revenue generation while meeting all the requirements mentioned in Cheakamus Project GOO. These requirements are defined as hard constraints in the model. The water discharge at Brackendale area (the residential area analyzed in our study for flood damage impacts) is one of the variables of the model. In our study we define different operational alternatives with regard to the volume of water in the reservoir at the start of the high inflow period. We discretize this volume from the minimum to the target maximum that have been mentioned in the GOO. The performance of each alternative on the other objectives is determined with the use of the water discharge at Brackendale, determined by the optimization model, and the streamflow impact curves.

In the early analysis, we noticed that 2% of the inflow scenarios were much larger than the others. In accordance with Cheakamus Project GOO, the Daisy Lake reservoir should be kept above elevation 367.45 m from January 1 to October 31 to satisfy the minimum flows at Brackendale gauge. The elevation of 367.45 in Daisy Lake reservoir almost corresponds to the volume of 87 cmsd (obtained from the available data at BC Hydro). The operational alternatives of our study differ from each other in terms of the volume of water in the storage at the start of the high inflow event (October 17). Therefore, the most conservative alternative is where the volume of water is 87 cmsd on October 17. For the 2% outstanding inflow scenarios, the early analysis revealed that none of the alternatives, even the most conservative one, was able to reduce the amount of flood damage. This means that these inflow scenarios are so large that operational planning has little effect on their disastrous consequences and the maximum flood damage would happen regardless of how the reservoir is operated. After realizing this, through oral conversation with specialist engineers at BC Hydro another important piece of information was obtained. We realized that in accordance with the Cheakamus Project GOO, in October, operation planning engineers usually keep the reservoir level near target maximum level that is 373.5 m. This approximately corresponds to the volume of 300 cmsd (obtained from the available data at BC Hydro). Therefore, in accordance with the OPE's proposal, we decided to diminish the scope of our study to the inflow scenarios that are neither too large (when the operation has no influence on their consequences), nor too small that cannot be defined as a high inflow event in the Cheakamus River.

This at first seemed to be a very interesting analysis as the results could provide the operation planning engineers with very important information regarding the critical inflow scenarios. Therefore, analysis was carried out with the use of two optimization models (a deterministic model and an equivalent deterministic model) developed for the case study. We realized that for the five-day inflow sequences from October 17 to October 21, the inflow scenarios that have a magnitude of 300 to 350 cms on October 17 are the critical scenarios for planners. Depending on the selected operation, flood damage could range from none to significant for these scenarios. Afterwards 10000 inflow scenarios were generated with the use of historical data and the 57 that took place within the critical range were identified. With the use of the optimization models, these 57 inflow scenarios were analyzed for 5 different operational alternatives.

Afterwards, we decided that for the specific goals of our study we needed to cover the entire possible range of inflows. Consequently 100 inflow scenarios were generated as explained in the previous section and a unique optimization model was developed based on Cheakamus Project GOO. The model includes a non-linear constraint.

A version of AMPL modeling language (Fourer et al., 2003) available at BC Hydro was used to develop the first two optimization models; and the early analysis to determine the critical inflow scenarios for OPEs was done with the use of the linear solver at BC Hydro. To do the analysis for the set of inflows of 100, which cover the entire range of possible inflows, the MINOS solver (NEOS Server, 2012) was used. A mathematical formulation of the model is presented next.

3.1.2.1 Sets

T = Set of time steps (days),

M = Set of months.

3.1.2.2 Parameters

I_t = Inflow into Daisy Lake Reservoir in cms at time 't',

IB_t = Inflow downstream of Daisy Lake Reservoir to Brackendale in cms at time 't',

P = Market price for energy,

Q_{max} = Maximum turbine discharge in cms,

Q_{min} = Minimum turbine discharge in cms,

$Smin_m$ = Minimum spill immediately downstream of the dam in cms at month 'm',

QB_{max} = Maximum discharge at Brackendale in cms,

$QBmin_m$ = Minimum discharge at Brackendale in cms at month 'm',

V_0 = Initial storage volume in cmsd,

G_{max} = Maximum generation limit in MW,

G_{min} = Minimum generation limit in MW,

HK = Conversion factor between turbine discharge and power generation in MW/cms,

VG1 = Minimum required reservoir storage for maximum 75 MW generation, in cmsd,

VG2 = Minimum required reservoir storage for maximum 100 MW generation, in cmsd,

VG3 = Minimum required reservoir storage for generation with no restriction, in cmsd,

VN_{max} = Normal maximum reservoir storage in cmsd,

$VNmin_m$ = Normal minimum reservoir storage in cmsd at month 'm',

NoTS = No of time steps,

MES = Maximum ending storage in cmsd.

3.1.2.3 Decision Variables

V0 = Initial storage volume in cmsd,

Q_t = Turbine discharge in cms at time 't',

QB_t = Discharge at Brackendale in cms at time 't',

S_t = Spill in cms at time 't',

G_t = Generation in MW at time 't',

V_t = Reservoir storage in cmsd at time 't'.

3.1.2.4 Constraints

Initial volume constraint:

$V0 = V_0;$ (3.1)

Continuity constraint:

$V_{t-1} + I_t - S_t - Q_t = V_t;$ (3.2)

Turbine limit constraint:

$QBmin_m \leq Q_t \leq QB_{max}$; (3.3)

Minimum spill constraint:

$Smin_m \leq S_t$; (3.4)

Brackendale continuity constraint:

$QB_t = S_t + IB_t$; (3.5)

Brackendale discharge constraint:

$QBmin_m \leq QB_t \leq QB_{max}$; (3.6)

Generation limit constraint:

$G_{min} \leq G_t \leq G_{max}$; (3.7)

Power generation constraint:

$G_t = Q_t * HK$; (3.8)

Exceptional generation ranges constraints:

$$G_t \leq \begin{cases} V_t < VG1 & 0 \\ V_t < VG2 & 75 \\ V_t < VG3 & 100 \\ V_t > VG3 & 155 \end{cases} \qquad (3.9)$$

Normal reservoir operations constraint:

$VNmin_m \leq V_t \leq VN_{max}$; (3.10)

Ending storage constraint:

$V_T \leq MES$. (3.11)

3.1.2.5 Objective Function

Maximize Benefits:

$$\sum_t P * G_t * 24 \qquad (3.12)$$

3.1.3 Risk-Taking Level of Decision Makers

Extracting the desirable risk-taking level of decision makers on each objective requires comprehensive conversations with the decision makers so that they can be provided with the information on the existing risks and possible consequences. Moreover, after the framework has created recommendations for implementation, decision makers will consider their preferences and depending on their risk-proneness or risk-averseness might refuse to implement the recommended alternative and request development of new alternatives. For the purposes of our study, we assumed a set of risk-taking levels and also examined three more sets; one, more risk-prone, one, more risk-averse, and one, very conservative. For each alternative, the related risk-taking level to each objective, except hydropower revenue generation, will be used in the Brackendale outflow CDFs to extract the related outflows from October 17 to October 21; and these outflows will be used to extract the corresponding impacts from streamflow impact curves and the impacts will be input into MCDM software package. Note that for extracting the environmental, flood damage, and public image impacts from streamflow impact curves, the highest outflow from October 17 to October 21 will be used.

For hydropower revenue generation, the risk-taking level and the revenue generation CDFs will be used to extract the amount of revenue generation. Furthermore, as opposed to the other objectives, for hydropower revenue generation, the summation of generation from October 17 to October 21 is the value of the objective function of the optimization model that will be used to form revenue generation CDFs; and these CDFs will be used to generate the inputs into MCDM software package.

3.1.4 Streamflow Impact Curves

In order to translate the water discharges at Brackendale into alternatives' performance over the objectives of our study, except maximizing hydropower revenue generation, we needed to utilize a number of streamflow impact curves. These curves represent the relationship between streamflow at Brackendale and the alternatives' performance.

To show the relationship between Brackendale flow and adverse environmental impacts, the proxy fish habitat impact curve was regenerated from Zaman (2010) as shown in figure 18. For flood damage, the pertaining proxy curve was regenerated from Sadeque (2010) as presented in figure 19. The proxy relationship between adverse public image impacts and Brackendale flow was approximated with the use of the available information at BC Hydro and also the flood damage and environmental proxy impacts curves. We used media coverage and linguistic variables to define this relationship as presented in table 5.

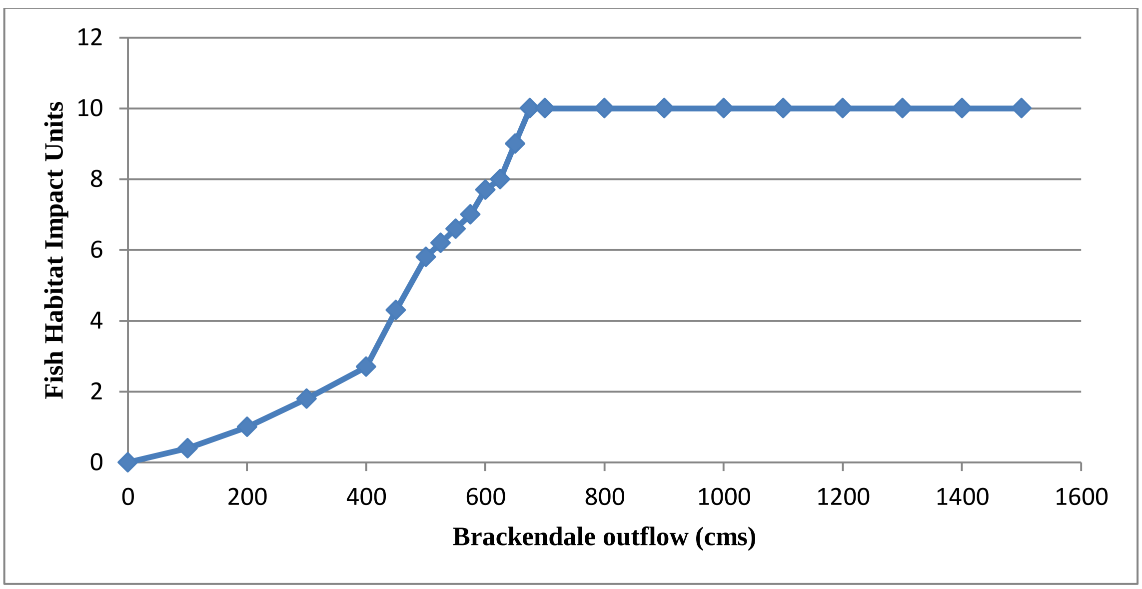


Figure 18: Adverse environmental impacts proxy curve (regenerated from Zaman, 2010)

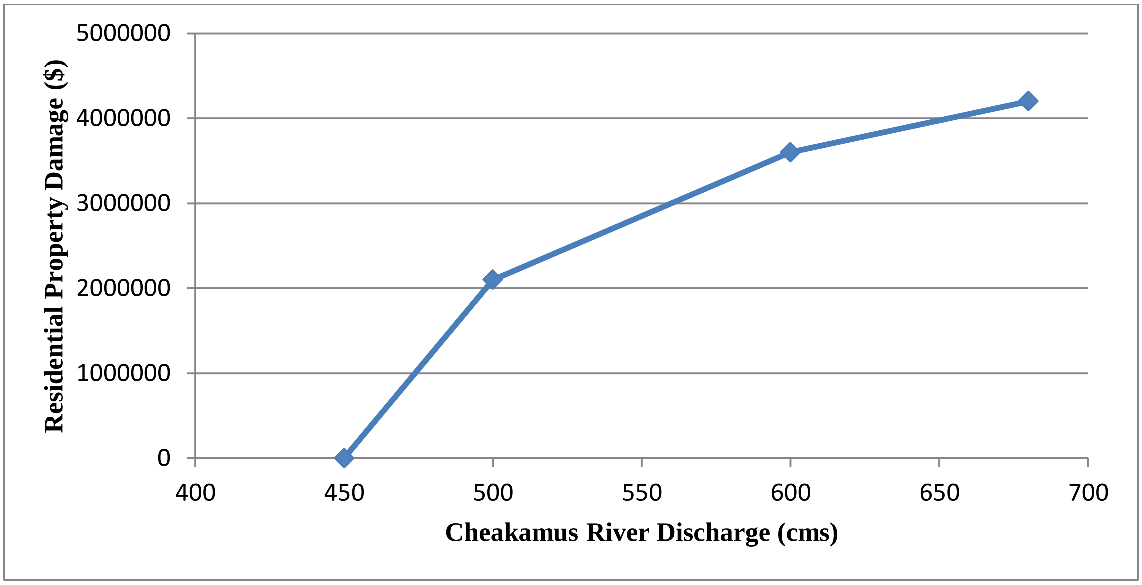


Figure 19: Flood damage proxy curve (regenerated from Sadeque, 2010)

Table 5: Adverse public image impacts table

Brackendale Outflow (cms)	Media Coverage
680	Extremely High
625	Very High
575	High
525	Medium
500	Low
450	Very Low
400	None

3.1.5 Multi-Criteria Decision Making (MCDM)

After preparing the necessary information and data to form the MCDM problem, choosing a compatible MCDM software package with our problem was the next step of our study. After reviewing the work by Zaman (2010) on MCDM software packages, Logical Decisions for Windows (LDW) was chosen as one of the candidates. Moreover, based on the previous experience in working with Expert Choice and its qualities, it was also seriously considered as another candidate. After analyzing the qualities of both software packages and the type of our MCDM problem, Logical Decisions for Windows was selected for assessing and ranking the alternatives of the study.

In order to define the problem in LDW, the first step was defining the alternatives. Alternatives set of the Cheakamus River study consists of five alternatives that differ from each other in terms of the volume of stored water in the reservoir at the start of the high inflow period. In order to create these alternatives, the reservoir storage was discretized from minimum to target maximum as described in Cheakamus Project GOO as follows:

- Alternative 1: Starting storage volume = 87 cmsd
- Alternative 2: Starting storage volume = 150 cmsd
- Alternative 3: Starting storage volume = 200 cmsd
- Alternative 4: Starting storage volume = 250 cmsd
- Alternative 5: Starting storage volume = 300 cmsd

Next step was defining the goals hierarchy of the problem. In order to do this, more general concerns are placed at the top of the hierarchy and more specific concerns at the bottom. The overall goal of our study is finding the best operational alternative and this is carried out with comparing the alternatives' hydropower revenue generation, environmental impacts, public image impacts, and flood damage. Accordingly, the created goals hierarchy in LDW is presented in figure 20.

Defining measures for evaluating alternatives was the next step of forming the problem in LDW. For our problem, these measures consisted of revenue gain or loss (in dollars) for hydropower revenue generation, fish habitat impact for environmental impacts (in units), media coverage for public image impacts (in a linguistic scale), and residential property damage for flood damage (in dollars).

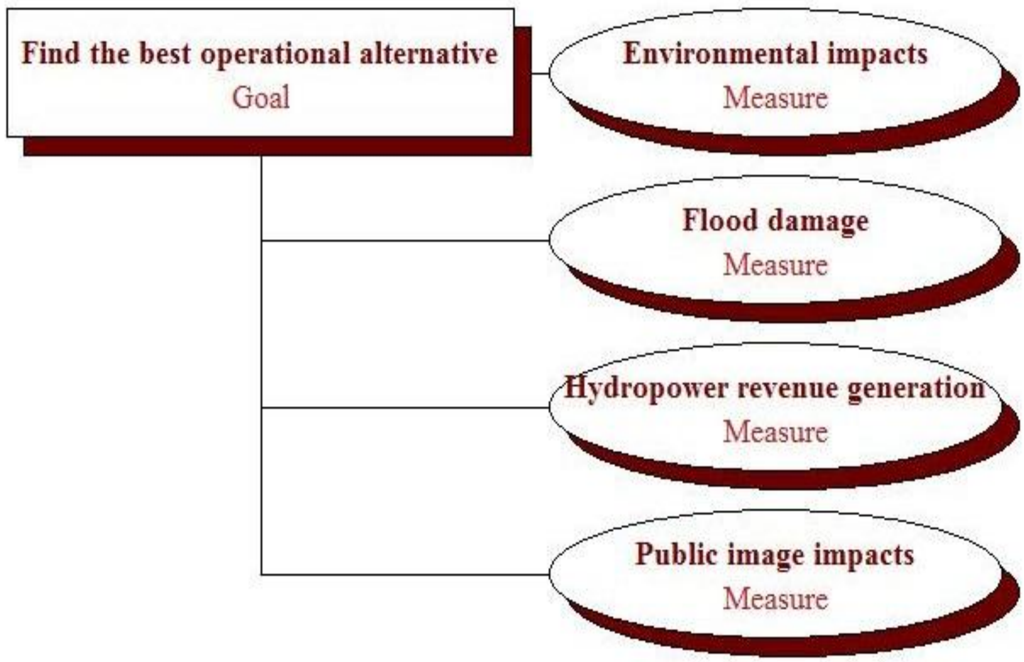


Figure 20: Cheakamus River system problem goals hierarchy in LDW

Afterwards we needed to enter the data for alternatives. This process was carried out with the use of the generated cumulative distribution functions from the outputs of the optimization model and the idea in NASA's RIDM handbook. Accordingly, the risk taking level of decision makers on each objective was the basis for finding the corresponding points in the related cumulative distribution functions. For hydropower revenue generation, the extracted point was input to LDW; and for the rest of the objectives, the extracted points were translated into performances with the use of the streamflow impact curves. The created performance matrix for each risk-taking attitude was inserted into LDW separately; and later, the problem was solved for each risk-taking attitude separately. Figures 21 to 24 respectively display the LDW performance matrices for neutral, risk-prone, risk-averse, and very conservative attitudes. The values in these matrices are explained in detail in section 4.5.

Matrix: Find the best operational alternative Goal

	Environmental impacts	Flood damage	Hydropower revenue generation	Public image impacts
Operational Alternative 1	0.2	0	528262	None
Operational Alternative 2	0.205	0	928942	None
Operational Alternative 3	0.205	0	1.24694e+006	None
Operational Alternative 4	0.205	0	1.56494e+006	None
Operational Alternative 5	0.21	0	1.85681e+006	None

Figure 21: LDW decision making matrix for neutral risk-taking attitude

Matrix: Find the best operational alternative Goal

	Environmental impacts	Flood damage	Hydropower revenue generation	Public image impacts
Operational Alternative 1	0.1	0	693240	None
Operational Alternative 2	0.105	0	1084380	None
Operational Alternative 3	0.105	0	1402380	None
Operational Alternative 4	0.105	0	1720380	None
Operational Alternative 5	0.11	0	1860000	None

Figure 22: LDW decision making matrix for risk-prone attitude

Matrix: Find the best operational alternative Goal

	Environmental impacts	Flood damage	Hydropower revenue generation	Public image impacts
Operational Alternative 1	0.55	99960	373650	None
Operational Alternative 2	0.94	108780	774330	None
Operational Alternative 3	1.32	115920	1092326	None
Operational Alternative 4	1.72	123060	1410326	None
Operational Alternative 5	2.2	132720	1728326	None

Figure 23: LDW decision making matrix for risk-averse attitude

Matrix: Find the best operational alternative Goal

	Environmental impacts	Flood damage	Hydropower revenue generation	Public image impacts
Operational Alternative 1	4.45	4200000	150541.2	Very Low
Operational Alternative 2	4.6	4200000	551221.2	Very Low
Operational Alternative 3	4.63	4200000	869221.2	Very Low
Operational Alternative 4	4.66	4200000	1187221	Very Low
Operational Alternative 5	4.69	4200000	1505221	Very Low

Figure 24: LDW decision making matrix for very conservative attitude

Converting different levels on each measure into common units with the use of Single-measure Utility Functions (SUFs) was the next step of the research. The utility of zero is assigned to the least preferred level on each measure and the utility of one to the most preferred level. For the other levels between the least and most preferred levels, we can define as many levels as desired and even use non-linear SUFs. For hydropower revenue generation, environmental impacts, and flood damage, we used linear SUFs; and for public image impacts, due to the fact that linguistic variables were used to analyze the performance of alternatives on this objective, direct assessment method was used to do the common unit conversion. In this method, a utility is assigned to each linguistic variable. Figures 25, 26, and 27 respectively show the linear SUFs for hydropower revenue generation, environmental impacts, and flood damage; and figure 28 shows the direct assessment for public image impacts.

Defining the objectives' relative importances was the next and last task in order to completely define the MCDM problem in LDW. This could be done with the use of a number of approaches in LDW including tradeoffs, direct entry, smart method (swing weights), smarter method (rank order), pairwise weight ratios, and analytic hierarchy process. For our study, we used the direct entry approach to define the relative importance of each objective. Figure 29 displays the assigned weights to each objective.

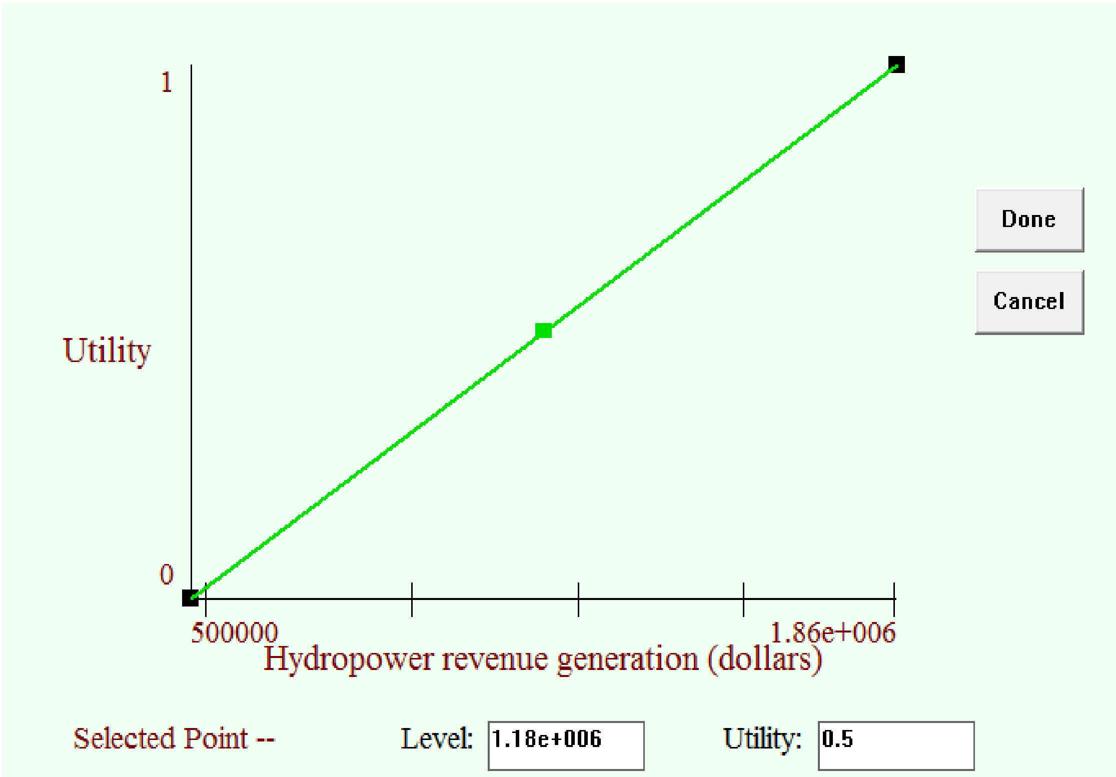


Figure 25: Hydropower revenue generation SUF

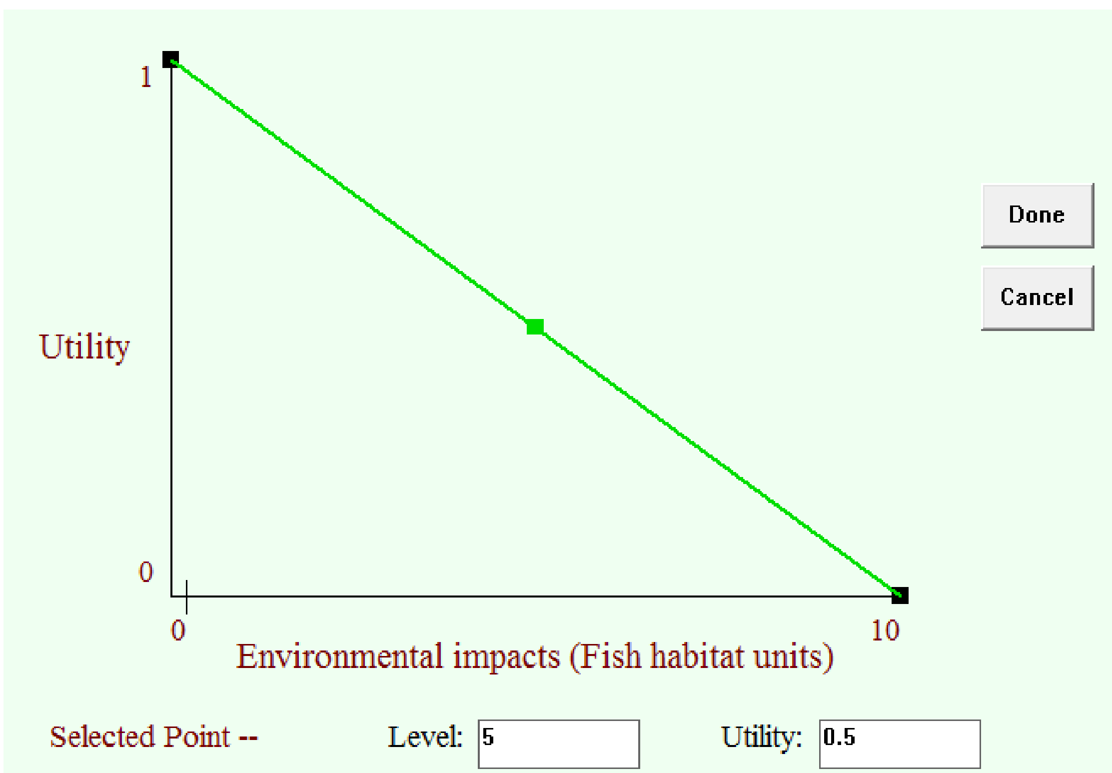


Figure 26: Environmental impacts SUF

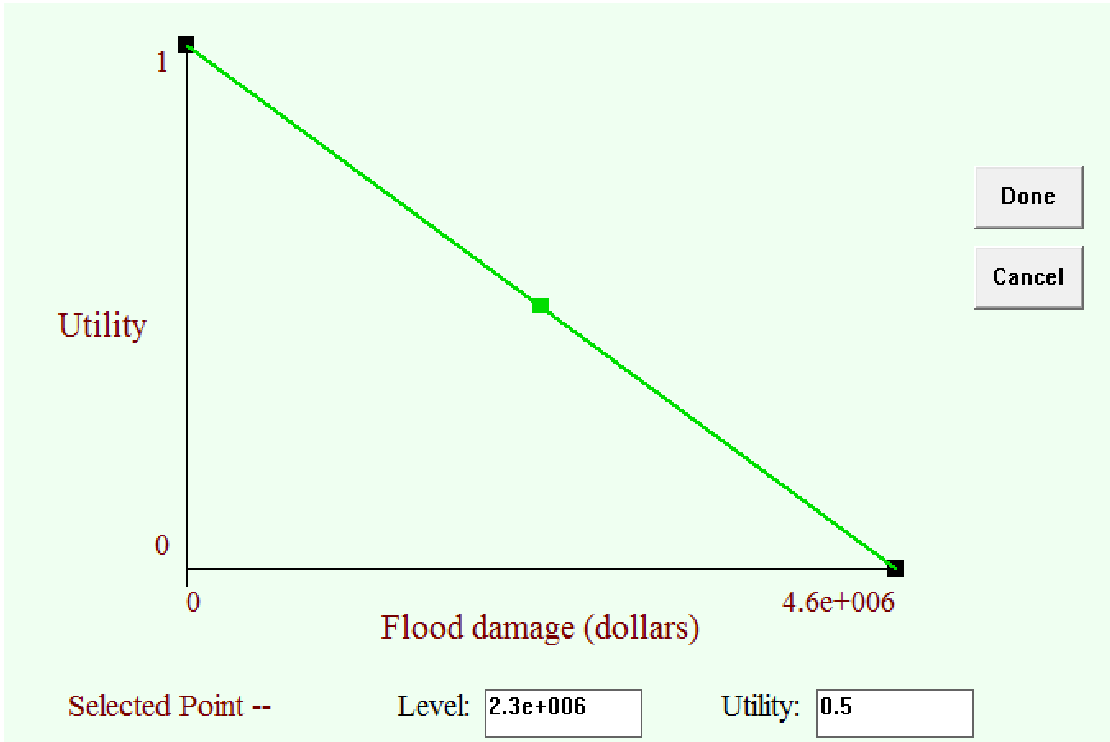


Figure 27: Flood damage SUF

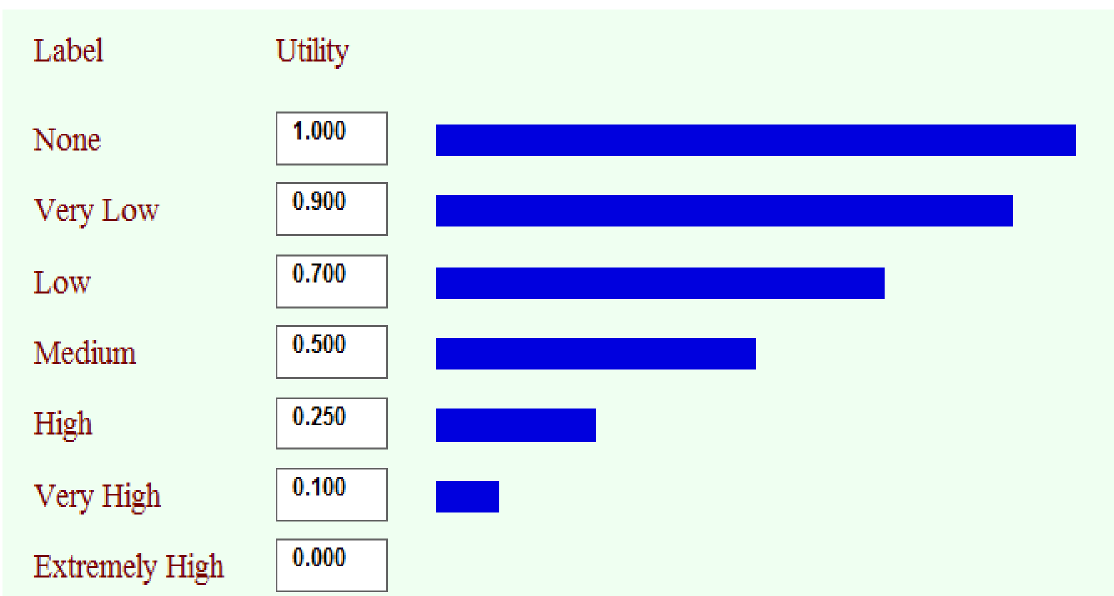
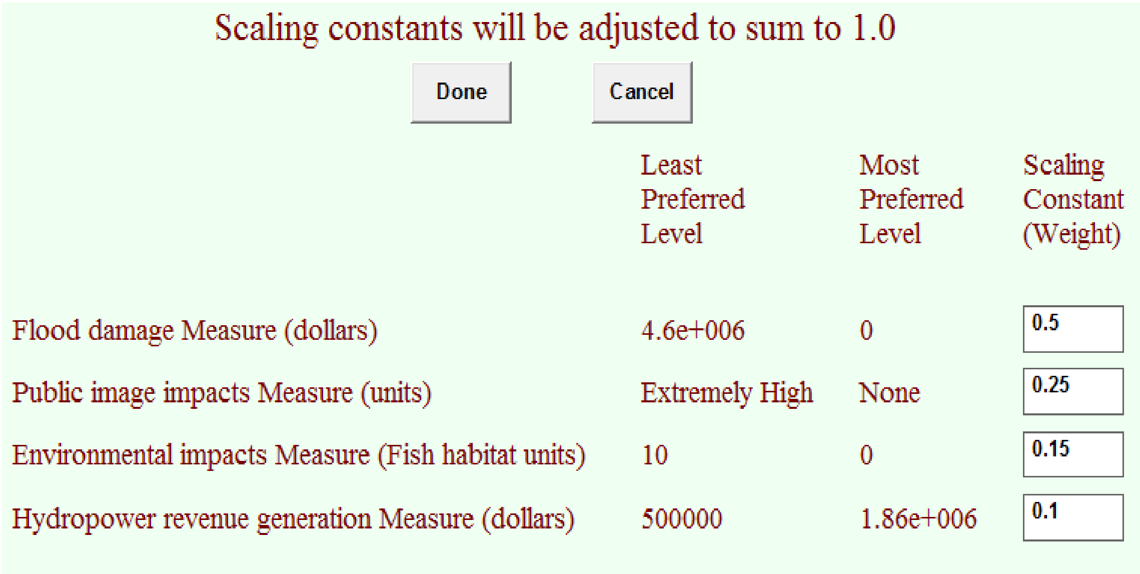


Figure 28: Public image impacts SUF



Scaling constants will be adjusted to sum to 1.0

Done Cancel

	Least Preferred Level	Most Preferred Level	Scaling Constant (Weight)
Flood damage Measure (dollars)	4.6e+006	0	0.5
Public image impacts Measure (units)	Extremely High	None	0.25
Environmental impacts Measure (Fish habitat units)	10	0	0.15
Hydropower revenue generation Measure (dollars)	500000	1.86e+006	0.1

Figure 29: Assigned weights to the objectives

Chapter 4: Case Study and Results

In this chapter we present the results of applying the developed RIDM framework in the previous chapter to the Cheakamus River system in British Columbia. At first, we give some background information on Cheakamus River System. Next, as the framework consists of multiple elements and several tools and techniques, we present the results of applying the framework to our case study in a number of subsection as the application of the framework to the case study is a step by step procedure.

4.1 Background

The Cheakamus basin is a major tributary of Squamish River. The Squamish River has experienced several major floods in the past century such as flooding events in 1921, 1940, 1955, 1968, 1975, 1980-1984, 1989-1991, and 2003. These floods have caused millions of dollars of damage and indirect loss (Journeay, 2005).

Daisy Lake Reservoir is located on Cheakamus River in south of Whistler and immediately north of Garibaldi in the Sea to Sky Corridor of south-western British Columbia. The Daisy Lake dam was built in the 1950s and the created reservoir merged the former natural Daisy Lake and another lake named Shadow Lake. Water is diverted from Daisy Lake reservoir to Cheakamus powerhouse on the Squamish River via a tunnel beneath the mountain range that divides the two rivers.

The Daisy dam and reservoir are of relatively small size. The watershed area is about 1,070 square kilometres and its highest elevation is 2,300 meters above sea level at its headwaters, dropping down to 30 meters above sea level at its confluence with the Squamish River (BC Hydro, 2005).

The Cheakamus power plant is located on the Squamish River and water is diverted from Daisy Lake reservoir to the plant by a 10.8 km long power tunnel (See figure 30). A number of private and public properties are located downstream of Daisy Dam. In 2003, from October 16th to October 19th, the towns of Squamish and Pemberton and the areas in between experienced record rainfall (Zaman et al., 2010).

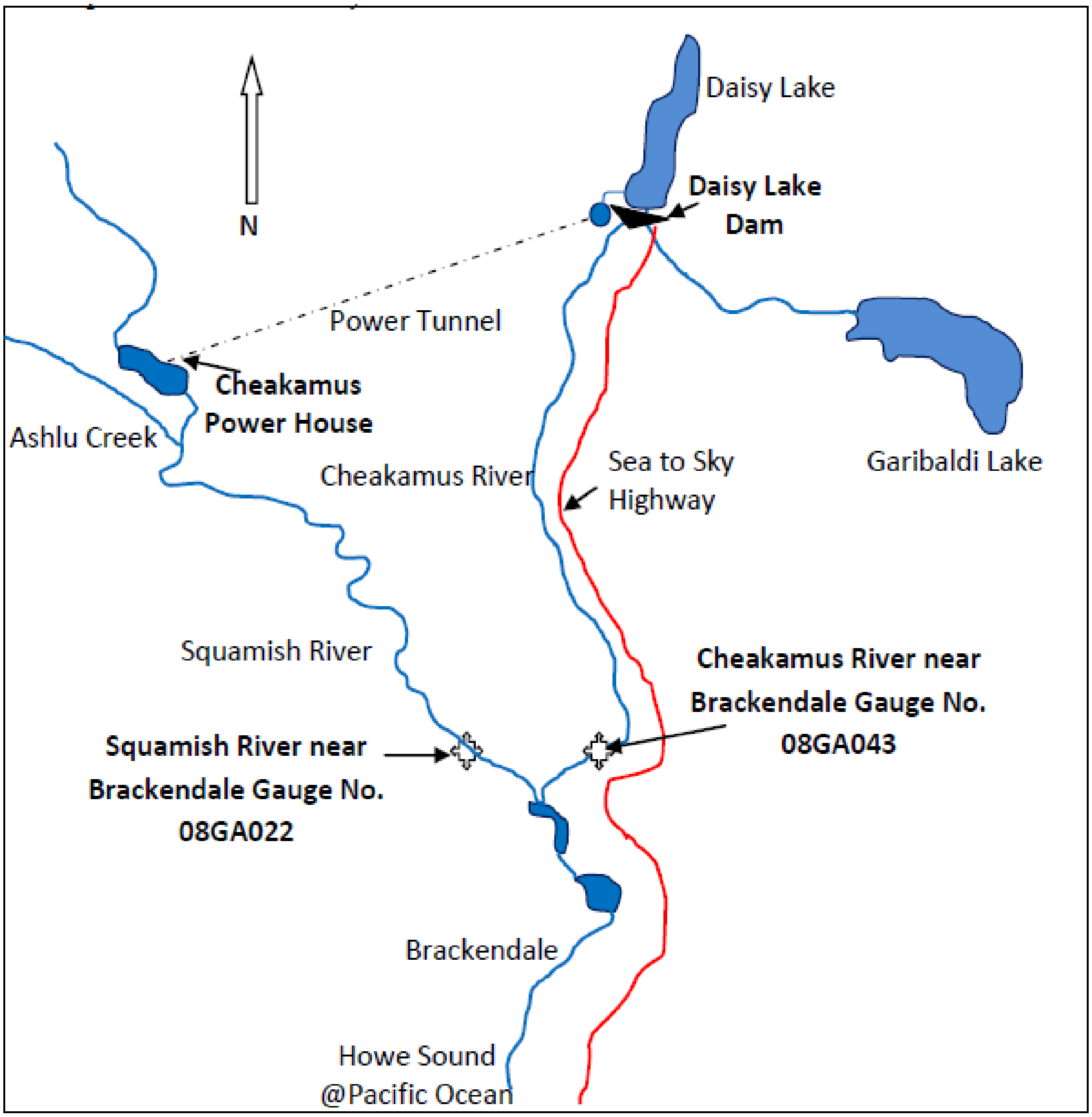


Figure 30: Cheakamus River system (Zaman, 2010)

4.2 Scenario Generation

For scenario generation in our study, we used the developed algorithm and computer code by Hoyland et al. (2003) that can be used to generate scenarios with similar statistical moments to the historical (input) data with some allowance for difference. This algorithm does not require the marginal distributions to be known. Kaut and Lium (2007) published a paper on generalizing the algorithm so that in the cases where the marginal distributions are known, they can be described directly instead of describing them using their moments. In our study we used the original Moment Matching algorithm and used the historical inflows moments and correlations instead of marginal distributions. With the use of Moment Matching algorithm and the calculated historical moments and correlation coefficients, 100 equally-probable five-day inflow scenario sequences were generated for the period of October 17 to October 21 for both Daisy Lake reservoir and downstream of the reservoir as shown in figures 31 and 32.

As can be seen, 2 of the 100 generated scenarios show a much higher magnitude than the others. Our explanation for this is that as there is only 1 outstanding high magnitude inflow event (in 2003) in the historical data (44 years for Daisy Lake and 27 years for downstream) used to generate scenarios, for 100 scenarios that replicate the historical data moments and correlations, only 2 or 3 outstanding events would be expected. The generated scenarios form part of the inputs of the optimization model of our study.

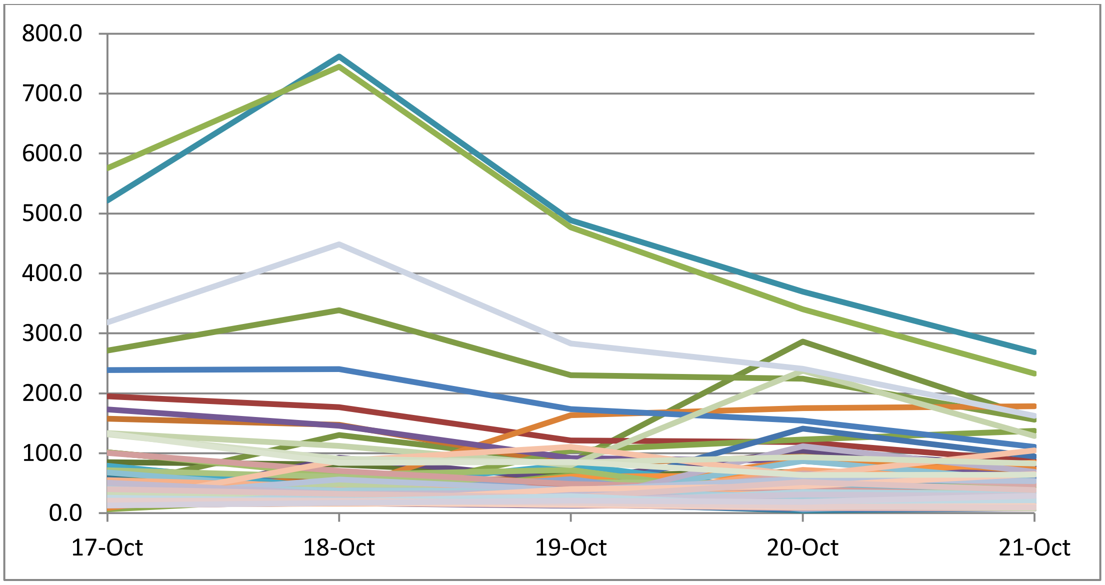


Figure 31: Five-day inflow scenario sequences for Daisy Lake reservoir (cms)

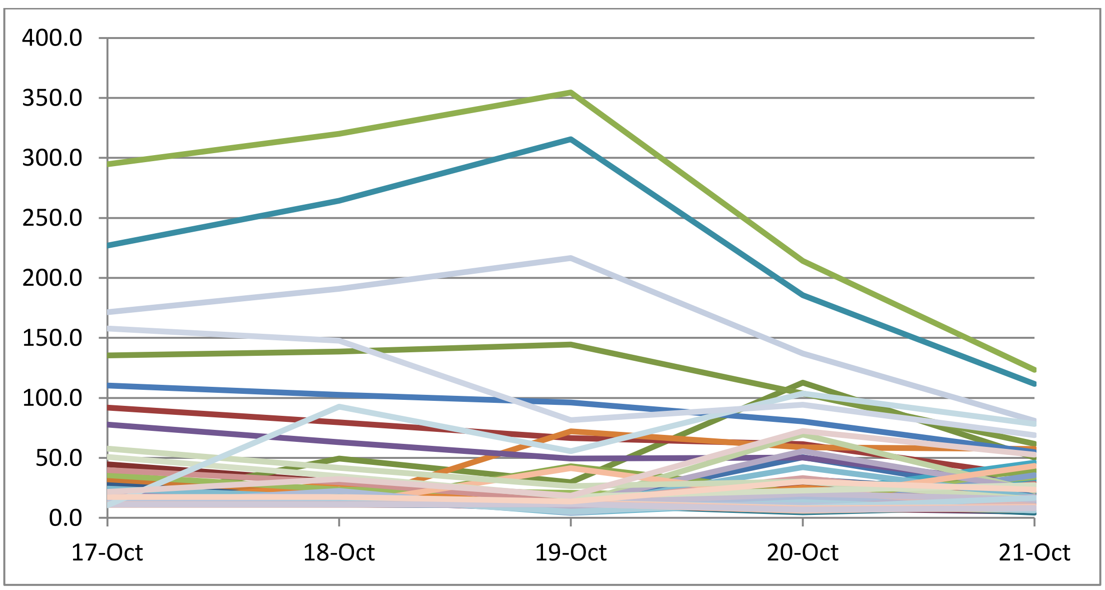


Figure 32: Five-day inflow scenario sequences for downstream of Daisy Lake reservoir (cms)

4.3 Optimization Model

The optimization model was run for each operational alternative over the entire set of inflows of 100. The alternatives were different in terms of the volume of water in the reservoir on October 17, which was discretized from the minimum to the target maximum mentioned in Cheakamus Project GOO. Accordingly, the volume of water in the reservoir on October 17 was 87, 150, 200, 250, and 300 cmsd respectively for alternatives 1 to 5. For each combination of a specific alternative and a specific inflow scenario, the model generated a specific operating policy. Note that when we were running the model for different alternatives and inflow scenarios, there were cases in which the model simply failed to generate outputs. Given the fact that the model had to satisfy the requirements mentioned in the GOO (the constraints of the model) and also the fact that the generated inflow scenarios must have all been considered, regardless of how low or high their probability of occurrence might have been, we needed to find the reason why the model failed. The failure obviously occurred due to the fact that for those specific combinations of alternatives and inflow scenarios, there was no feasible operating policy that could satisfy all of the hard constraints of the model. In order to resolve this problem, whenever the failure occurred, we tried running the model again with a higher value allowed for maximum discharge at Brackendale. This value was increased just enough to enable running the model without failure and then it was documented. To better understand the dynamic of the optimization model, we try to explain the role of the value of maximum discharge at Brackendale in our model. The value of maximum discharge at Brackendale is either directly or indirectly connected with the constraints of the model. It is directly connected with the Brackendale discharge constraint (equation 3.6). The Brackendale discharge constraint is concerned with the variable of discharge at Brackendale; and as can be seen in Brackendale continuity constraint (equation 3.5), this variable is connected with the spill variable. Moreover, the continuity constraint (equation 3.2) shows that spill is connected with the variables of turbine discharge and reservoir storage. The power generation constraint (equation 3.8) also shows the connection between turbine discharge and the variable of generation. Overall, the optimization model includes multiple variables and constraints that generate a complicated dynamic to solve the problem and find the optimal value for the objective function of the model.

The values of the other parameters of the model, except inflows that are presented in figures 31 and 32, are presented below:

Market price for energy = $100/MWh,

Maximum turbine discharge = 65 cms,

Minimum turbine discharge = 0 cms,

Minimum spill immediately downstream of the dam in cms =

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5	5	5	7	7	7	7	7	7	7	3	3

Minimum discharge at Brackendale in cms =

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
15	15	15	20	20	20	38	38	20	20	15	15

Initial storage volume = 300 cmsd,

Maximum generation limit = 155 MW,

Minimum generation limit = 0 MW,

Conversion factor between turbine discharge and power generation = 2.65 MW/cms,

Minimum required reservoir storage for maximum 75 MW generation = 8.86 cmsd,

Minimum required reservoir storage for maximum 100 MW generation = 23.8 cmsd,

Minimum required reservoir storage for generation with no restriction = 63.5 cmsd,

Normal maximum reservoir storage = 427 cmsd,

Normal minimum reservoir storage =

January	87 cmsd
February	87 cmsd
March	87 cmsd
April	87 cmsd
May	87 cmsd
June	87 cmsd
July	87 cmsd
August	87 cmsd

September 87 cmsd

October 87 cmsd

November 8.86 cmsd

December 8.86 cmsd

No of time steps = 5,

Maximum ending storage = 427 cmsd.

The important outputs of the model for our problem include the value of objective function (maximizing hydropower revenue generation) and outflow at Brackendale. Figure 33 shows the histogram of revenue for the first operational alternative (V0 = 87 cmsd) and figure 34 shows the related cumulative distribution function. Revenue histograms and cumulative distribution functions for alternatives 2 to 5 are presented in figures 35 to 42. Note that the minimum revenue over all the alternatives and scenarios was almost 0.5 M$.

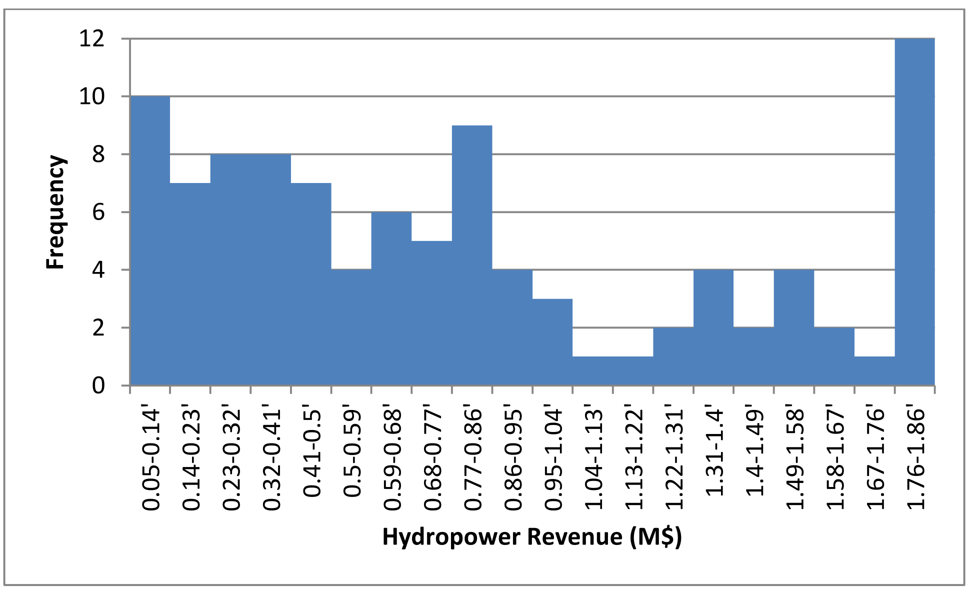


Figure 33: Hydropower revenue histogram for alternative 1

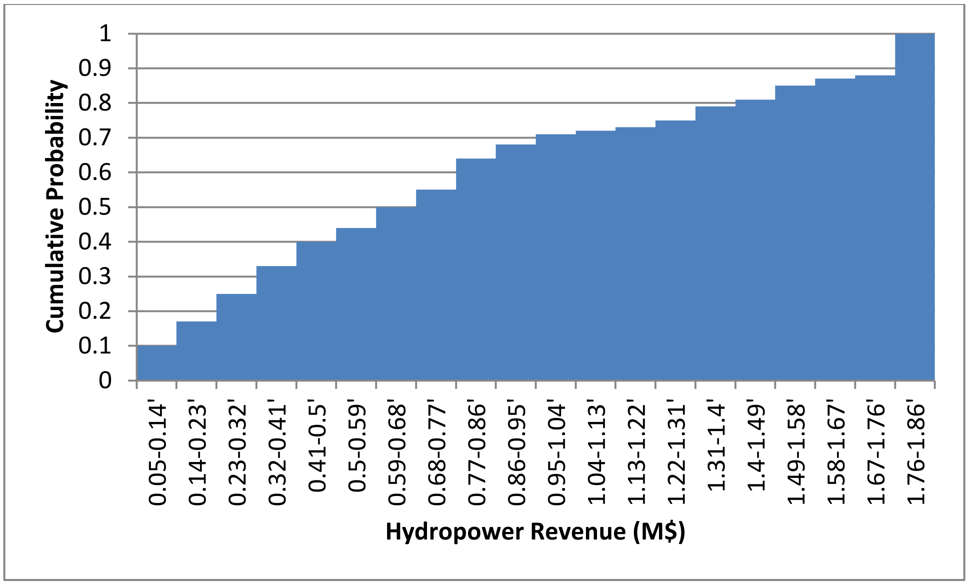


Figure 34: Hydropower revenue cumulative distribution function for alternative 1

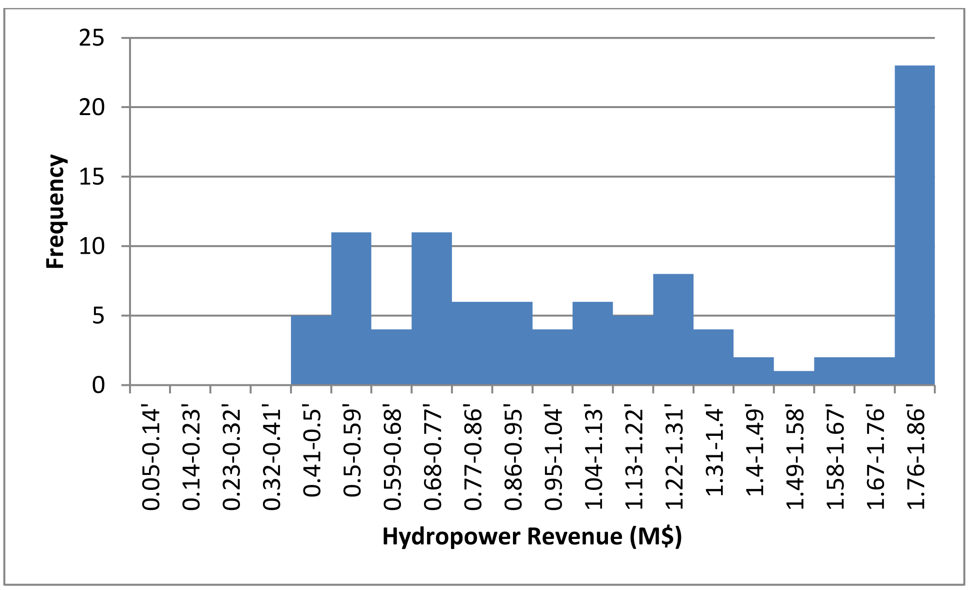


Figure 35: Hydropower revenue histogram for alternative 2

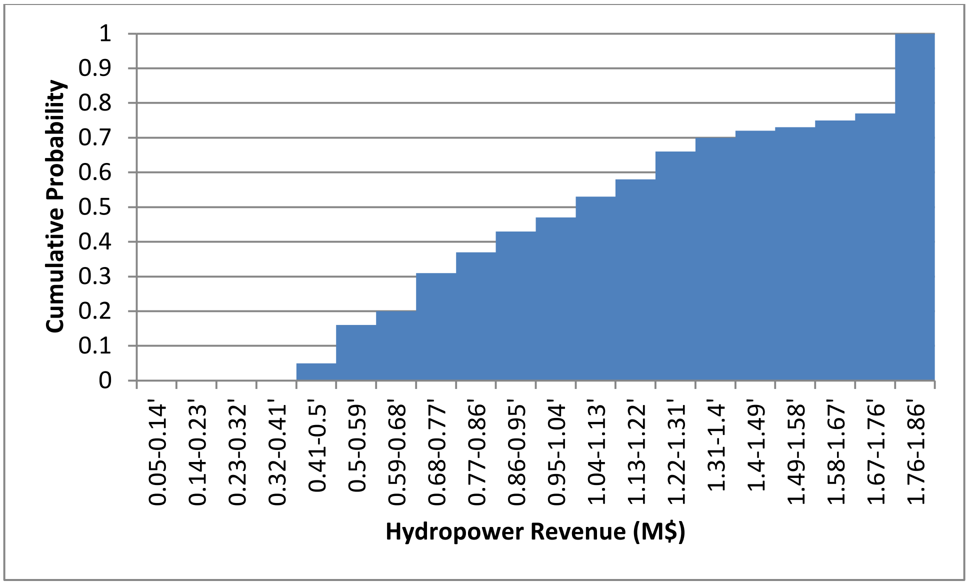


Figure 36: Hydropower revenue cumulative distribution function for alternative 2

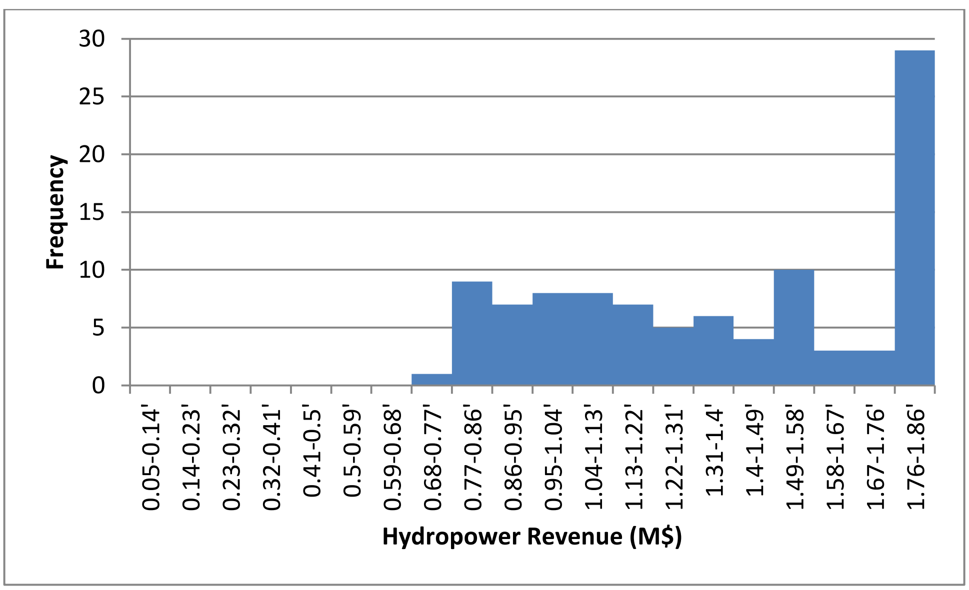


Figure 37: Hydropower revenue histogram for alternative 3

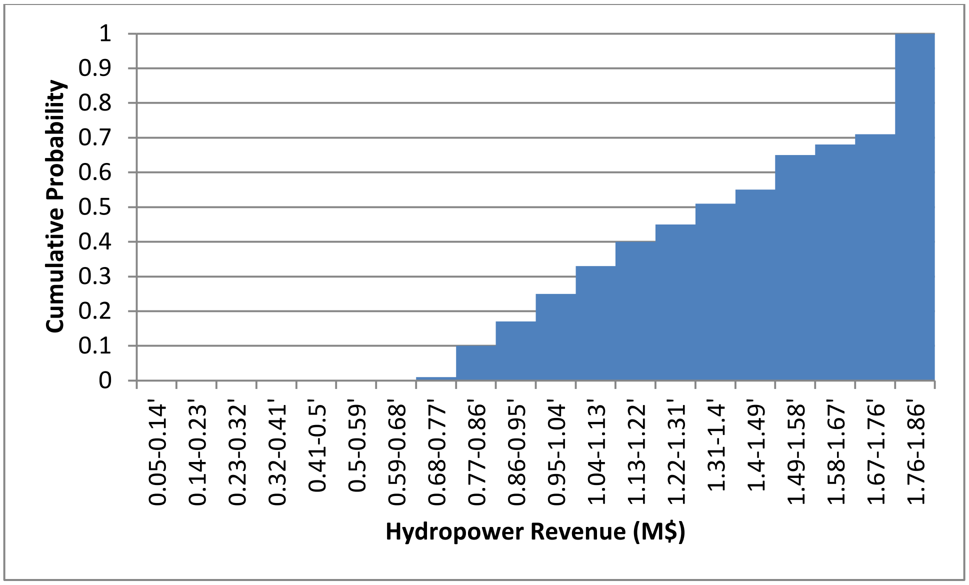


Figure 38: Hydropower revenue cumulative distribution function for alternative 3

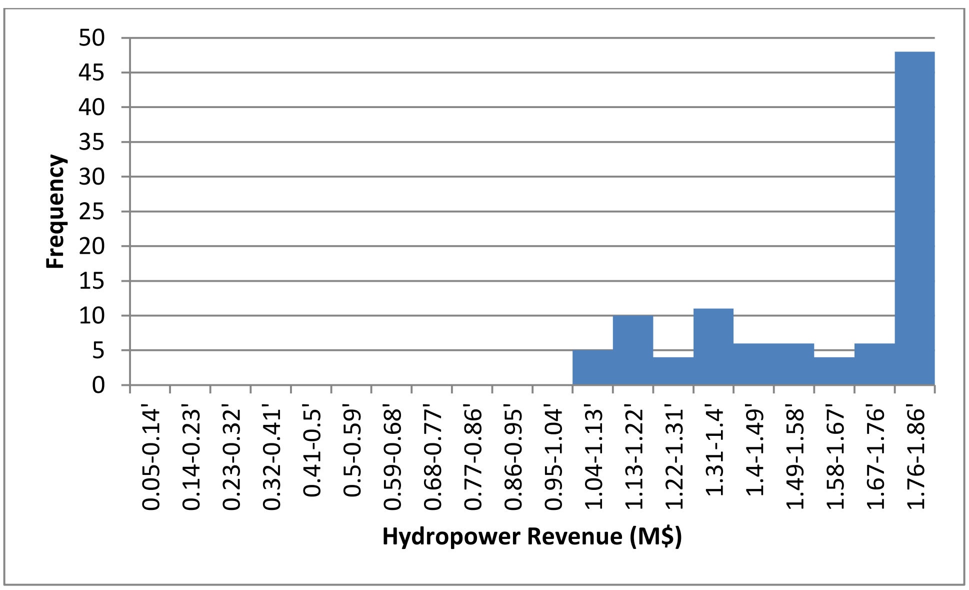


Figure 39: Hydropower revenue histogram for alternative 4

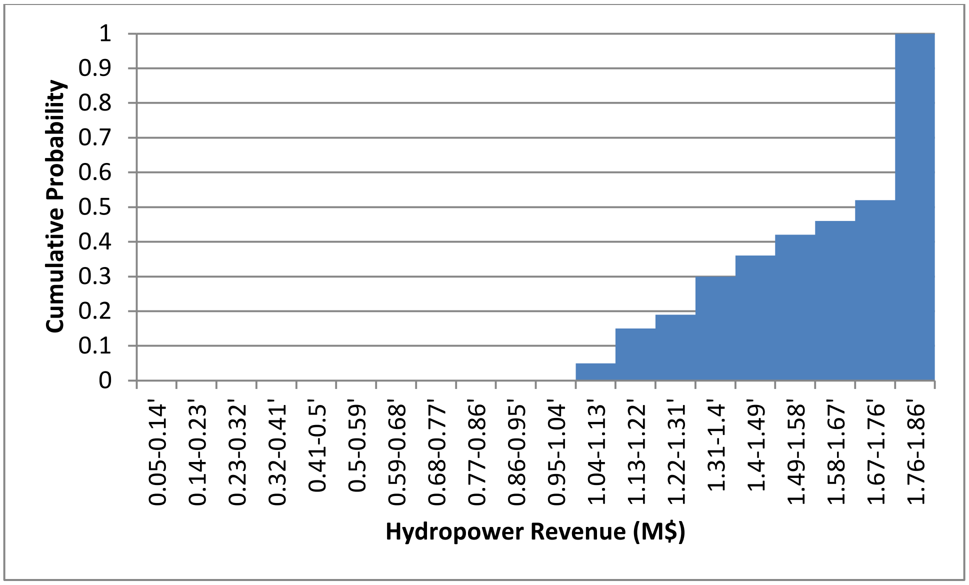


Figure 40: Hydropower revenue cumulative distribution function for alternative 4

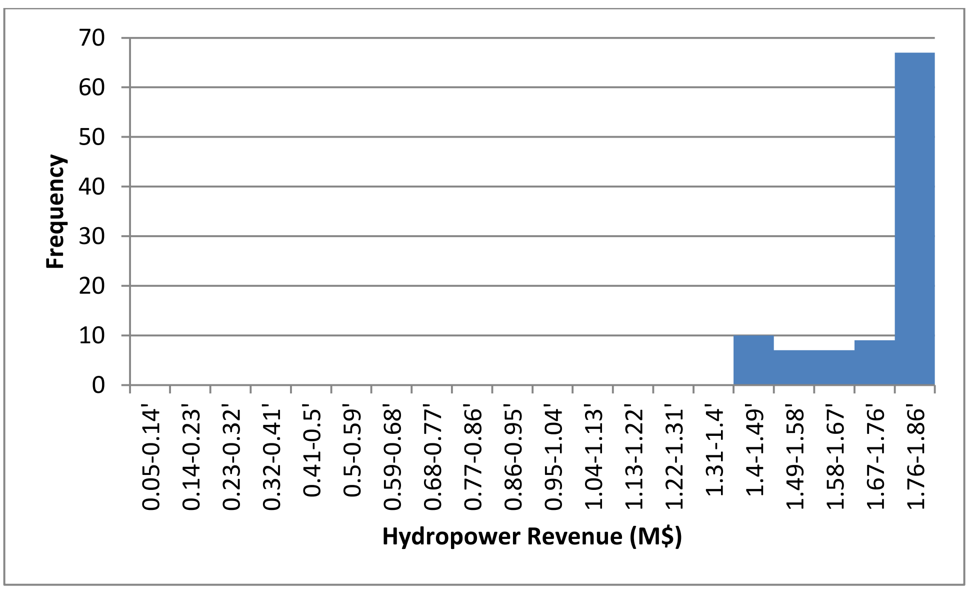


Figure 41: Hydropower revenue histogram for alternative 5

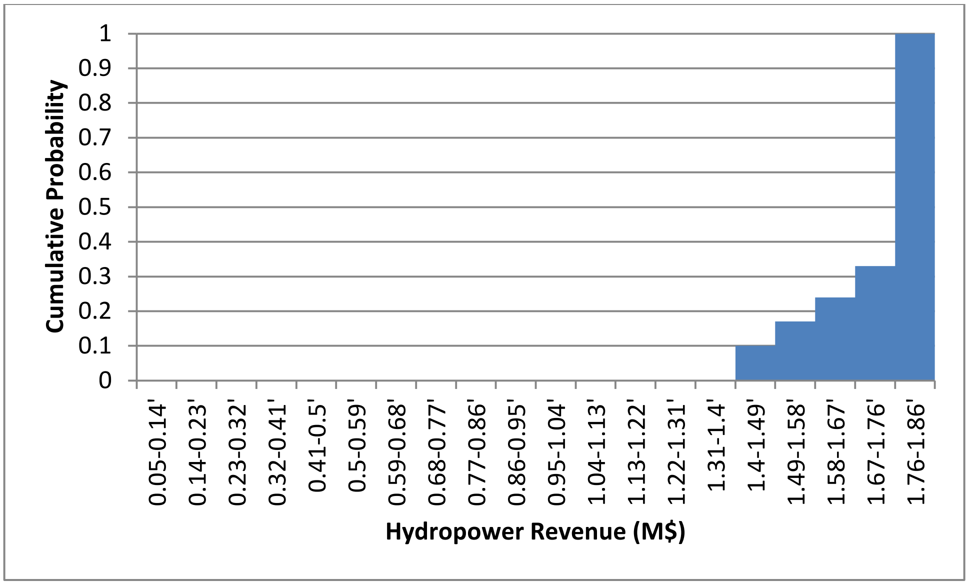


Figure 42: Hydropower revenue cumulative distribution function for alternative 5

In order to analyze the performance of the alternatives on the other objectives, besides hydropower revenue generation, we needed to develop cumulative distribution functions for outflow at Brackendale. Figures 43, 45, 47, 49, and 51 display the histogram of Brackendale outflow for the first alternative respectively on October 17, 18, 19, 20, and 21; and figures 44, 46, 48, 50, and 52 display the related cumulative distribution functions. Note that the minimum and maximum Brackendale outflow over all the alternatives and scenarios were respectively 20 and 846 cms.

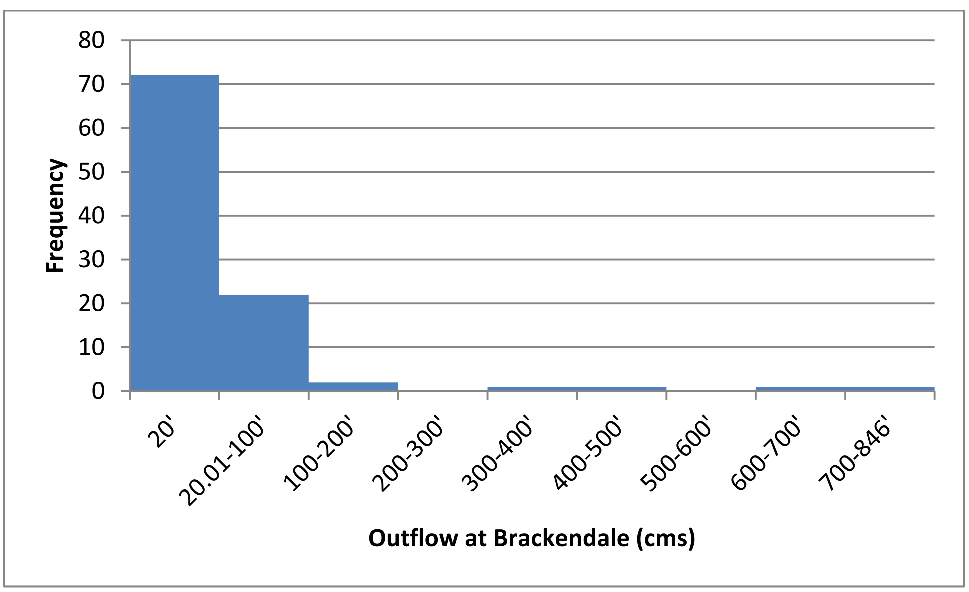


Figure 43: Brackendale outflow histogram on October 17 for alternative 1

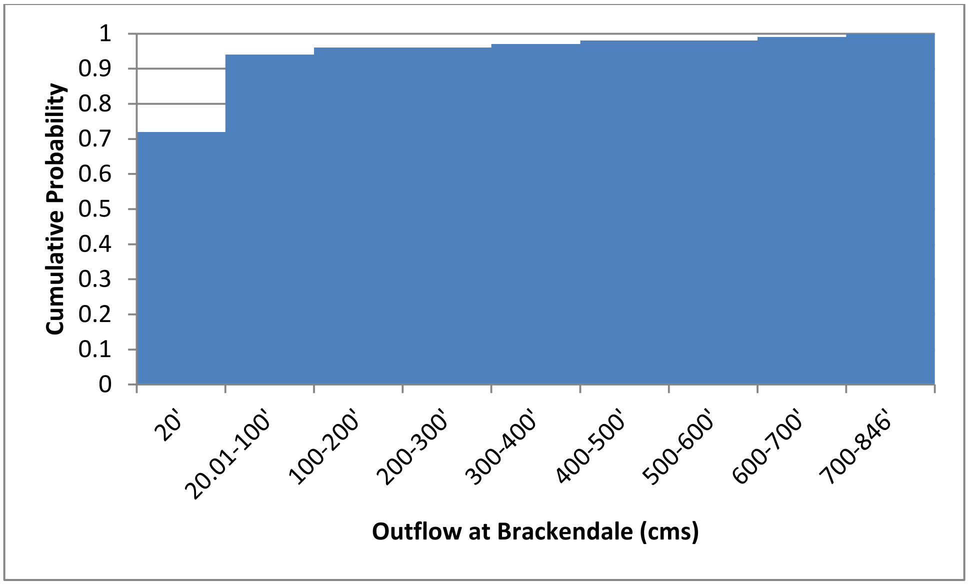


Figure 44: Brackendale outflow CDF on October 17 for alternative 1

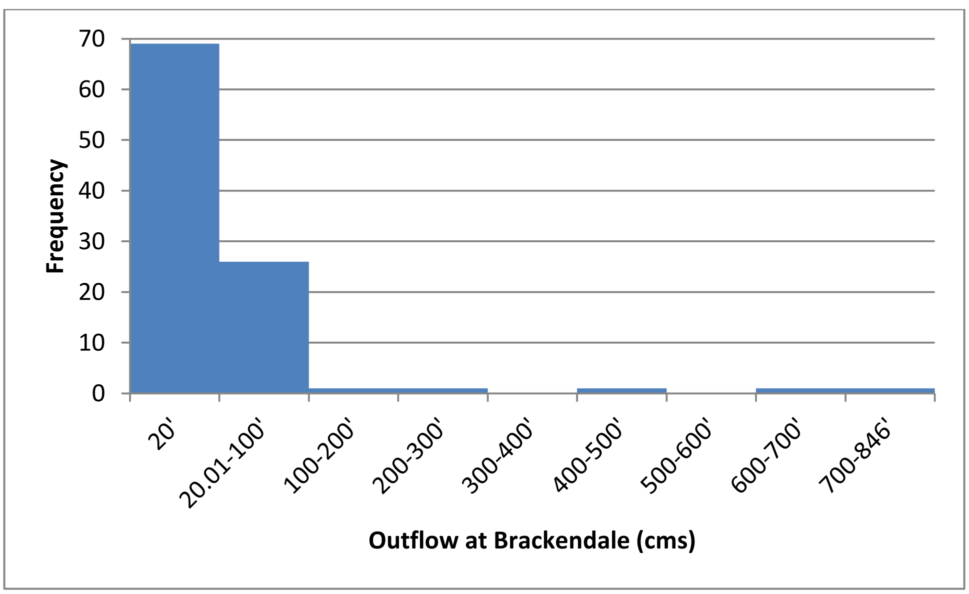


Figure 45: Brackendale outflow histogram on October 18 for alternative 1

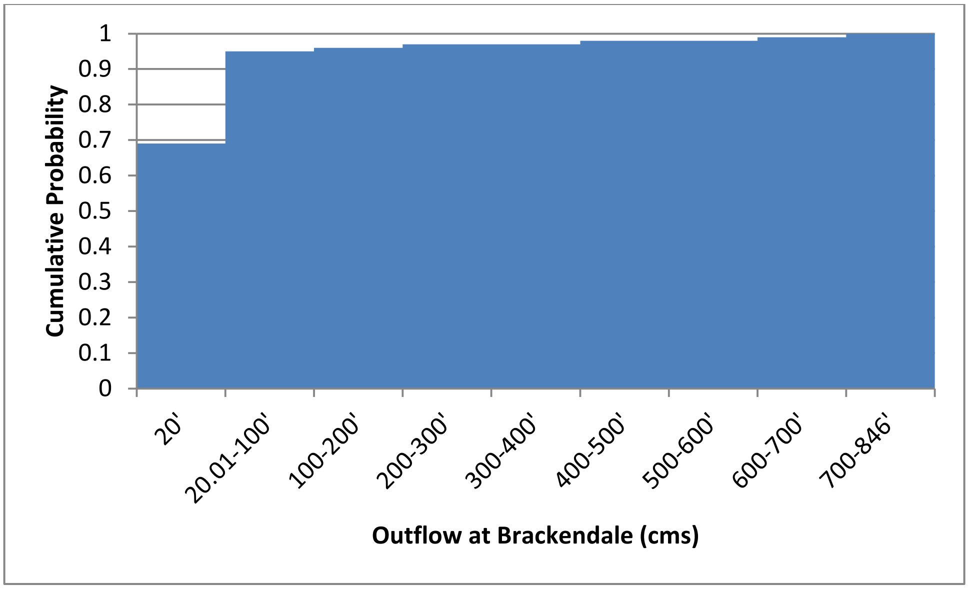


Figure 46: Brackendale outflow CDF on October 18 for alternative 1

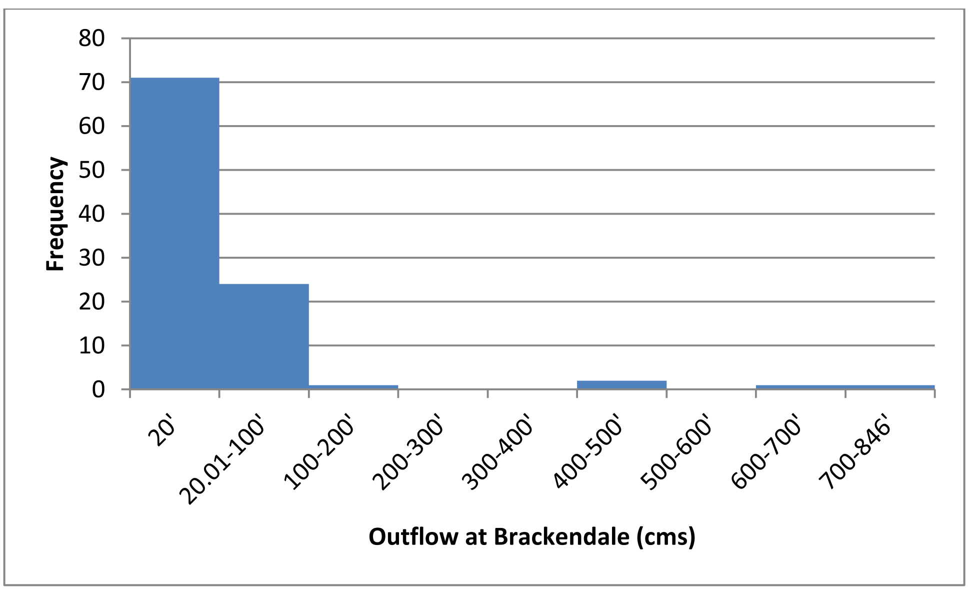


Figure 47: Brackendale outflow histogram on October 19 for alternative 1

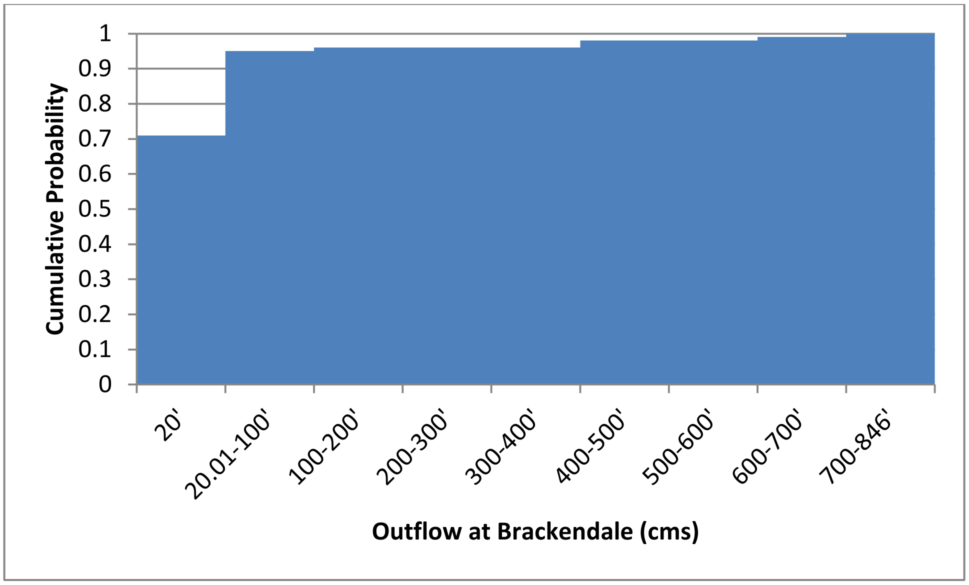


Figure 48: Brackendale outflow CDF on October 19 for alternative 1

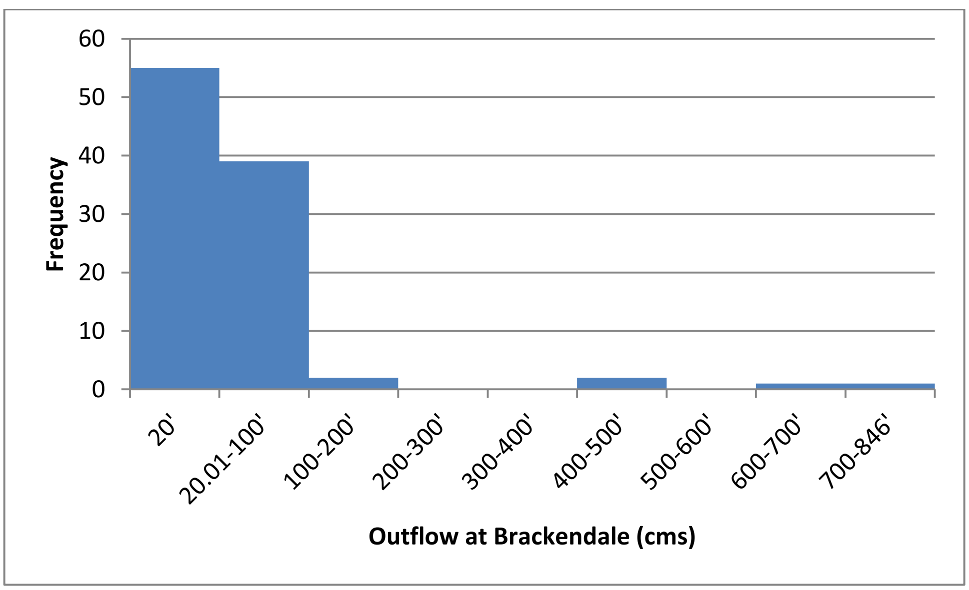


Figure 49: Brackendale outflow histogram on October 20 for alternative 1

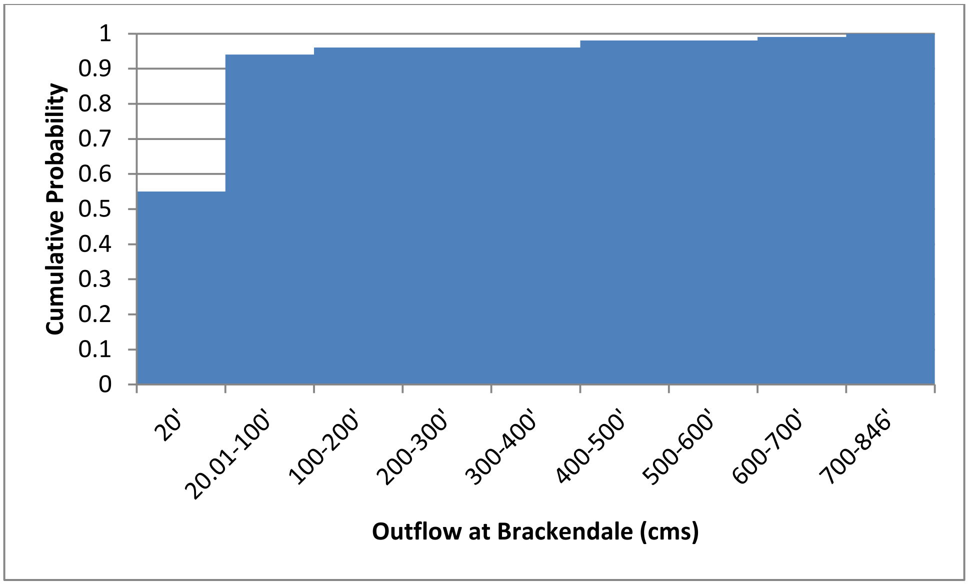


Figure 50: Brackendale outflow CDF on October 20 for alternative 1

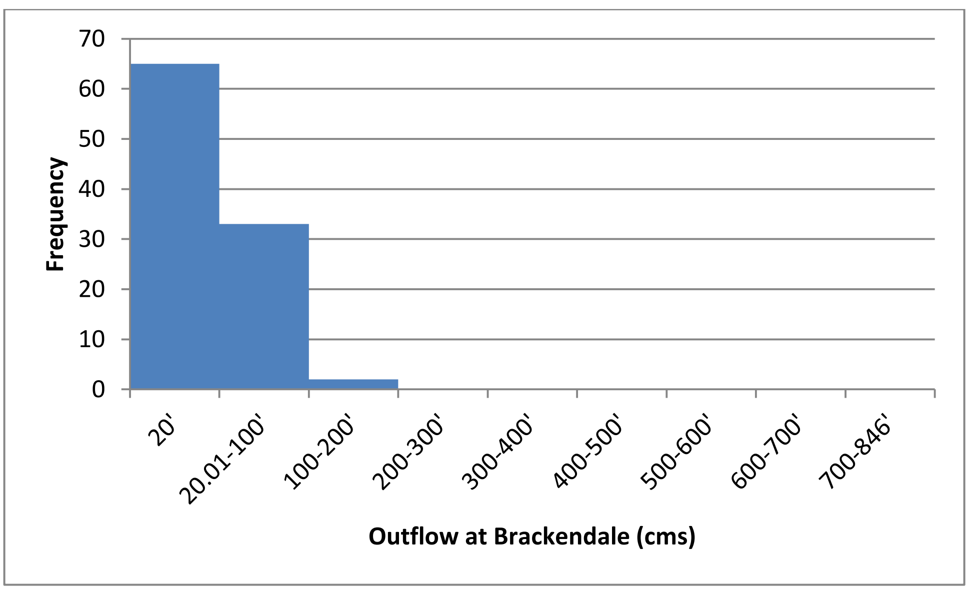


Figure 51: Brackendale outflow histogram on October 21 for alternative 1

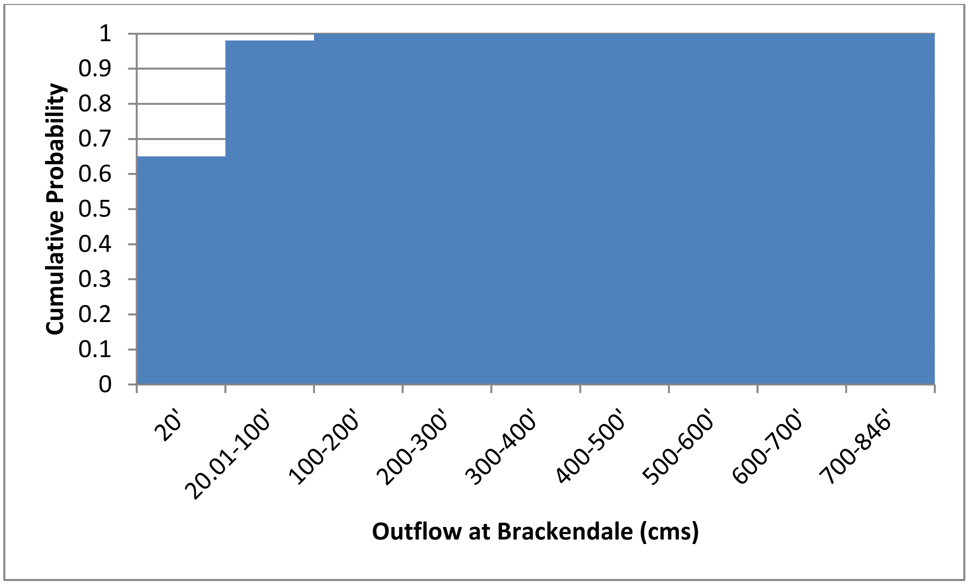


Figure 52: Brackendale outflow CDF on October 21 for alternative 1

4.4 Risk Assessment

The assumption for neutral risk-taking level of decision makers on each objective in our study is presented in table 6; and the corresponding risk-taking levels to risk-prone, risk-averse, and very conservative attitudes are presented in tables 7, 8, and 9.

Table 6: Decision makers' neutral risk-taking level

Objective	Risk-Taking Level (%)
Hydropower Revenue Generation	40
Environmental Impacts	10
Public Image Impacts	15
Flood Damage	5

Table 7: Risk-prone decision makers‘ risk-taking level

Objective	Risk-Taking Level (%)
Hydropower Revenue Generation	50
Environmental Impacts	20
Public Image Impacts	30
Flood Damage	10

Table 8: Risk-averse decision makers‘ risk-taking level

Objective	Risk-Taking Level (%)
Hydropower Revenue Generation	30
Environmental Impacts	5
Public Image Impacts	7
Flood Damage	2

Table 9: Very conservative decision makers‘ risk-taking level

Objective	Risk-Taking Level (%)
Hydropower Revenue Generation	10
Environmental Impacts	2
Public Image Impacts	2
Flood Damage	1

For revenue generation, the corresponding hydropower revenues to the neutral, risk-prone, risk-averse, and very conservative levels were extracted from hydropower revenue CDFs.

For the other objectives, first the neutral, risk-prone, risk-averse, and very conservative levels were subtracted from 100% and then the corresponding outflows were extracted from Brackendale outflow CDFs. The results for alternative 1 and for different risk-taking levels are presented in tables 10 to 13.

Table 10: Corresponding hydropower revenues and Brackendale discharges to the neutral risk-taking levels for alternative 1

Objective	Risk-Taking Level (%)	Corresponding Cumulative Probability (%)	Corresponding Revenue ($) or Discharge (cms)
Hydropower Revenue Generation	40	40	$528261.6
Environmental Impacts on October 17	10	90	52.29
Environmental Impacts on October 18	10	90	46.81
Environmental Impacts on October 19	10	90	43.55
Environmental Impacts on October 20	10	90	62.73
Environmental Impacts on October 21	10	90	42.97
Public Image Impacts on October 17	15	85	33.99
Public Image Impacts on October 18	15	85	31.22
Public Image Impacts on October 19	15	85	26.3
Public Image Impacts on October 20	15	85	44.99
Public Image Impacts on October 21	15	85	34.96
Flood Damage on October 17	5	95	125.52
Flood Damage on October 18	5	95	87.66
Flood Damage on October 19	5	95	82.63
Flood Damage on October 20	5	95	114.44
Flood Damage on October 21	5	95	62.03

Table 11: Corresponding hydropower revenues and Brackendale discharges to the risk-prone levels for alternative 1

Objective	Risk-Taking Level (%)	Corresponding Cumulative Probability (%)	Corresponding Revenue ($) or Discharge (cms)
Hydropower Revenue Generation	50	50	$693240
Environmental Impacts on October 17	20	80	25.54
Environmental Impacts on October 18	20	80	25.28
Environmental Impacts on October 19	20	80	20.5
Environmental Impacts on October 20	20	80	33.92
Environmental Impacts on October 21	20	80	28.04
Public Image Impacts on October 17	30	70	20
Public Image Impacts on October 18	30	70	20.13
Public Image Impacts on October 19	30	70	20
Public Image Impacts on October 20	30	70	26.48
Public Image Impacts on October 21	30	70	22.4
Flood Damage on October 17	10	90	52.29
Flood Damage on October 18	10	90	46.81
Flood Damage on October 19	10	90	43.55
Flood Damage on October 20	10	90	62.73
Flood Damage on October 21	10	90	42.97

Table 12: Corresponding hydropower revenues and Brackendale discharges to the risk-averse levels for alternative 1

Objective	Risk-Taking Level (%)	Corresponding Cumulative Probability (%)	Corresponding Revenue ($) or Discharge (cms)
Hydropower Revenue Generation	30	30	$373650
Environmental Impacts on October 17	5	95	125.52
Environmental Impacts on October 18	5	95	87.66
Environmental Impacts on October 19	5	95	82.63
Environmental Impacts on October 20	5	95	114.44
Environmental Impacts on October 21	5	95	62.03
Public Image Impacts on October 17	7	93	74.47
Public Image Impacts on October 18	7	93	58.1
Public Image Impacts on October 19	7	93	57.7
Public Image Impacts on October 20	7	93	77.17
Public Image Impacts on October 21	7	93	53.39
Flood Damage on October 17	2	98	428.24
Flood Damage on October 18	2	98	454.76
Flood Damage on October 19	2	98	454.76
Flood Damage on October 20	2	98	454.76
Flood Damage on October 21	2	98	88.74

Table 13: Corresponding hydropower revenues and Brackendale discharges to the very conservative risk-taking levels for alternative 1

Objective	Risk-Taking Level (%)	Corresponding Cumulative Probability (%)	Corresponding Revenue ($) or Discharge (cms)
Hydropower Revenue Generation	10	10	$150541.2
Environmental Impacts on October 17	2	98	428.24
Environmental Impacts on October 18	2	98	454.76
Environmental Impacts on October 19	2	98	454.76
Environmental Impacts on October 20	2	98	454.76
Environmental Impacts on October 21	2	98	88.74
Public Image Impacts on October 17	2	98	428.24
Public Image Impacts on October 18	2	98	454.76
Public Image Impacts on October 19	2	98	454.76
Public Image Impacts on October 20	2	98	454.76
Public Image Impacts on October 21	2	98	88.74
Flood Damage on October 17	1	99	688.63
Flood Damage on October 18	1	99	688.63
Flood Damage on October 19	1	99	688.63
Flood Damage on October 20	1	99	688.63
Flood Damage on October 21	1	99	129.95

4.5 Performance Matrices

With the use of the streamflow impact curves and the revenue and Brackendale discharge tables in the previous section, the performance matrices for the four different risk-taking attitudes were generated. In order to do this, for the objectives of minimizing environmental impacts, public image impacts, and flood damage, the highest Brackendale discharge in the period of October 17 to October 21 was extracted from the corresponding table to the related alternative. Afterwards, with the use of the related streamflow impact curve, the corresponding performance was extracted and inserted to the performance matrix. As an example, for neutral risk-taking attitudes and the objective of minimizing environmental impacts and for alternative 1, the highest Brackendale outflow from table 10 is 62.73 cms on October 20.

Table 14 displays the performance matrix for neutral risk taking levels. Table 15, 16, and 17 respectively display the performance matrices for risk-prone, risk-averse, and very conservative attitudes.

Table 14: performance matrix for neutral risk taking levels

Objective	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Hydropower Revenue Generation	$528,261.6	$928,941.6	$1,246,942	$1,564,942	$1,856,812
Environmental Impacts	0.2	0.205	0.205	0.205	0.21
Public Image Impacts	None	None	None	None	None
Flood Damage	0	0	0	0	0

Table 15: performance matrix for risk-prone attitude

Objective	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Hydropower Revenue Generation	$693,240	$1,084,380	$1,402,380	$1,720,380	$1,860,000
Environmental Impacts	0.1	0.105	0.105	0.105	0.11
Public Image Impacts	None	None	None	None	None
Flood Damage	0	0	0	0	0

Table 16: performance matrix for risk-averse attitude

Objective	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Hydropower Revenue Generation	$373,650	$774,330	$1,092,326	$1,410,326	$1,728,326
Environmental Impacts	0.55	0.94	1.32	1.72	2.2
Public Image Impacts	None	None	None	None	None
Flood Damage	$99,960	$108,780	$115,920	$123,060	$132,720

Table 17: performance matrix for very conservative attitude

Objective	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Hydropower Revenue Generation	$150,541.2	$551,221.2	$869,221.2	$1,187,221	$1,505,221
Environmental Impacts	4.45	4.6	4.63	4.66	4.69
Public Image Impacts	Very Low	Very Low	Very Low	Very Low	Very Low
Flood Damage	$4,200,000	$4,200,000	$4,200,000	$4,200,000	$4,200,000

To better understand the process by means of which the values in the performance matrices were calculated, we try to explain this process in detail for a number of these values:

As can be seen in Table 14, the environmental impact of Alternative 1 at neutral risk taking level is estimated to be 0.2. To calculate this, first, the decision makers' neutral risk taking level on the objective of environmental impacts was acquired from table 6 which is equal to 10 percent. This means that at the neutral risk taking levels and for the environmental impacts, the decision makers are concerned with the scenario that 90 percent of all the generated scenarios would cause a lower environmental damage than that. Therefore, for October 17 to 21, we need to acquire the Brackendale outflows corresponding to the cumulative probability of 90 percent from the figures 44, 46, 48, 50, and 52. For example for October 17, from figure 44, it can be seen that 94 percent of the outflows are less than 100 and 72 percent of them are greater than 20. Obviously, the outflow corresponding to the cumulative probability of 90 percent is something between 20 and 100 cms. From the detailed data generated for the purpose of this study we identified this outflow to be equal to 52.29. As can be seen in table 10, the outflows for October 18 to 21 are respectively equal to 46.81, 43.55, 62.73, and 42.97. Now we need to take the highest calculated outflow, which is

62.73 cms, and find its corresponding environmental impact from figure 18. This value is almost equal to 0.2 as shown in table 14.

As can be seen in Table 15, the public image impact of Alternative 1 at risk-prone level is estimated to be none. To calculate this, first, the risk-prone decision makers' risk taking level on the objective of public image impacts was acquired from table 7 which is equal to 30 percent. This means that at the risk-prone levels and for the public image impacts, the decision makers are concerned with the scenario that 70 percent of all the generated scenarios would cause a lower public image impact than that. Therefore, for October 17 to 21, we need to acquire the Brackendale outflows corresponding to the cumulative probability of 70 percent from the figures 44, 46, 48, 50, and 52. For example for October 17, from figure 44, it can be seen that 72 percent of the outflows are less than or equal to 20. Obviously, the outflow corresponding to the cumulative probability of 70 percent is something less than or equal to 20 cms. From the detailed data generated for the purpose of this study we identified this outflow to be equal to 20. As can be seen in table 11, the outflows for October 18 to 21 are respectively equal to 20.13, 20, 26.48, and 22.4. Now we need to take the highest calculated outflow, which is 26.48 cms, and find its corresponding public image impact from table 5. This value is none as any outflow lower than 400 cms causes no public image impact.

As can be seen in Table 14, the flood damage of Alternative 1 at neutral risk taking level is estimated to be 0. To calculate this, first, the decision makers' neutral risk taking level on the objective of flood damage was acquired from table 6 which is equal to 5 percent. This means that at the neutral risk taking levels and for the flood damage, the decision makers are concerned with the scenario that 95 percent of all the generated scenarios would cause a lower flood damage than that. Therefore, for October 17 to 21, we need to acquire the Brackendale outflows corresponding to the cumulative probability of 95 percent from the figures 44, 46, 48, 50, and 52. For example for October 17, from figure 44, it can be seen that 96 percent of the outflows are less than 200 and 94 percent of them are greater than 100. Obviously, the outflow corresponding to the cumulative probability of 95 percent is something between 100 and 200 cms. From the detailed data generated for the purpose of this study we identified this outflow to be equal to 125.52. As can be seen in table 10, the outflows for October 18 to 21 are respectively equal to 87.66, 82.63, 114.44, and 62.03. Now we need to take the highest calculated outflow, which is 125.52 cms, and find its corresponding flood damage from figure 19. This value is equal to 0 as any outflow lower than 450 cms causes no flood damage.

4.6 Multi-Criteria Decision Making

At this point, LDW is ready to analyze the inputted data and information to generate the results. Figures 53, 55, 57, and 59 respectively display the ranking of alternatives for neutral, risk-prone, risk-averse, and very conservative attitudes; and figures 54, 56, 58, and 60 respectively display the utilities for the recommended alternative at each risk-taking attitude.

Figure 53: Ranking of alternatives for neutral risk-taking attitude

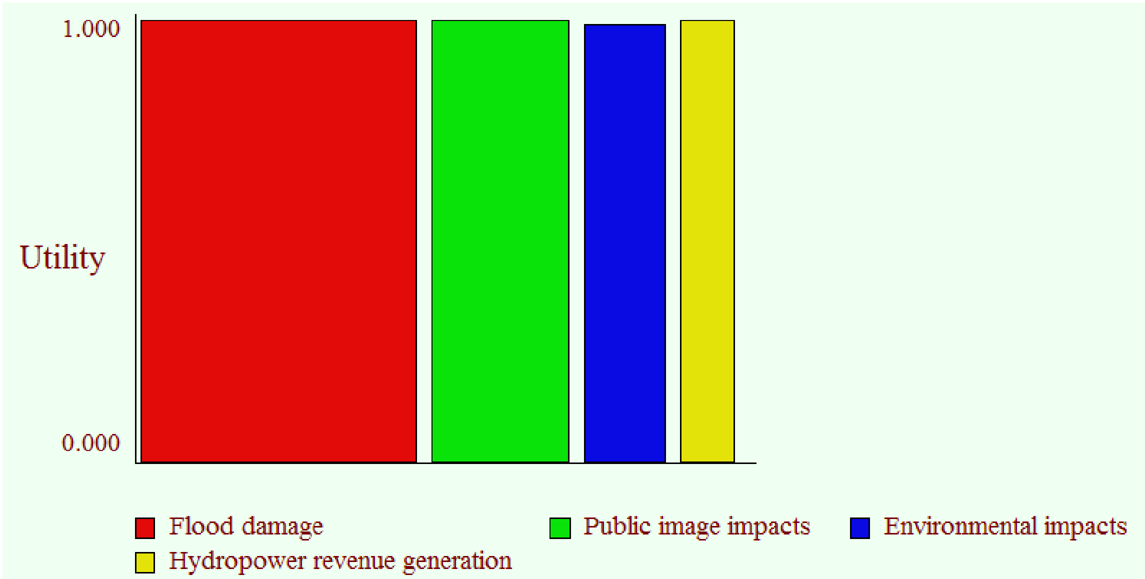


Figure 54: Utilities for Operational Alternative 5 at neutral risk-taking attitude

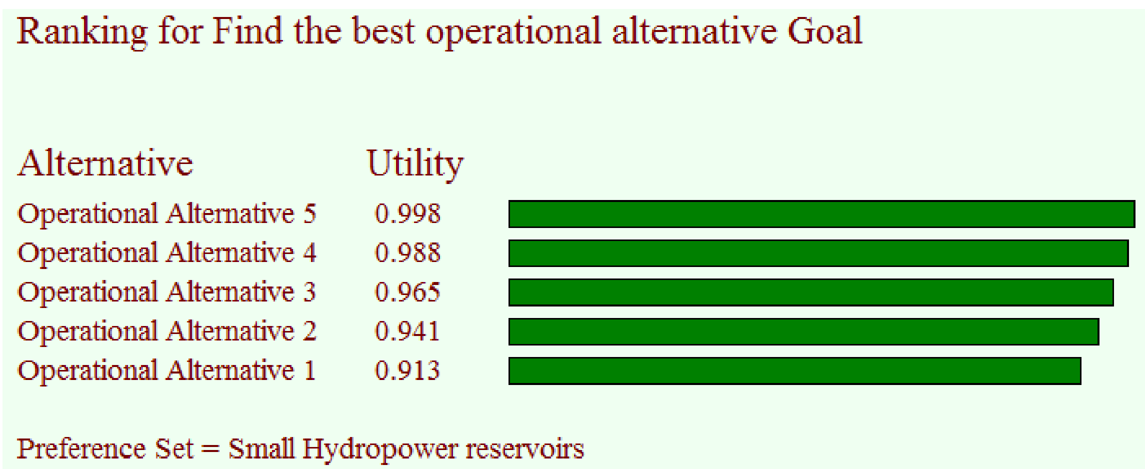


Figure 55: Ranking of alternatives for risk-prone attitude

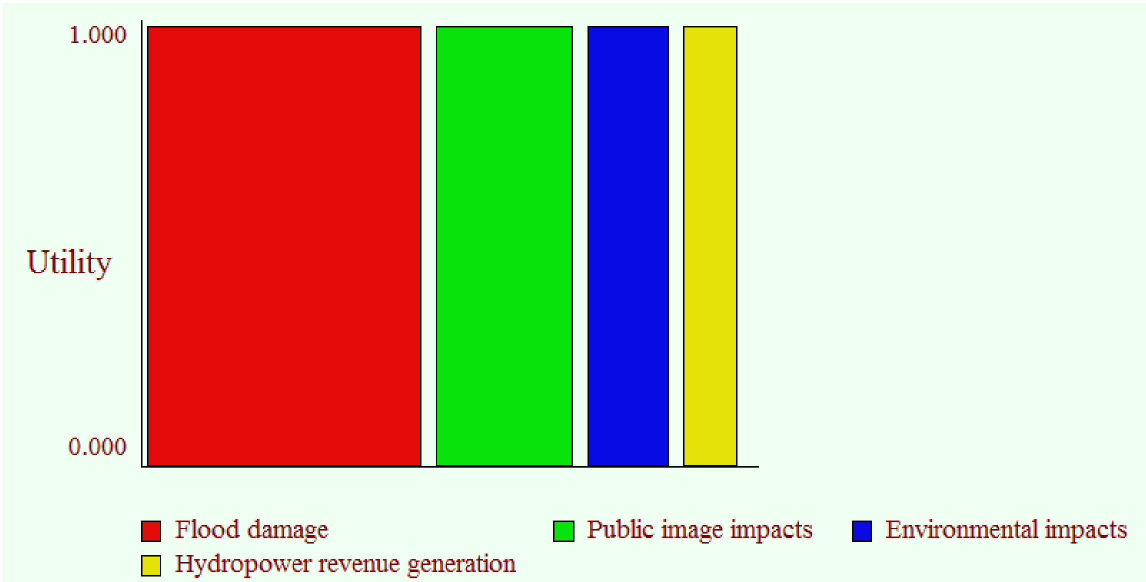


Figure 56: Utilities for Operational Alternative 5 at risk-prone attitude

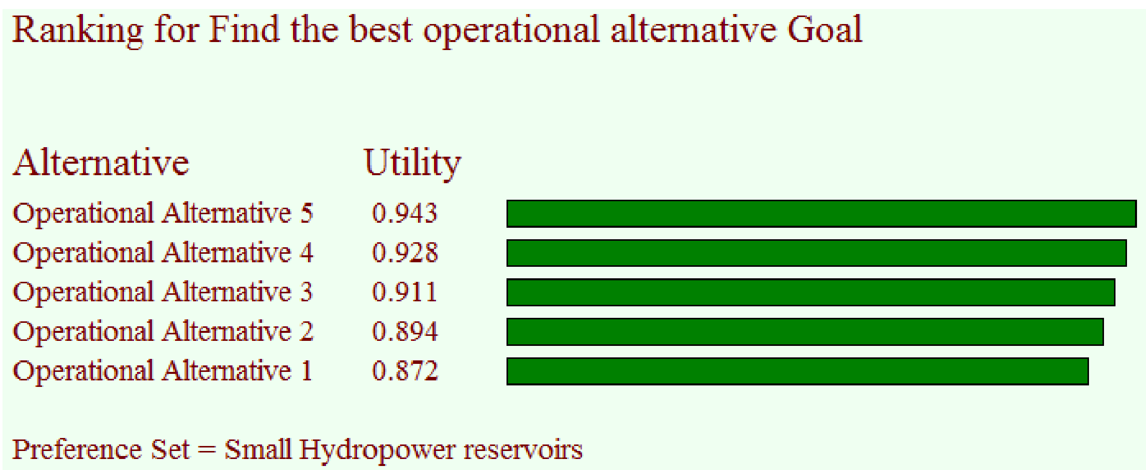


Figure 57: Ranking of alternatives for risk-averse attitude

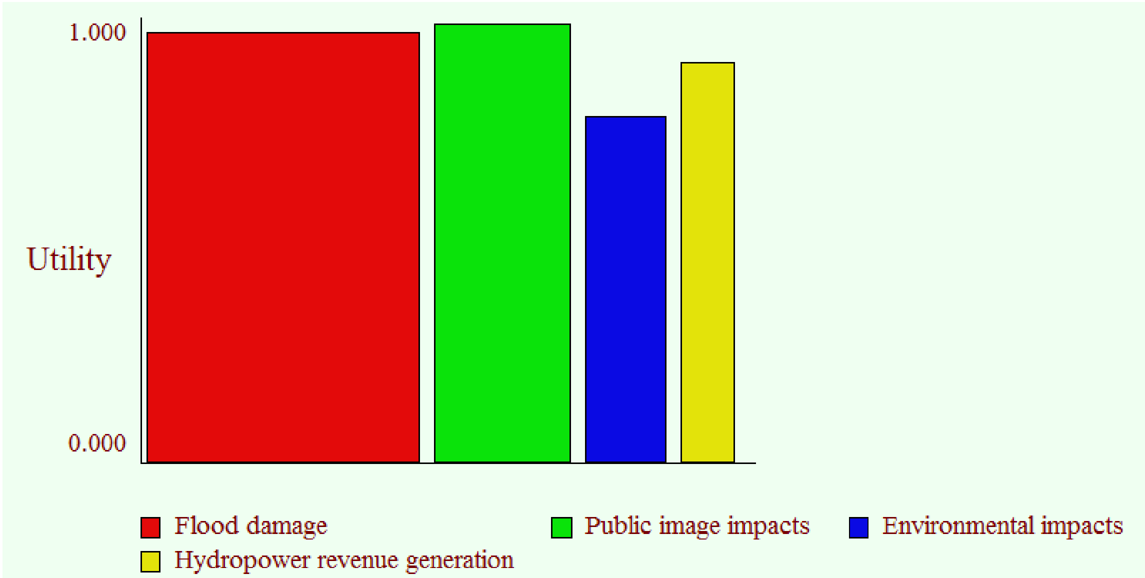


Figure 58: Utilities for Operational Alternative 5 at risk-averse attitude

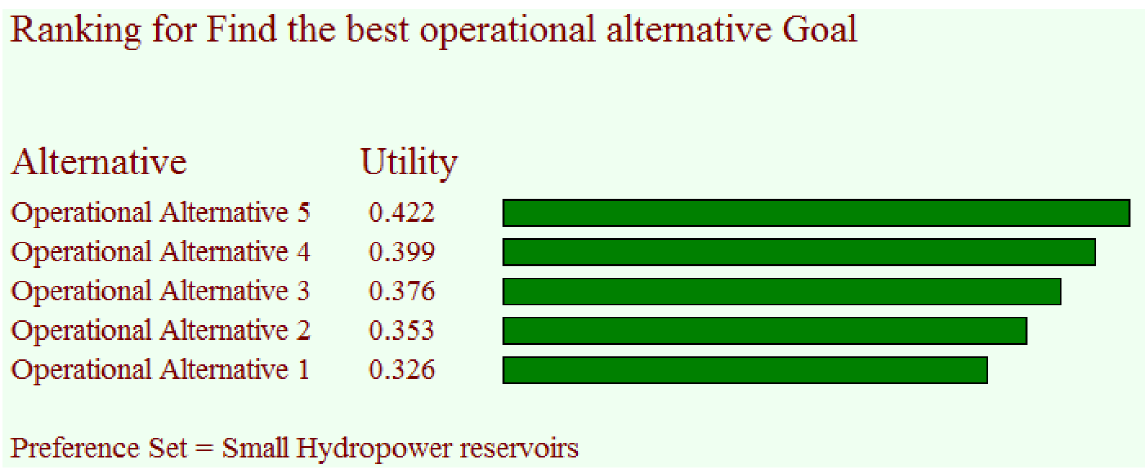


Figure 59: Ranking of alternatives for very conservative attitude

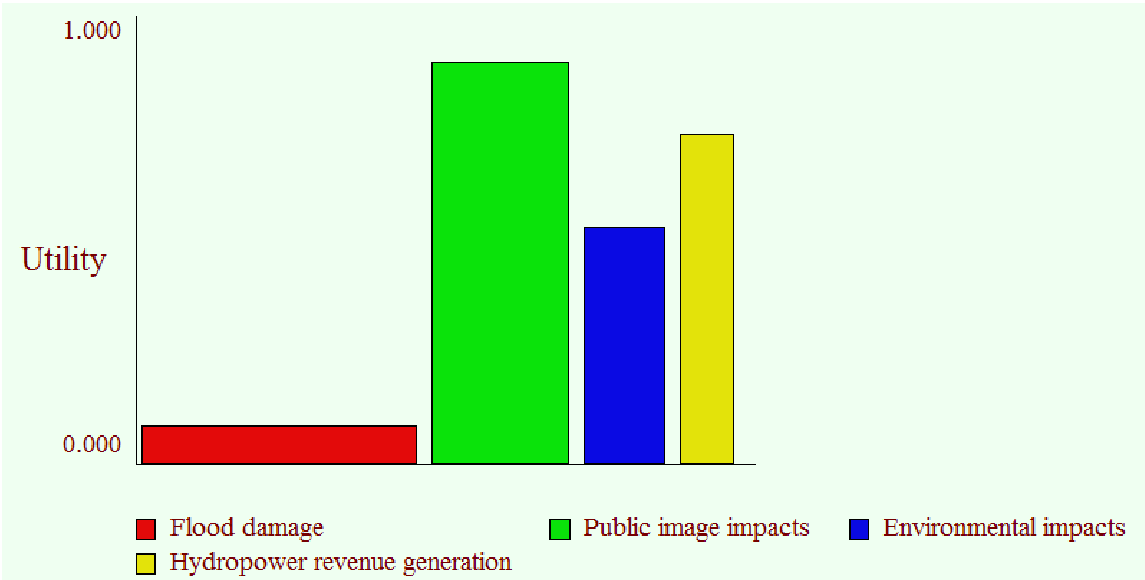


Figure 60: Utilities for Operational Alternative 5 at very conservative attitude

Now that we have the ranking of alternatives, it is important to do sensitivity analysis to realize the effect of different weights on the ranking of alternatives. Figures 61 to 64 respectively illustrate the sensitivity graphs for different objectives at neutral risk-taking levels. Figures 65 to 68, 69 to 72, and 73 to 76 illustrate the sensitivity graphs for different objectives respectively at risk-prone, risk-averse, and very conservative attitudes.

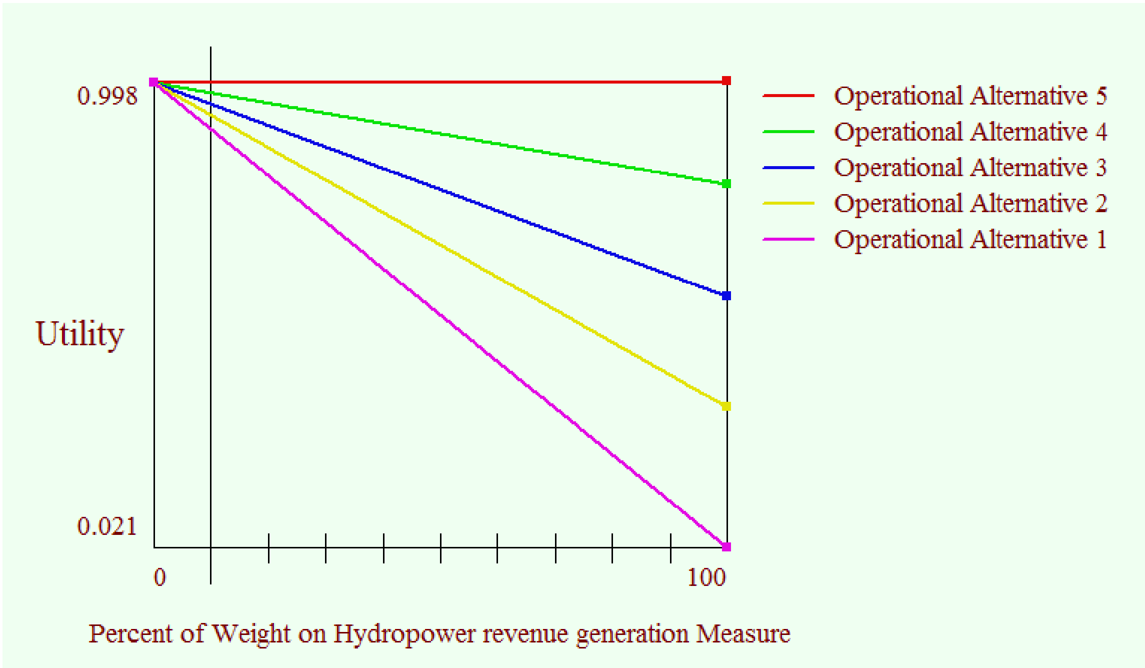


Figure 61: Sensitivity graph for hydropower revenue generation at neutral risk-taking levels

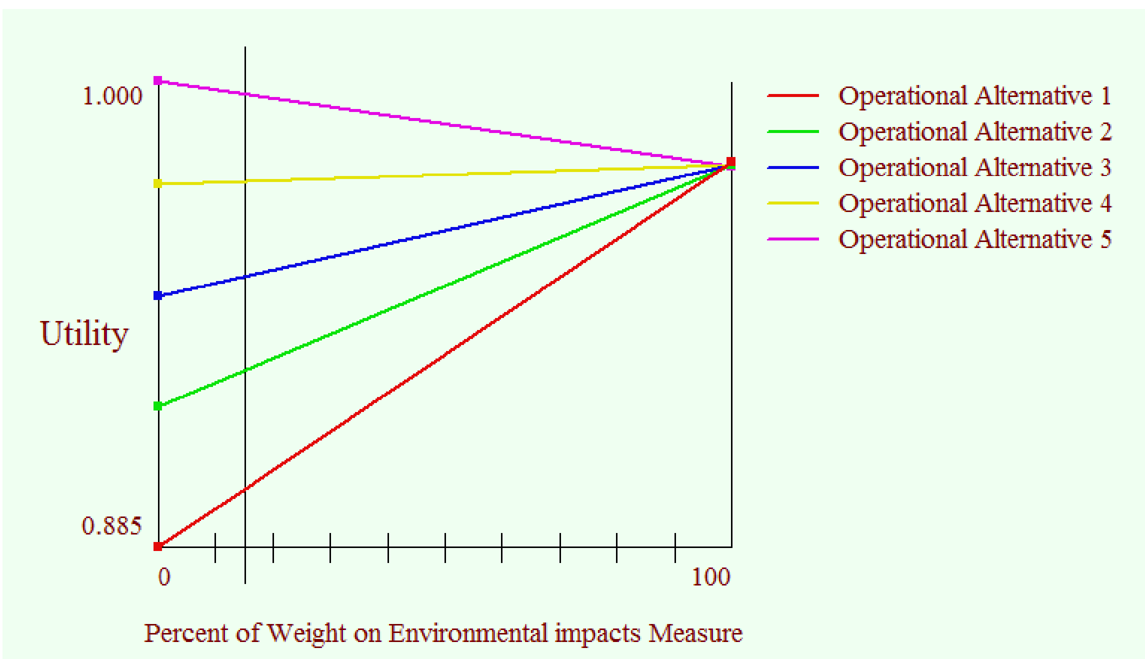


Figure 62: Sensitivity graph for environmental impacts at neutral risk-taking levels

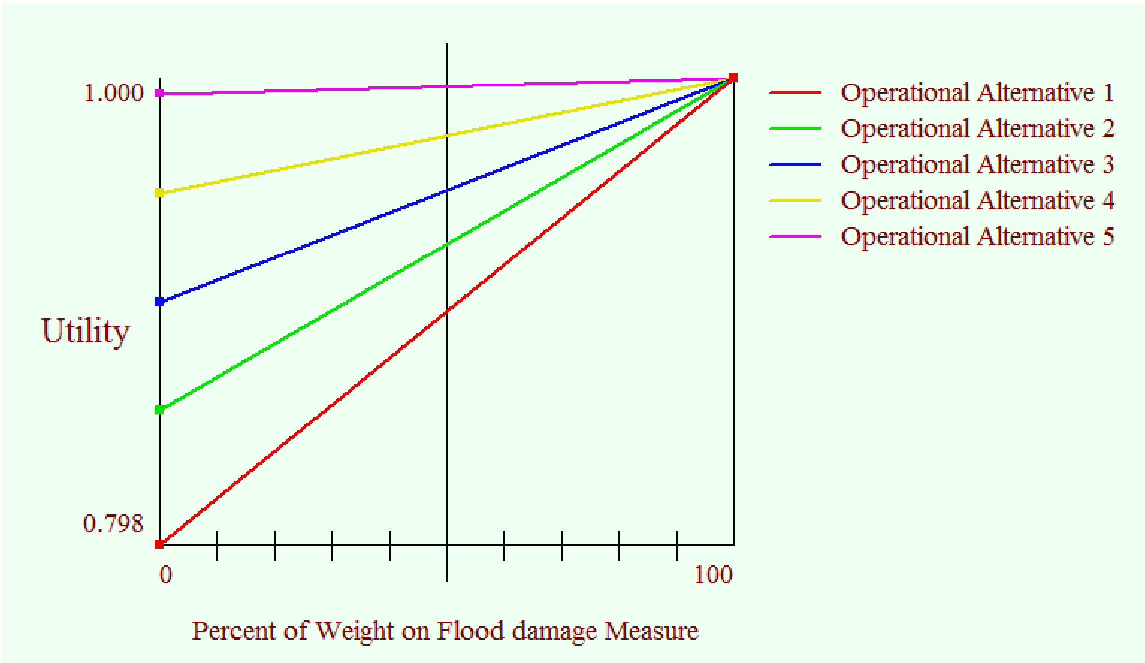


Figure 63: Sensitivity graph for flood damage at neutral risk-taking levels

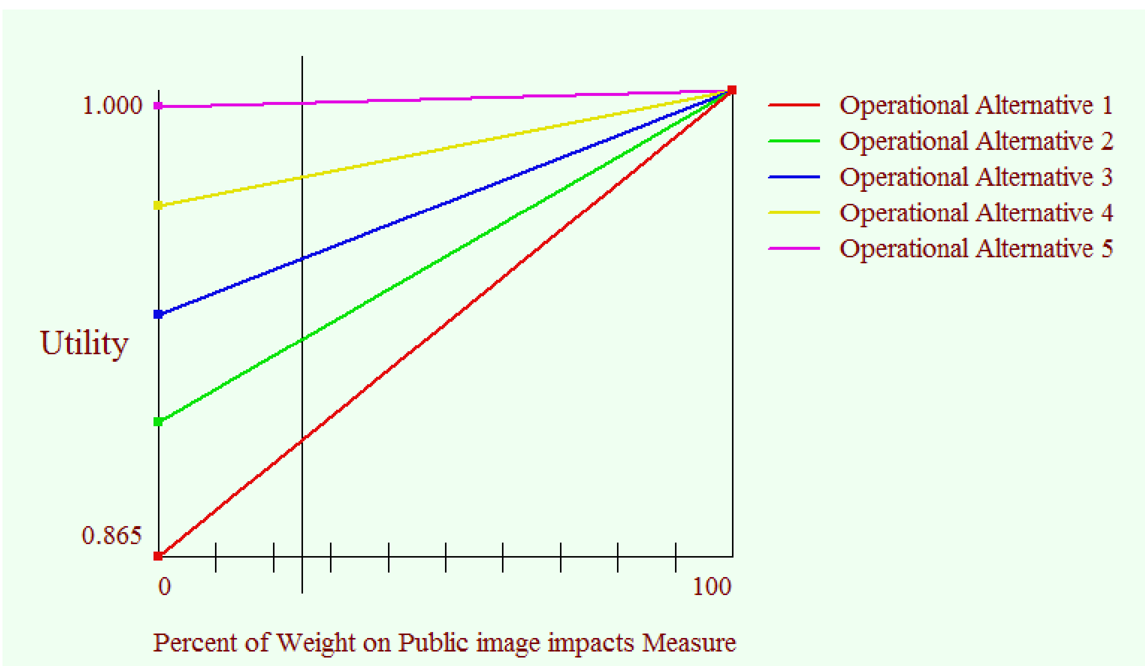


Figure 64: Sensitivity graph for public image impacts at neutral risk-taking levels

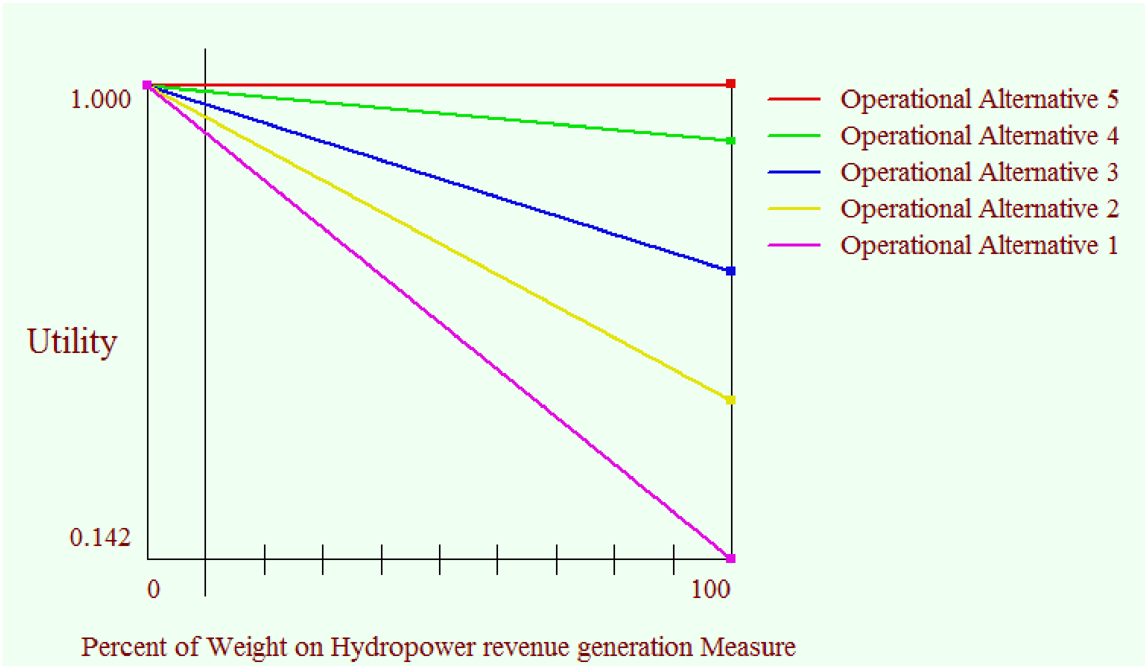


Figure 65: Sensitivity graph for hydropower revenue generation at risk-prone attitude

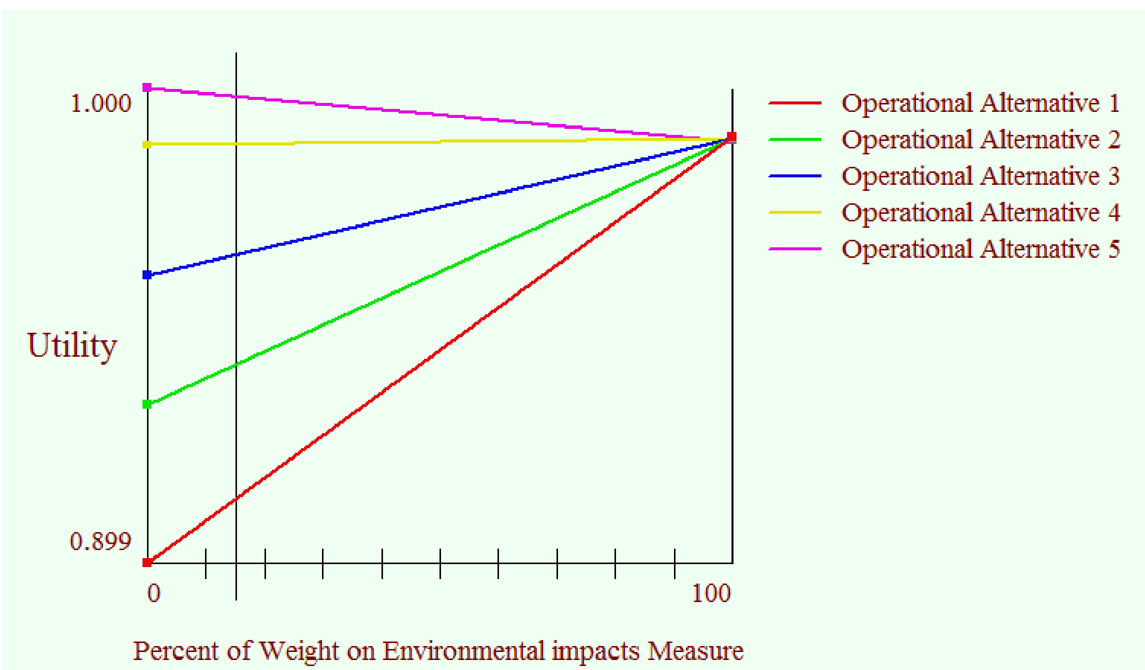


Figure 66: Sensitivity graph for environmental impacts at risk-prone attitude

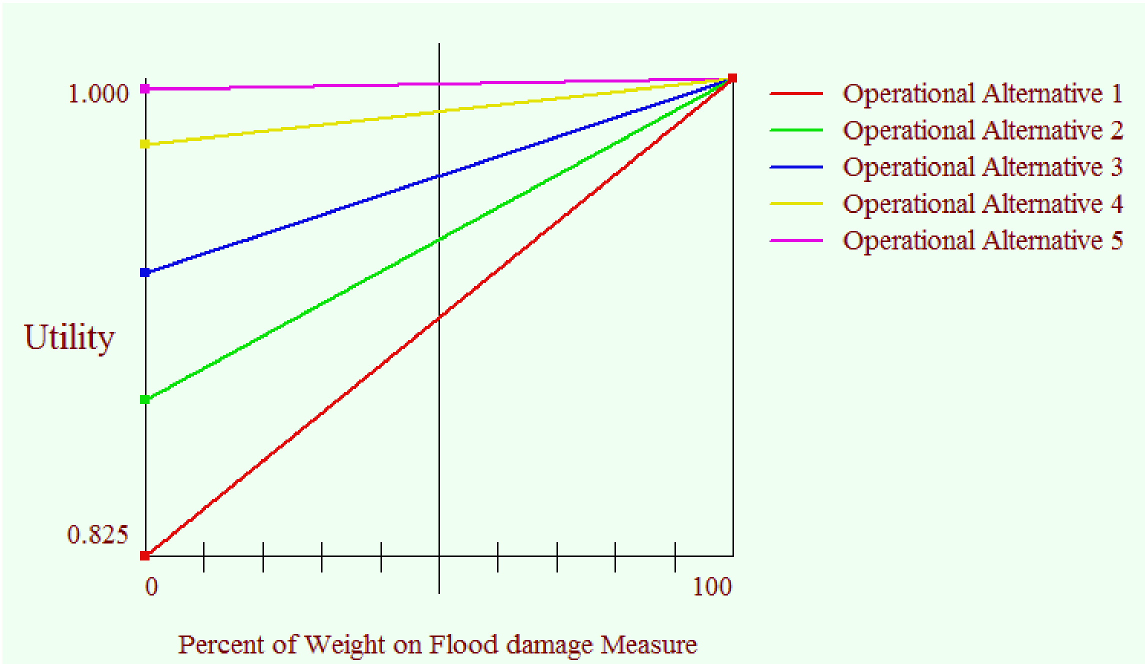


Figure 67: Sensitivity graph for flood damage at risk-prone attitude

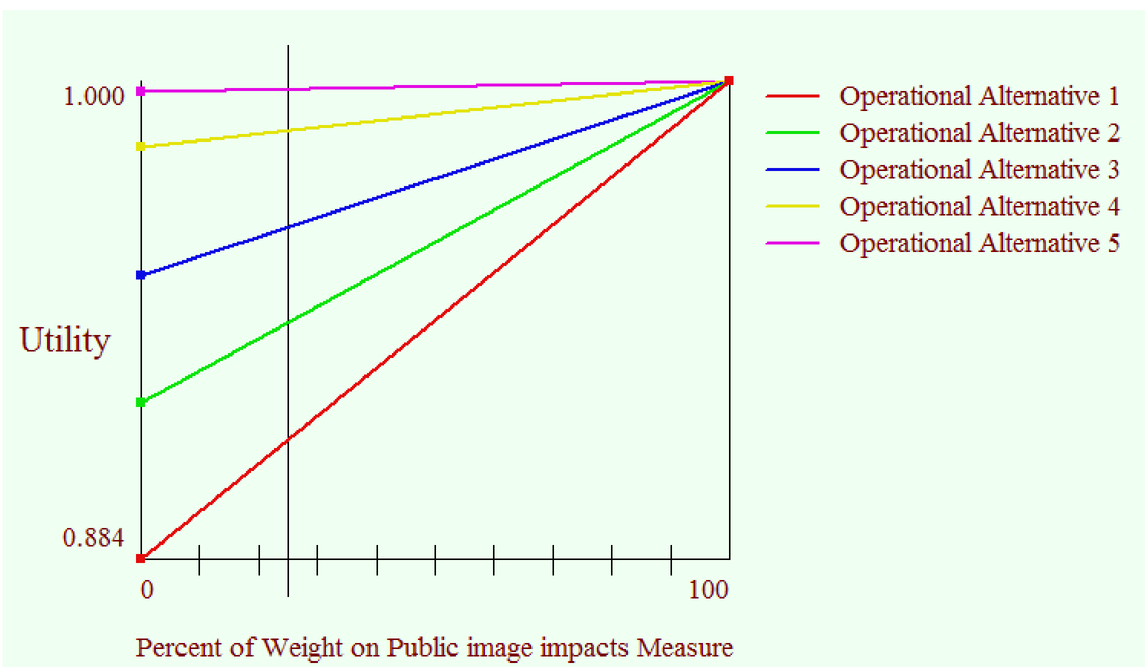


Figure 68: Sensitivity graph for public image impacts at risk-prone attitude

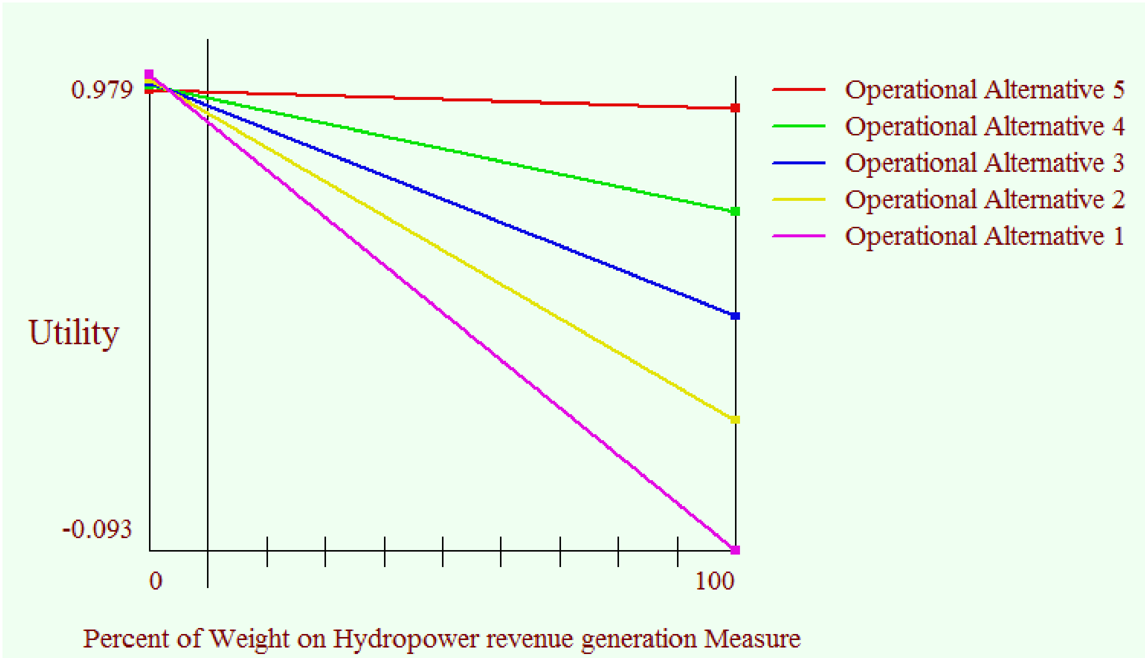


Figure 69: Sensitivity graph for hydropower revenue generation at risk-averse attitude

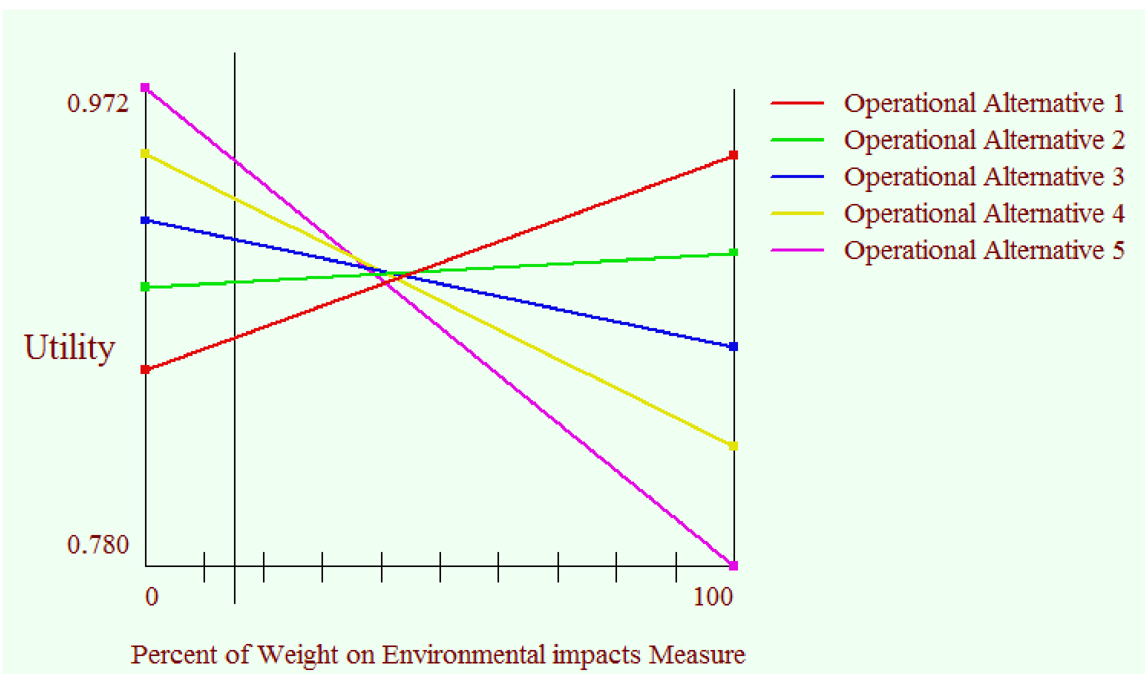


Figure 70: Sensitivity graph for environmental impacts at risk-averse attitude

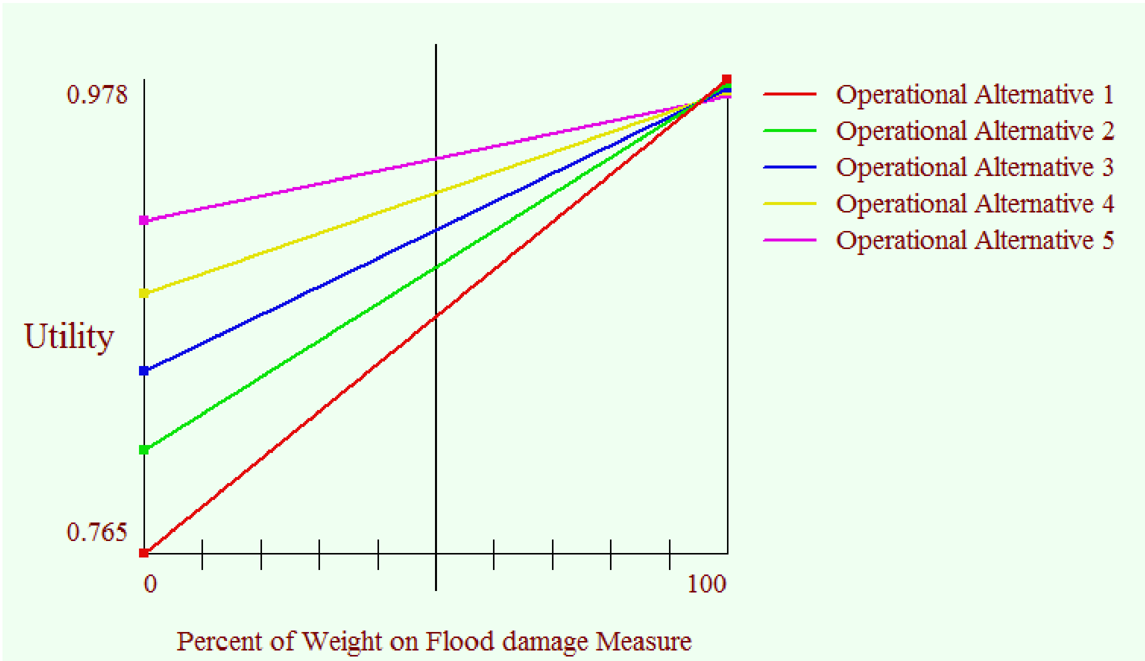


Figure 71: Sensitivity graph for flood damage at risk-averse attitude

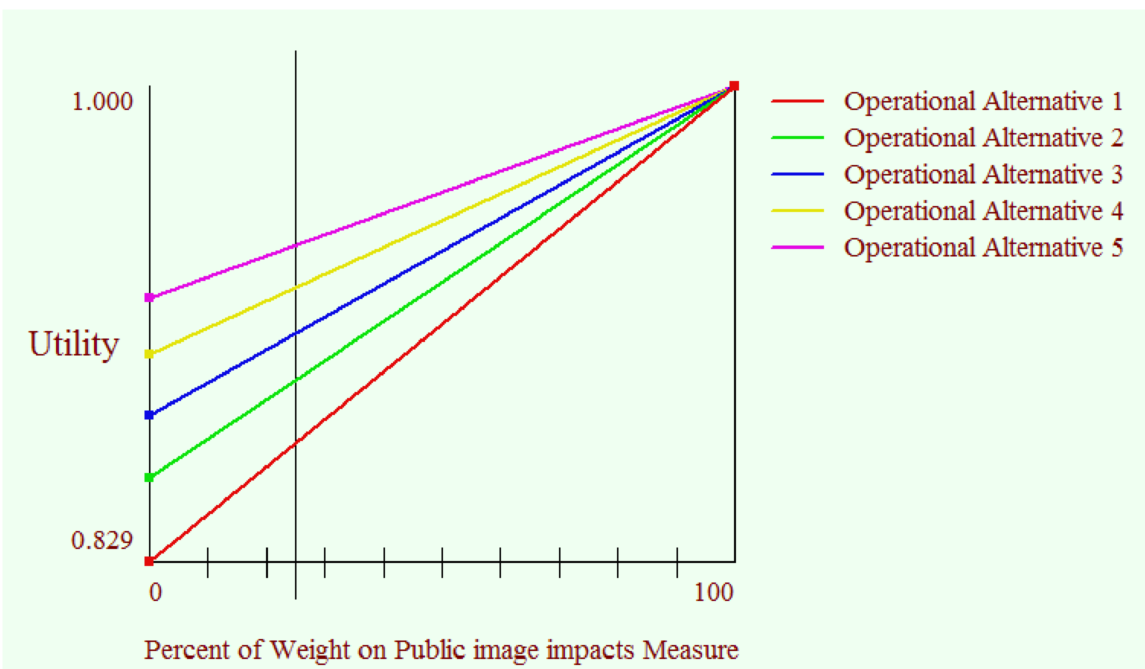


Figure 72: Sensitivity graph for public image impacts at risk-averse attitude

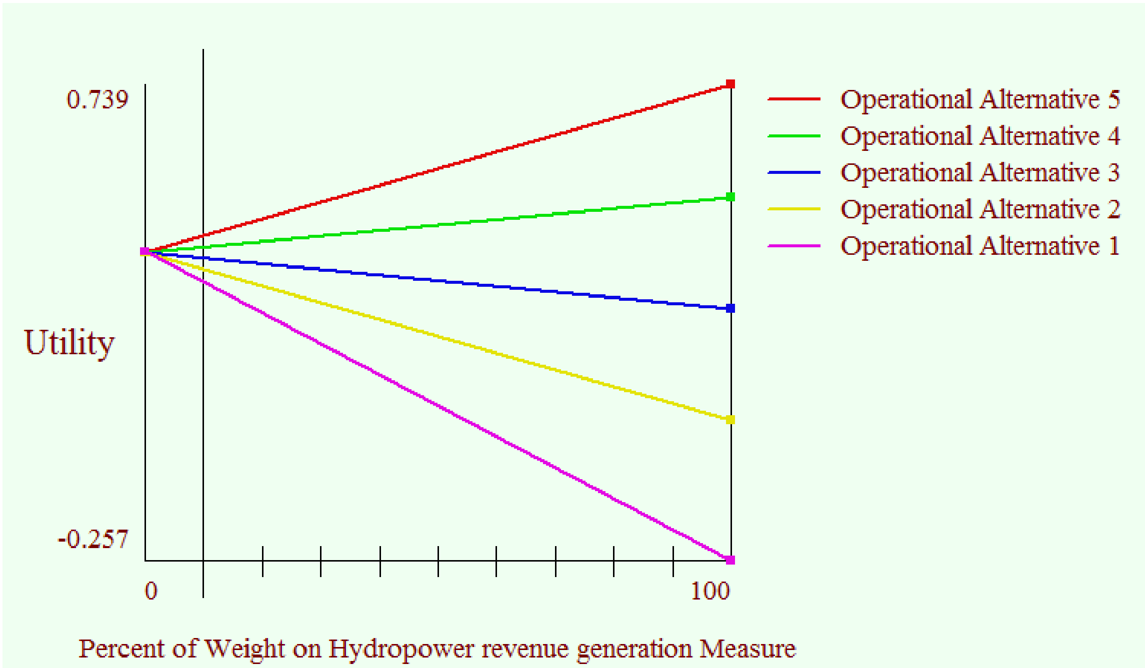


Figure 73: Sensitivity graph for hydropower revenue generation at very conservative attitude

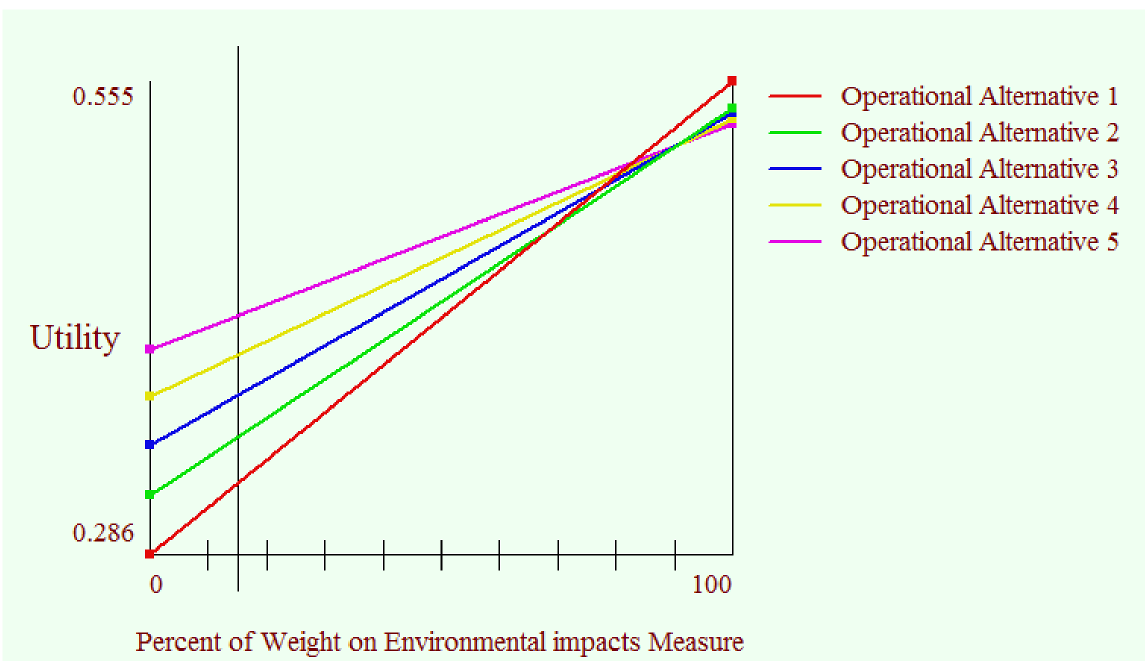


Figure 74: Sensitivity graph for environmental impacts at very conservative attitude

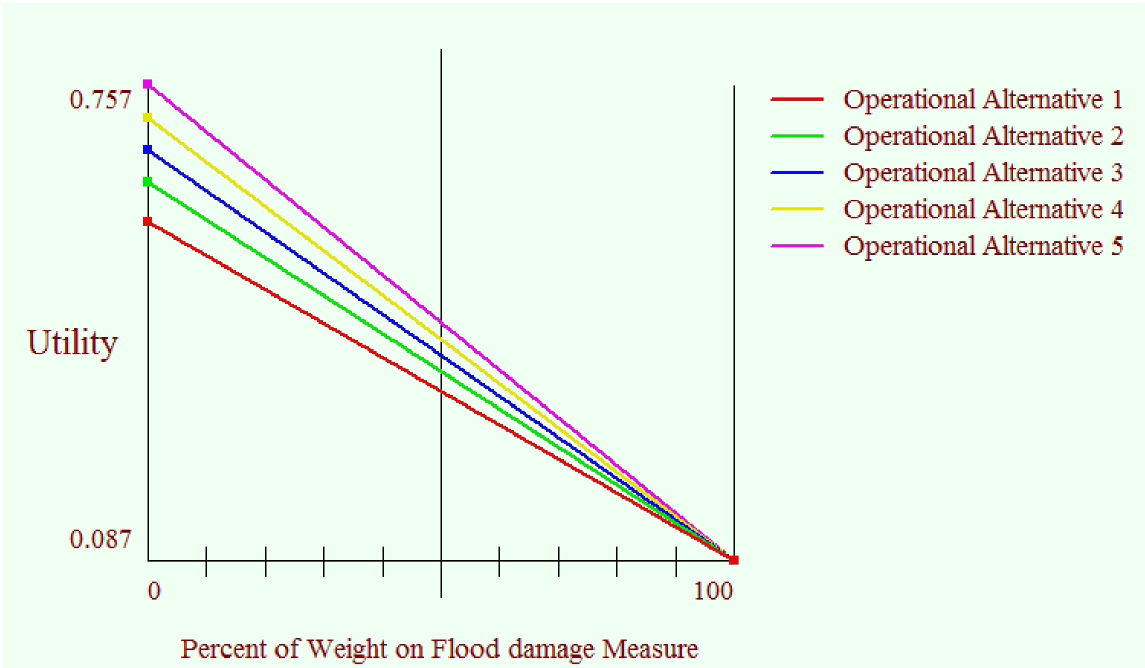


Figure 75: Sensitivity graph for flood damage at very conservative attitude

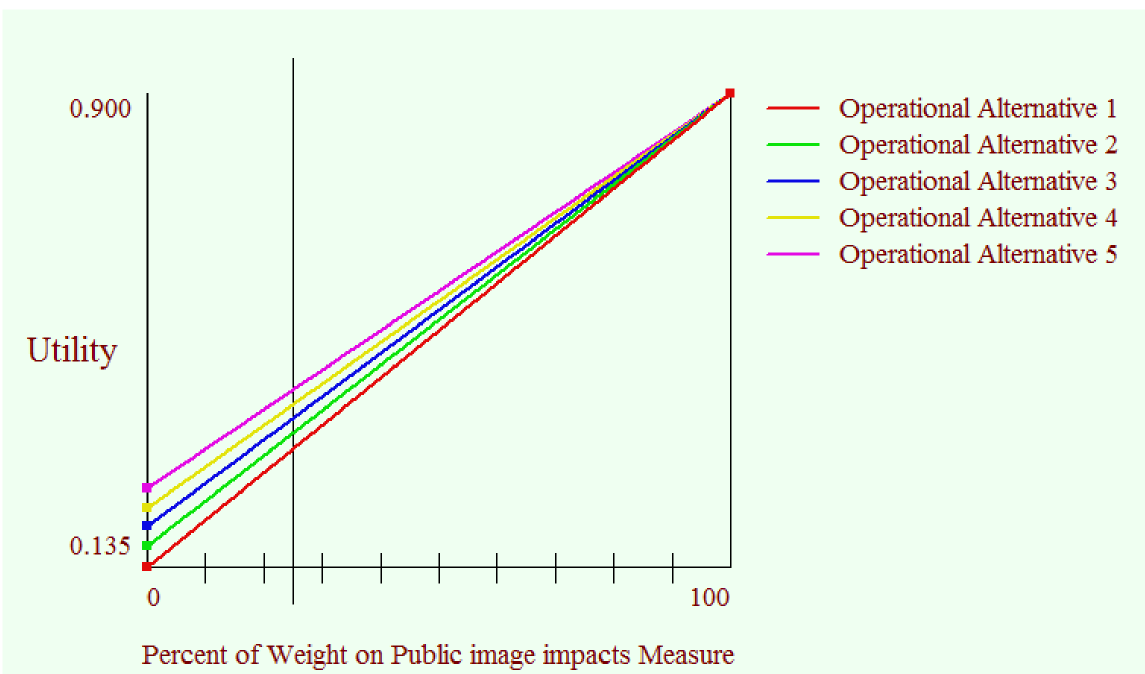


Figure 76: Sensitivity graph for public image impacts at very conservative attitude

4.7 Discussion

As explained in the introduction chapter, the overall goal of this study was using a general structure for an RIDM framework that can help OPEs in the process of identifying the best operational alternative during high inflow events. As described how we implemented this in the current and previous chapter, we also intended to apply the framework to Cheakamus River system and develop the required elements. The results were meant to evaluate the recommended target maximum level in Cheakamus Project GOO.

As can be seen in figures 53, 55, 57, and 59, for all the different risk-taking attitudes, the operational alternative 5 is the recommended operational alternative by the framework. This alternative is actually an operational plan for Daisy Lake reservoir that has a filled storage volume of 300 cmsd in the reservoir at the beginning of high inflow period, October 17. The 300 cmsd is the same as the corresponding storage to target maximum level indicated in Cheakamus Project GOO. This means that the outcomes of the developed framework confirm the soundness of the recommendation in the GOO for target maximum level, even though different risk-taking attitudes have been examined.

For the neutral risk-taking attitude and at the corresponding risk levels, as can be seen in table 14, none of the alternatives causes any flood damage or public image impacts. The environmental impacts increase very slightly for alternative 1 to alternative 5. In contrast, hydropower revenue generation increases considerably from alternative 1 to alternative 5. This is because a decision maker with the neutral risk-taking attitude tends to omit the very large and less probable inflow scenarios and their consequences. Accordingly, the water level in the reservoir on October 17 has a significant impact on power generation while the change in the negative environmental impacts is negligible. Furthermore, as can be seen in figures 61 to 64, changing objectives weights does not affect the ranking of alternatives at neutral risk-taking levels. Therefore, for a decision maker with the neutral risk taking attitude in our study, the recommended target maximum level in Cheakamus Project GOO is a perfect recommendation under the available data, information, and utilized techniques.

For the risk-prone attitude and at the corresponding risk levels, as can be seen in table 15, none of the alternatives causes any flood damage or public image impacts; and the environmental impacts are less significant than those for neutral risk-taking attitude. In contrast, the hydropower revenue generation is more significant than that for neutral risk-taking attitude. This is because a risk-prone decision maker is willing to take more risks to increase the revenues at the cost of more considerable damages in the case that a high inflow event occurs. Accordingly, such a decision maker tends to underestimate the probability of occurrence of high inflow events with significant negative impacts to increase the revenues. In accordance with the results of our study as shown in figure 55, for such a decision maker the alternatives with higher water level in the reservoir at the start of the high inflow period are more preferable. Similar to neutral risk-taking attitude, changing weights has no effect on the ranking of alternatives. Consequently we could say for a risk-prone decision maker, the recommended target maximum level in Cheakamus Project GOO is a perfect recommendation as well.

For the risk-averse attitude and at the corresponding risk levels, as opposed to the neutral and risk-prone attitudes, some flood damage is taken into account in the process of making a judgement on the best alternative; although, still no public image impacts are anticipated. Moreover, as you can see in table 16, for alternatives with higher water levels in the reservoir, the environmental impacts are more significant. However, for these alternatives the revenue from power generation is more considerable as well. As displayed in figure 57, for a risk-averse decision maker, alternatives with higher water levels in the reservoir at the start of high inflow period are still more preferable. This is because the revenues are still more considerable than the likely damages and negative impacts at the related risk levels. Although, Figures 69 to 72 show that changing objectives weights could make a difference in this. As can be seen in Figure 70, increasing percent of weight on environmental impacts totally changes the ranking of alternatives. Therefore, we could say for a risk-averse decision maker without an unusual extra attention to environmental impacts, the recommended target maximum level in Cheakamus Project GOO is a reasonable recommendation.

For a very conservative decision maker who is not willing to take the risk of possible flood damage, negative environmental impacts, and public image impacts to increase the profitability of the operational plan, as displayed in figure 59, ironically, alternatives with higher water levels in the reservoir at the beginning of high inflow event are still more preferable. This at first is confusing because we expect that conservative thinking should lead to emptying the reservoir as much as possible before a possible high inflow or flooding event begins. This usually is correct but not for the case study of Cheakamus River system and Daisy Lake reservoir. A simple analysis of the results of inflow scenario generation clarify that 2% of the generated inflow scenarios are much larger than the others. Therefore, a very conservative decision maker tends to consider these inflow scenarios when it comes to estimating flood damages. Accordingly, given the small size of Daisy Lake reservoir, for these inflow scenarios the maximum flood damage would occur regardless of the water level in the reservoir at the beginning of the flooding period and how the reservoir is operated. Therefore, flood damage does not make any difference in the ranking of alternatives. Moreover, as you can see in table 17, at the corresponding risk taking levels to very conservative attitude, for different alternatives the changes in negative environmental and public image impacts are negligible while the power generation revenues are highly affected by the reservoir level at the start of high inflow period. Therefore, even changing objectives weights cannot make any difference in the recommendation that alternative 5 is the best operational alternative, unless environmental concerns become the main and only matter in the process of decision making.

To sum up, the results of our study prove that with the available data, information, and technologies at BC Hydro, and given the small size of Daisy Lake reservoir, keeping the reservoir level at the target maximum level in October as recommended in the Cheakamus Project GOO seems to be the best strategy to follow for operating this system. Note that the conclusion we come to from the results of our study tells us that for October in general and for the period of October 17 to 21 in specific, with the current information, data, and modeling technologies available to us, keeping the reservoir at the recommended level in the Cheakamus Project GOO seems to be the best approach. However, in the light of new information, data, and technologies we could re-examine this conclusion (and possibly reassess the GOO recommendations). We also do not generalize this conclusion to the entire high inflow season as we ran our models and did the decision making process for a specific time period in the year just to show how to utilize the virtual structure of the RIDM framework; how to utilize the specific modeling techniques developed or used in our study; and how to take account of the uncertainties and risks in the process. The entire process would be repeated in a similar manner for any other case study and/or time period in the year with the specific data and information for that case study and/or period.

Chapter 5: Summary, Conclusions, and Future Research

This chapter includes a summary, contributions of the author, and conclusions of this research. Future research and improvements are also explained in this chapter.

5.1 Summary

The purpose of this study was using the virtual structure of Risk-Informed Decision Making (RIDM) framework on reservoir operation during high inflow events; and then developing the necessary components of such a framework for Cheakamus River system in British Columbia. The process started with utilizing the structure of reservoir operation RIDM framework developed by Zaman (2010) and modifying it. Then, the work in advance and real time work were identified. Afterwards, in order to practically form the RIDM framework for Cheakamus River system, two types of required components were developed. The first type included components that held information and data, such as streamflow impact curves, and were all about work in advance. The second type was components that needed development or utilization of tools and methods that would be used in real time to implement the real time work. This included inflow forecast method, optimization model(s), decision makers' risk-taking assessment method, and multi-criteria decision making software package. For the Cheakamus River system, the selected tools and methods respectively included Moment Matching, the optimization model(s) developed based on Cheakamus Project GOO, the method in NASA's RIDM handbook for taking account of decision makers' risk taking attitude, and Logical Decisions for Windows MCDM software package.

The developed structure for reservoir operation RIDM framework during high inflow events is a general structure that can be applied to any watershed system. The practical applicability and merits of the framework were illustrated through applying it to Cheakamus River system. In order to examine the performance of the framework, the high inflow period of October 2003 from October 17 to October 21 was selected as a case study. However, we do not compare the real operational policies at that period with the recommendations of our framework, as at the time of developing the framework we had access to information that was not available at the time of the event. Instead, we use the framework to test the quality of the recommended operational requirements at Cheakamus Project GOO.

5.2 Contributions of the Author

In this study, we have used the existing virtual structure for an RIDM framework and either developed or utilized a number of techniques to form this structure in practice. The virtual RIDM structure for an RIDM framework can be found in several studies such as Lyubarskiy et al. (2011); and Zaman (2010) showed such a structure for reservoir operation. Two optimization models were developed and continuously modified; and in the end one single non-linear optimization model was developed and used based on the Cheakamus Project GOO. We also spent a great deal of time and effort studying, selecting, learning, adapting, and working with several existing techniques used in our study including Moment Matching, streamflow impact curves, and Logical Decisions for Windows. Moreover, we were able to make a meaningful connection between these models as the outputs of some were processed and used as the inputs of another. In the end, we applied our approach to the case study of Cheakamus River and generated results and conclusions that cannot be found in any other work.

5.3 Conclusions

This research presents the merits of developing a risk-informed decision making framework to handle the task of reservoir operation planning during high inflow and flooding periods. We show how such a framework can modify the decision makers' knowledge and participation in the process of decision making. In addition, we show how the framework can provide systematic and recorded evidence to justify the basis of a decision that can be used as recorded documents of decision making process to justify the actions taken in such events.

The developed framework in our study has a general structure that can be used in any watershed system. We show the practical applicability of the framework through applying it to the case study of Cheakamus River system. This application provides an example on how to apply the framework to a watershed system and the components that could be developed to create a coherent and solid decision making framework.

The framework also enables systematic and comprehensive risk assessment. Given the considerable amount of uncertainties in the process of reservoir operation, especially from inflow forecast, and the possible significant consequences of a poor reservoir operation plan, all-inclusive risk consideration and involvement in the decision making process is a requirement. The RIDM framework provides decision makers with thorough information on the existing risks and the possible outcomes of each decision.

Another benefit of using the developed framework in this research is adding efficiency to the decision making process. In the case of a flooding or high inflow event, the available time for making a decision is very short. Therefore, operation planning engineers need a pre-developed guideline to assist them with the task of planning for reservoir operation during the flooding or high inflow period. The developed framework in this study provides OPEs with a guideline that can be updated continuously in the light of new information, data, and technologies. Moreover, the framework provides the entity with a guideline that enables maximum and continuous stakeholder involvement in the process of decision making.

5.4 Future Research

While the framework used makes considerable contribution to modifying the current decision making process for reservoir operation during flooding or high inflow events, there are several areas to improve and extend the conducted analysis in this research. This could be implemented through:

- Applying the framework to other watershed systems
- Analyzing other inflow forecast methods
- Adding simulation models to the framework
- Increasing the quality and accuracy of streamflow impact curves
- Examining other risk assessment methods
- Examining other MCDM software packages and their recommendations

- Examining a wider range of risk-taking attitudes

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