Decision Analysis Framework for High Inflow Events for Small Hydropower Reservoir Systems

by
MD. SAZID ZAMAN

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Abstract

Hydro system operators are often confronted with a myriad of conflicting and challenging decision situations. In particular, managing hydroelectric facilities during high inflow or unusual events can be complex, time consuming and challenging. Most high inflow events that challenge operational planners are driven by hydrology, with either too much or too little water being available. Other factors such as unusual electricity market conditions, dam safety or equipment concerns also drive decision making.

In a typical case operators try to balance multiple, and at times, competing objectives during high inflow events. In the case of high inflow subject flood events, Operation Planning Engineers are usually under time pressure to make decisions when the potential outcomes of different management options are highly uncertain. In such situations, planners must quickly make critical and important decisions taking into account the current state of the system and latest available information and forecasts. Their decisions can have environmental, social and financial consequences.

The purpose of this research is to develop an effective tool for the Operation Planning Engineers in Generation Resource Management of BC Hydro (British Columbia Hydro and Power Authority), which can be quickly and efficiently used during high inflow events at some of BC Hydro facilities. We describe the process that we have developed to build a tool to implement a Structured Decision Making Framework for a typical BC Hydro facility. The tool addresses the inflow uncertainties associated with high inflow floods and includes multiple objectives that are difficult to measure by means of a common unit, which necessitated the development of utility functions and required a trade-off analysis to be carried out. In this paper we also describe a methodology to do the tradeoff analysis among the objectives.

We present the results of the analysis for a flood event in the Cheakamus River, October, 2003. At the end of the project decisions made in real-time will be less dependent on the planner's own risk tolerance and more aligned with corporate risk tolerances that are acceptable to senior management.

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List of Acronyms

AHP	Analytic Hierarchy Process
ALCAN	Aluminum Company of Canada Limited
ANP	Analytic network process
BC	British Columbia
BN	Bayesian Network
BPA	Bonneville Power Administration
CDF	Cumulative Distribution Function
CM	Commercial Management
CRO	Commercial Resource Optimization
DA	Decision Analysis
DAF	Decision Analysis Framework
DP	Dynamic Programming
DSS	Decision Support system
ESP	Ensemble Stream flow Prediction
Fortis BC	Fortis British Columbia
HEC	Hydrologic Engineering Center
H&TS	Hydrology and Technical Services
IPP	Independent Power Producer
IWRM	Integrated Water Resource Management
LDW	Logical Decisions for Windows
LP	linear programming
MAUT	Multi-Attribute Utility Theory
MCDM	Multiple criteria decision making
MCM	marginal cost model

MIP	mixed integer programming
MUF	Multi-measure Utility Function
NLP	Non Linear Programming
OI	Operational Information
OPE	Operation Planning Engineers
OPT	Operations Planning Tool
PI	Plant Information
PSOSE	Planning, Scheduling and Operations Engineers
RFS	River Forecasting System
SAW	Simple Additive Weighted
SCL	Seattle City Light
SDP	Stochastic Dynamic programming
SP	Stochastic Programming
SLP	Stochastic linear programming
STOM	short term optimization model
SUF	Single Utility Function
TBL	Triple Bottom Line
TVA	Tennessee Valley Authority
UBCWM	UBC Watershed Model
USACE	United States Army Corps of Engineers
WCT	Water Compliance Tool

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Chapter 1: Introduction

1.1 Background

BC Hydro is the third largest electric utility in Canada, serving 95% of the population of British Columbia. It is a provincial crown corporation, accountable to the BC government through the Ministry of Energy, Mines and Petroleum Resources, and has been in operation as the BC Hydro and Power Authority since 1961 (Power Pioneers, 2010). Regulated by the BC Utilities Commission, BC Hydro currently operates 31 hydroelectric facilities, and three natural gas-fueled thermal power plants in several regions of British Columbia contribute to energy production in the Province. In British Columbia, almost 90% of the electricity is produced by hydropower plants located throughout the Province with a total generating capacity of 10,700 megawatts (MW) and an average annual energy production of 48,000 GWh (BC Hydro Annual Report, 2009).

BC Hydro manages its hydroelectric dams in order to maximize electricity generation and revenue, subject to numerous constraints such as dam failure, downstream water level requirements for fish spawning and local water supply, navigation, upstream recreational activities etc. Reservoir management must consider day to day level operation, as well as infrequent high inflow flood events, which are an important part of the watershed hydrology.

BC Hydro periodically deals with high inflow flood events in their systems. For instance in 1980 a large spill at the Ruskin dam was a necessary due to very high inflow. The spill caused flooding in the downstream floodplain and caused significant property damage. The 1992 spill over the La Joie Dam on the Bridge River causes serious impacts on the downstream spawning channels and public property (Foutiou, 1993), which created serious public image impact for the BC Hydro management. Another serious flooding risk regularly affects the Cheakamus basin, which is a major tributary of the Squamish River. The Squamish River respectively experienced a number of major flood events in 1921, 1940, 1955, 1968, 1975, 1980-1984, 1989-1991, and 2003. These floods have resulted in property damages and other indirect losses (Journeay, 2005).

This study focuses on the development of a decision making framework which can be integrated with in BC Hydro operations' tools to support efficient early decision making during high inflow flood events in order to minimize the property damages and other impacts.

1.2 Problem Definition

BC Hydro Operation Planning Engineers (OPEs) department consists of a team of engineers who are responsible for the operation and planning the BC Hydro system of reservoirs. Operation Planning Engineers (OPEs) plan the overall day-to-day operations of BC Hydro's numerous facilities. The time frame for these operations is from near real time to one or several years in the future. During high inflow events, OPEs need to make several flood routing decisions taking into consideration concerns which can be very difficult to resolve efficiently in a very short period of time. In most of the cases, they are required to make choices among competing objectives such as impact to residential areas, fish spawning channels downstream, small or large industries downstream, etc., which must be aligned with the risk tolerances and the BC Hydro Triple Bottom Line guidelines (BC Hydro TBL Guideline, 1999).

Another major concern for the OP engineers is the use of probabilistic inflow forecasts to develop operating strategies. BC Hydro's inflow forecast team (Hydrology and Technical Service Department) issue deterministic forecasts for short-term inflows and probabilistic forecasts for long-term seasonal inflows using the UBC Watershed Model (UBCWM, Quick 1995). For the short term forecast 5-day (or 7-day) inflow forecasts are issued each morning, daily average inflow sequences which correspond roughly to 25% (highest), 50% (mean) and 75% (lowest) exceedance probabilities. Using the inflow forecasts, the OPE's currently use a number of simulation and optimization models to aid them in developing a strategy to operate the dams in the system. However during high inflow events, the forecasts do not reliably capture the magnitude of the actual inflows. Therefore, currently the OPEs had to rely mainly on past experience to develop a strategy to manage the high inflow event. These strategies are typically updated daily as new forecasts are issued.

The difficulty of decision making during high inflow events, together with current reliance on subjective experience, which must account for many constraints on reservoir operation, shows a need for an objective, rational decision framework which can be applied during high inflow events. This can be achieved by implementing a Decision Analysis Framework.

1.3 Objective and Deliverables of this Research

The purpose of this research is to develop a Decision Analysis Framework (DAF) for responding to the high inflow events in a manner that reflects the preferences and values of BC Hydro. The framework will allow planners to more quickly respond to flood emergencies and openly and transparently communicate operational decisions made to stakeholders and senior management.
The deliverables of this research will include the following:

- Test DAF concept for at least one project. One case study has been chosen for this research, which is the Cheakamus Flood event of October 14th to October 18th, 2003;
- Upgrade the present operations and planning tools of the Operation Planning Engineers group to be appropriate for the project;
- Select a suitable Decision Analysis software package to fit the requirement for these kinds of high inflow event reservoir operations;
- Participate in a number of workshops to train the Operation Planning Engineers and BC Hydro management on the Decision Analysis Framework;
- Write a report summarizing findings and recommendations in the form of this thesis.

1.4 Organization of Thesis

The thesis is organized into five chapters. **This chapter** represents an introduction to the problem and the motivation for the work on this research topic. It also outlines the goals and objectives of this research. **Chapter 2** reviews the literature on the decision analysis techniques, with emphasis on the practical modeling and optimization techniques that are used by utilities in the industry today. **Chapter 3** describes the importance of integrating a Decision Analysis Framework (DAF) in the OPEs operation tools and the analysis of the appropriate methodology to implement DAF. **Chapter 4** presents a short description of the case study which has been chosen for this research and is followed by the results of the methodology described in the previous chapter.

Chapter 5 describes the summary and conclusions of this study, which includes an evaluation of the strengths and limitations of the proposed modeling methodology, and the lessons learned from developing and implementing the Decision Analysis Framework. This chapter also gives recommendations for future development of the Decision Analysis Framework.

Chapter 2: Literature Review

This chapter reviews the literature on multi criteria decision analysis and optimization techniques. The first section reviews the decision analysis techniques that are used for different water resources problems and discusses issues associated with using those techniques. Sections 2.2 through 2.4 review the literature on available techniques for performing the multi objective decision analysis using optimization models. Section 2.5 discusses current practices used to develop Decision Analysis Frameworks for real world problems.

2.1 Decision Analysis

"Decision Analysis is a formalization of common sense for decision problems which are too complex for informal use of common sense" (Keeney, 1982); this is one of the best definitions of decision analysis.

Dealing with a decision problem often results in uncertainties due to data unavailability, variability, and knowledge deficiency, which has been a major concern for decision making (Xu & Tung, 2009). Decision analysis technique help decision makers make better decisions and basically formalize the thinking and processes that decision maker wishes to use to solve the problem. Keeney (1982) discussed many examples and illustrated the complexity and has shown the many and interwoven characters involved in decision analysis situations. For example many issues must be clearly understood in multiple objectives, such as the difficulty of identifying good alternatives, intangibility, etc., which contribute to the complexity of the decision problems. Fundamentally, decision analysis does not solve the problem, though it provides some systematic ways or basic steps to rank the options or alternatives for the decision maker, which helps them choose the best option and document the underlying assumptions.

The decision analysis technique can be summarized by the following four steps, as illustrated in of Figure 1:

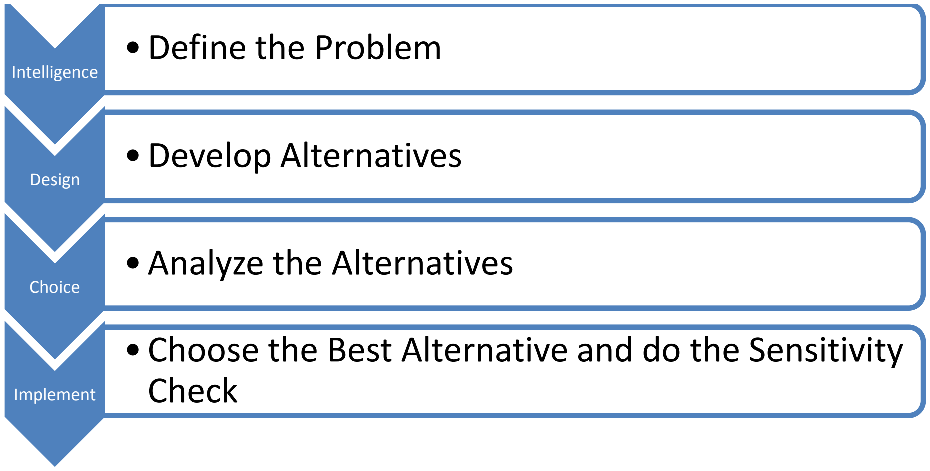


Figure 1: Decision analysis Steps

Step 1. Define the problem.

The goal of this step is to express the issue in a clear, one-sentence *problem statement* that describes both the initial conditions and the desired outcomes. Sometimes it is not possible to summarize the problem in one sentence due to the complexity of the problem. Still, the process must identify root causes, limiting assumptions, system and organizational boundaries and interfaces, and any stakeholder issues. In mathematical form, these requirements are the constraints describing the set of the feasible (admissible) solutions of the decision problem. On the basis of these requirements, some conflicting goals will be found that need to be reconciled in order to establish the solution for the problem. After selecting the goals, certain criteria will be set for each measure to provide the flexibility to compare among the alternatives.

Step 2. Develop Alternatives.

After identifying the main goals, the focus should be on alternatives which offer different approaches to changing the initial condition into the desired condition while meeting the problem requirements. The number of alternatives should be limited because sometimes the number of alternatives conflicts with expressing them within the associated criteria of the goals (Raiffa et al., 1999).

Step 3. Analyze the Alternatives.

There are several techniques and tools which can be used to solve the decision analysis problem. The selection of an appropriate tool or technique is not an easy task and depends on the type of the decision problem, as well as on the objectives of the decision makers. The criterion helps to make the assessment on the basis of the objective (factual), with respect to some commonly shared and understood scale of measurement (e.g. money) or can be subjective (judgmental), reflecting the subjective assessment of the decision maker. At the end of the assessment, the decision tool can rank the alternatives based on an overall score of the criterion.

Step 4. Choose the best alternative.

The final step is to choose the best alternative, but it must be validated against the requirements and the goals of the decision problem. It may happen that the decision making tool recommendations were misinterpreted due to the complexity of the problem. The way to overcome this issue is to apply the sensitivity check and perform further analysis (possibly historical). But in the end, the execution of the alternative will entirely depend on the decision maker's 'gut feeling'.

The book 'Smart Choices' by Raiffa et al. (1999) demonstrates a set of eight elements they named 'PrOACT', which are the orderly steps that could be taken to carry out a formal decision analysis. According to them, the PrOACT elements provide a framework that can profoundly redirect one's possibilities and chances of finding satisfactory solutions as a decision maker.

2.2 Multi Criteria Decision Making

Sometimes in Decision Analysis for a problem, it becomes important to achieve several goals at the same time, which is one of the factors that contribute to the complexity of the decision analysis (Haimes et al., 1990). Multiple criteria decision making (MCDM) refers to making the decisions in the presence of multiple, usually conflicting, criteria. The problem may have multiple risk measures and uncertainties that need to be analyzed and assigns them internal weights to incorporate them into a common objective of the larger problem. In this process, each objective has its own constraints or limitations, and this often create difficulties for decision makers in coming up with the best solution. A very important aspect of multi criteria decision analysis is environmental decision making where the decision maker must consider the inherent tradeoffs between sociopolitical, environmental, ecological and economic factors (McDaniels et al., 1999, Kiker et al., 2005). This analysis is usually carried out with stakeholder's participation in decision analysis procedure and is now considered to be one of the common practices in performing the multi objective decision analysis today.

There are many examples that can be found in current literature on multi objective decision analysis. In their book, Keeney and Raffia (1976) explain a case study on 'Airport Development for Mexico City' where they use multi attribute utility functions to solve the decision problem. Recently, interesting research was done by Han, Diekmann, Lee and Ock (2004) where they show how a multi criteria decision analysis technique maximizes the value of a firm after creating a financial risk management portfolio of international projects, integrating the risk hierarchy of both individual projects and the corporate level.

2.2.1 Multi Criteria Decision Analysis in Reservoir Operations

Reservoir operation is challenging decision problem due to the presence of multiple conflicting objectives and the probabilistic or stochastic nature of inflows. There are many conflicting decision objectives such as reservoir level (storage capacity), power generation (market price), flood mitigation, recreation and fish issues, etc. Among them, the most important issue is flood management or mitigation during the high inflow seasons (Agrell et al., 1998). Sometimes downstream water quality becomes a more important issue due to the fish spawning channels or water supply requirements. It becomes even more complex if there are a number of reservoirs in a series with each having their own upstream and downstream constraints. In his report, Kickzo (2008) gives a comprehensive explanation of the steps he and his group have taken into consideration to develop a multi criteria decision support system for the Siemianowka reservoir system after considering reservoir storage and fisheries, wetland and agriculture, energy production and flood protection criteria.

i) General Multi Criteria Decision Analysis Techniques

The main four criteria to apply the MCDA are: capturing the nature of the decision-making process so that it creates a win-win process; identifying the uncertainty in making the trade-offs in the objective functions and the preferences; maintaining sufficient generality, and being able to analyze the results of the decision making process (Cohon, 1973). In these days, a large number of Multi-Criteria Analysis (MCA) techniques and approaches have been developed for different specialized projects (Keeney and Raiffa, 1976; McCartney, 2007). Typical MCDA methods are the Simple Additive Weighted method (McCartney, 2007), the Analytical Hierarchy Approach (Willett & Sharda, 1991), Analytic Network Process (Saaty, 1996), and Multi Attribute Utility Function (Keeny & Raffia, 1976). Among them, the most commonly used methods are the Analytic Network Process and the Multi-Attribute Value Function approach (Keeny and Raiffa, 1976), where criteria are either organized into a hierarchy or else separated into a small set of important criteria within which the options are weighted and compared. Some of these methodologies are discussed below:

a. ***<u>Simple Additive Weighted method (SAW)</u>***

The main theory of the SAW method is to obtain a weighted sum of the performance measures for each alternative. The basic steps of SAW method are: (1) scale the values of all attributes to make them comparable and (2) sum up all the values of the attributes for each alternative (Kabassi and Virvou, 2004). In weighted summation all criteria are transformed into a commensurate scale (usually 0 to 1, where 1 represents best performance), multiplied by weights and then summed to an overall utility. If u_i represents the utility of an alternative i and *v* and *w* are the value of an attribute and the weight for that attribute respectively then:

$$\mathrm{u_i} = \sum_{j=1}^{m} v_{i,j}\, w_j$$

Where,

$$\sum_{j=1}^{m} w_j = 1;$$

$$0 \leq w_j \leq 1.$$

There are many examples of the weighted summation method in environmental management and water resource planning (Howard, 1991).

b. ***<u>The Analytical Hierarchy Approach (AHP)</u>***

AHP was proposed by Saaty (1980) as a method of solving socio-economic decision making problems and has been used to solve a wide range of problems. According to Zahedi (1986), the Analytic Hierarchy Process (AHP) needs four steps to solve a decision problem. Those are:

1. Break down the decision hierarchy in such a way that the decision problem will be a hierarchy of interrelated decision attributes;
2. The input data is organized so a pair-wise comparison of the attributes can be done. Collect input data by pair-wise comparisons of decision elements;
3. "Eigen value" is used to give the relative weight for the pair-wise comparison of the objectives,
4. Aggregating the relative weights of decision elements to arrive at a set of ratings for the decision alternatives (or outcomes).

There are many uses of the AHP method to solve the problems related to water resources planning and management issues. In their paper, Willett and Sharda (1991) describe how they selected the best flood control project for the U.S. Army Corps of Engineers through this technique. Jaber and Mohsen (2001) shows how they built their AHP-based decision support system considering economical, technical, availability, reliability and environmental criteria for the evaluation and selection of potential non-conventional water resource supply, which include desalination of brackish and seawater, treated waste water, importation of water across boundaries and water harvesting.

c. ***<u>The Analytic network process (ANP)</u>***

This is the so-called super matrix technique of the analytic hierarchy process as it becomes difficult to develop the decision problem in a structured hierarchical way using an analytic network process and goal programming for interdependent information system project selection due to the interaction and the dependence of higher-level elements on a lower-level element (Lee & Kim, 2000). Hämäläinen and Seppäläinen (1986) show a case study on Energy Planning decision problem, using an ANP method, and explain that careful use of the analytic network process can indeed provide help in problem structuring in planning energy sources.

d. Multi-Attribute Utility Theory (MAUT)

Multi-Attribute Utility Theory is an evaluation scheme which is very popular amongst consumer organizations for evaluating products. In their book, Keeney and Raffia (1976) explain the mathematics of expressing the utilities of multiple-attribute outcomes or consequences as a function of the utilities. According to them, the possible functions may be additive, multiplicative or multi-linear. Each of the functions has a different mathematical algorithm and a different way of expressing the decision problem to the decision maker. Another way of developing these functions is the value judgment. Keeny et al. (1995) developed for BC Hydro a multi attribute utility value model (cost-equivalent function) which is based on value judgments provided by a group of senior system planners and a senior management authority of the project. McDaniels (1996) developed an index for evaluating environmental impact for BC Hydro based on multi-attribute utility theory where he used the weighting tradeoff method to perform the decision analysis.

ii) Other Practical MCDA Techniques for Reservoir Planning Operation

Many researchers have developed computer-based decision support systems for multi objective management and operation of reservoirs and river systems (e.g., Simonovic and Savic, 1989; Jolma, 1994; DeGagne et al., 1996; Koutsoyiannis et al., 2002). The most common reservoir system planning and operation is undertaken using simulation and optimization models (e.g., Lund and Guzman, 1999). These models are based on the simple physical engineering principles of dam operation such as reservoir storage level, power generation requirements, downstream flood control, water supply requirements etc. and different rules or seasonal operating strategies. Both simulation and optimization techniques require that the management 'problem', whether it be a long-term planning or an operational issue, is formulated explicitly in a mathematical algorithm.

a. Simulation Model:

Simulation models depict the physical behavior of a system using a computer to develop an abstraction of reality. Simulation is different from mathematical optimization programming techniques, which give the 'Optimal Decision' for system operation that meets all system constraints while maximizing or minimizing some objective (Yeh, 1985). Basically, simulation can aid the decision maker in analyzing different alternative scenarios after considering all the constraints and consequences of each alternative and choosing the best alternative (McCarteny, 2007). A good definition of a simulation model for a reservoir system is “a typical simulation model for a water resources system is simply a model that simulates the interval-by-interval operation of the system with specified inflows at all locations during each interval, specified system characteristics and specified operating rules” (Yeh, 1985).

Simulation models have been used for reservoir operations for many years and come in different model formats such as Excel worksheets, in the form of mathematical descriptions (Sigvaldason 1976), or as rule curves (Yeh, 1985). In his paper, Yeh (1985) gives a comprehensive review of the simulation models that were the current state-of-the-art. Nowadays, there are very user friendly software packages available on the market with well-designed Graphical User Interfaces that are being used for simulating reservoir operations. Many models are customized for a particular system. However, currently the trend has been to develop general simulation models that can be applied to any basin or reservoir system. In his paper, Wurbs (1993) summarizes some good examples of different simulation models both for specific reservoir systems and for general reservoir systems. Recently, the Hydrologic Engineering Center of the U. S. Army Corps of Engineers developed generalized software system (ResSim) that can be used for simulating almost all types of reservoir systems (HEC Website, 2010). The HEC ResSim can be used to perform reservoir operation modeling at one or more reservoirs for a variety of operational goals and constraints, including release requirements and constraints, hydropower requirements and downstream needs and constraints (McCarteny, 2007).

b. <u>Optimization Model</u>

Simulation models are useful for future planning and for making good choices for the next day’s operational alternatives, but they are not well suited to determining the ‘best’, or optimum, strategies when flexibility exists in coordinated system operations. These models’ outputs sometime become impossible for the decision makers to choose and to analyze for their specific study. Very small changes in the alternatives through the simulation models change some of the attributes’ preferences, and it could create difficulty for the decision maker in interpreting the results. The use of optimization techniques can overcome these problems and they have been applied by the decision makers to systematically derive optimal solutions, or families of solutions, under specified objectives and a set of constraints. The application of optimization techniques in reservoir studies has a long history (e.g., Yeh, 1985; Wurbs, 1993) and a diverse array of optimization methods for dam operation has been formulated. In most of the optimization models, the objective of the problem is to maximize or minimize a single, or a set, of goals on the basis of the decision makers' choice or the organization's general objectives, subject to a set of constraints. Such constraints include explicit upper and lower bounds on storage (e.g. for recreation, mitigation of the flood impact, and assuring minimum levels for dead storage and power plant operation) which limits the storage to maintain desired downstream flows. They could also include considerations for water quality control, fish and wildlife maintenance as well as protection from downstream flooding (McCarteny, 2007).

Currently, the most commonly used optimization techniques are Linear Programming (Yeh, 1985), Dynamic Programming (Buras, 1966) and Non-Linear Programming (Yeh, 1985). In recent years, these techniques have been extended to include new approaches such as "optimal control theory", "fuzzy logic" and "artificial neural networks" (McCarteny, 2007).

- Linear Programming (LP):

The Linear Programming technique has been widely used in the field of water resources management, especially for multi-reservoir system operation and management. It is the best technique to solve a problem in which all relations among the variables are linear, both in the constraints and the objective function. The main advantage of this type of model is in solving large scale problems, as it assures convergence to global optimum solutions, without having to have an initial solution. LP uses a well-developed duality theory for sensitivity analysis and the ease of problem formulation (Shabani, 2009).

Dorfman (1962 in Yeh, 1985) showed in his model how a LP could be used in three model versions with increasing complexity. In his model, he used storage capacities and target releases as decision variables, and his objective was to maximize an economic objective function while satisfying continuity and technological constraint.

Gilbert and Shane (1982 in Yeh, 1985) describe a LP model, which they named as HYDROSIM, which was used to simulate the 42 reservoirs of the Tennessee Valley Authority (TVA) system based on a set of operating rules. The model computes reservoir storages, releases, and hydroelectric power generation for each week of a 52-week period (Wurbs, 1993).

Shawwash (2000) developed a LP short term optimization model (STOM) to maximize the value of BC Hydro resources. The model has the capacity to maximize revenue, considering the US and Alberta transactions with BC, and the hourly load and demand of the whole BC Hydro system.

Sreckovic et al. developed an Operations Planning Tool (OPT) with a linear programming (LP) approach and a mixed integer programming (MIP) algorithm model to solve the reservoir operation problem for BC Hydro's Water Use Planning Process (Penner, Sreckovic & Vassilev, 2008).

- Dynamic Programming (DP):

Dynamic Programming (DP), a method for optimizing a multistage process, has been extensively used in the optimization of reservoir operations. In this programming model, release decisions are made sequentially, at different time-steps. It exploits the sequential decision structure of reservoir systems to determine an optimal solution to the problem. The dynamic programming method was developed by Bellman in 1957 (Yeh, 1985) as a procedure for optimizing a multistage decision process. Due to the capability to support non-linear and stochastic features which characterize water resource systems, it is being widely used in this sector. Until now, different approaches using DP have been applied to a variety of dam operation issues, including systems of multiple reservoirs, conjunctive uses of surface water and groundwater, or optimizing hydro plant efficiency in multi-turbine systems (Yeh, 1975; Klemes, 1977). Still, the computation time to run the DP models is a big problem, even when using the latest computers (McCartney, 2007).

- Non Linear Programming (NLP):

The NLP is more complicated that the other two techniques described above, and is more time consuming than the other two methods. It offers a more general mathematical formulation, which means that more effective algorithms for large-scale, multi-objective optimization can be utilized (Yeh, 1985). In his paper, McCarteny (2007) gives some examples of NLP models which have been used in the field of hydropower optimization problems that comprise several large-scale reservoirs, including Arnold et al., 1994, and Barros et al., 2003.

- Fuzzy Logic:

Fuzzy logic was first introduced by Zadeh (1965) and has been applied in various approaches within water resources such as decision making and control. The basic explanation of fuzzy arithmetic can be found in the works by Zimmermann in 1985 (McCarteny, 2007). Bardossy and Dissie (1993) give an interesting definition of fuzzy logic: “A fuzzy set is a set of objects without clear boundaries. In contrast to ordinary sets in the case of a fuzzy set a partial membership is also possible”. Fuzzy logic is being used to simulate the reservoir operation (e.g., Russell and Campbell, 1996; Shrestha et al., 1996). Recently Panigrahi and Mujumdar in 2000 (McCarteny, 2007) demonstrated the utility of fuzzy logic for reservoir operation through application to the Malaprabha Reservoir, in the Krishna Basin in India.

2.3 Dealing with Uncertainty in Optimization Models

The main problem with the water resources systems is the uncertainties that create a huge problem in developing mathematical models and their input parameters. This uncertainty may also include the spatial and temporal variability, the inherent nature of a problem, instrument measurement error, human or technology inaccuracy and other errors in modeling because of simplification or ignorance. Uncertainties also occur due to data unavailability and knowledge deficiency of the modeler, and could result in a major decision making concern (Xu & Tung, 2009). From the modeler’s point of view, considering these uncertainties makes the model larger, nonlinear, complex, and sometimes infeasible (Shabani, 2009).

There are many ways to deal with the uncertainties in an optimization model, such as the expected value, reliability, and return period of an uncertain quantity (Wang, 2005). From the beginning of the development of the optimization models, modelers were trying to input those criteria into the models to deal with the uncertainty, and at last they succeeded in modeling the stochastic behavior of the problem in these types of optimization models. Stochastic Programming (SP) is an extension of the linear and the nonlinear programming to decision models, where coefficients (parameters) are not known with certainty and have been given a probabilistic representation. In his book, Birge (1997) defined Stochastic Programming models as ‘optimization under uncertainty’. Later, these SP models were extended to the various versions of general optimization techniques such as Stochastic Linear programming with recourse, Stochastic Dual Dynamic programming, Stochastic Non-Linear programming, Multi

Stage Stochastic programming and Stochastic Integer Programming, etc. (Yeh, 1985, Shawwash, 2000, Sahinidis, 2004).

A stochastic LP model was first implemented in reservoir operation by Loucks, and was developed for a single reservoir that was subject to random, serially correlated net inflows (Yeh, 1985). Subsequently, much more complicated stochastic models have been developed to reflect stochastic nature of stream flows' more realistically, evaporation losses, and more complex systems involving multiple reservoirs (e.g., Dahe and Srivastava, 2002; Tu et al., 2003). MODSIM is a generic SP program based on LP approaches that has been developed specifically for modeling water resources systems and reservoir operation (McCartney, 2007). Recently, Zhang et al. (2007) developed a stochastic LP model that represents the allocation of irrigation water among the blocks of paddy rice fields in an agricultural district.

Another way to represent the stochastic reservoir operation is the Stochastic Dynamic Programming (SDP) model. Druce (1989, 1990) developed a Stochastic Dynamic Programming (SDP) model, which is called the marginal cost model (MCM), for long term planning of the BC Hydro system. It was used to calculate the monthly marginal value of water in the Williston reservoir (GMS plant) for each storage level over a planning period of 4 to 6 years. Gablinger and Loucks in 1973 and Wang et al. (1992 in Yeh, 1985) compared SDP with SLP, and all of them reached the conclusion that SDP is preferred to SLP for reservoir operation problems, because SDP has a much smaller computational effort (including computing time and memory) than SLP. But later, several investigators found that SDP does not provide feasible solutions when it is applied to complex large-scale water resources systems, because of the exponential increasing computational effort with the numbers of reservoirs, objectives, and the number of random variables used (Wang, 2005).

2.4 Multi Objective Trade-off Analysis

Multi objective optimization problems create the need for the decision makers to deal with the non-inferior solution points. For multi objective optimization the feasible range of solutions is much more complex than that of a single objective optimization (Neufville, 1990). That is why the non-inferior solutions (also named 'Pareto Optimal solutions') are the typically used in evaluations for multi-objective problems by decision makers.

One of the main concerns for the decision analyst is expressing those non-inferior sets for the decision makers. Some papers evaluate and illustrate these non-inferior points in a tabular format (Romero et al., 1987); while others evaluate them in a two or three dimensional graphical format (Neufville, 1990, Das & Dennis, 1997) or by a systematically varying weight on the other objectives (Tauxe et al., 1979, Neufville, 1990, Leung et al., 2001, Cotrutz et al., 2001)

For derivation, the two most popular ways to evaluate those non-inferior sets in an optimization technique are the Constraint method and the Weighting method. The basic difference between these two methodologies is their way of transforming the problem into a one dimensional problem (Neufville, 1990). There are both advantages and disadvantages for each of these methods. Below is a short description on the use of these methods in various research projects.

(a) Weighting Method:

Cohon & Marks (1973) indicated that the method was first developed by Kuhn and Tucker in 1951 to generate the set of non-inferior solutions. In this method the set of objectives is transformed into one objective function after assigning a weight to each of them. Suppose we need to optimize k objective functions denoted as g, for a set Y. Mathematically:

Optimize: $Y= g_1 (X), \ldots, g_k(X)$, where k is the number of objectives.

Subject to: constraints on X

In the weighting method this is done by assigning a set of weights, w_k, for each objective so that the objective function for the problem becomes:

Optimize: $\Sigma\, wY = \Sigma\, w_k\, g_k(X)$

Subject to: constraints on X

To develop the inferior set we need to vary the weights in the objective function in every optimization run. This technique was initially demonstrated by Gass and Saaty in 1955 (Cohon & Marks, 1973). According to Revelle et al. (2003) the sum of the weights in the objective function should sum to 1.

The weighting method is quite effective in finding the non-inferior solutions when the resolution of the weights is used to accurately define the set of non-inferior solutions (Revelle et al., 2003). Das & Dennis (1997) describe some of the drawbacks of the weighting method to generate a set of Pareto solutions.

In the field of water resources planning and operations this method has been used since the beginning of use of multi-objective optimization. Miller and Byers (1973) demonstrate the feasibility of using the weighting tradeoff method to describe some environmental enhancement occurring through land treatment programs. Tauxe et al. (1979) shows the generation of tradeoff curves for a reservoir operation with a slightly modified weighting method technique. Wang (2005) developed a stochastic multi-objective dynamic programming optimization model for finding noninferior solutions of the operation problem of some reservoirs which are in parallel. Zhang et al. (2007) used a stochastic multi-objective LP model to allocate irrigation waters to the plots of the paddy rice fields in an agricultural district by using the weighting technique. Higgins et al. (2008) applied a stochastic non-linear programming weighting method technique to derive the water resource allocation decision with uncertain inflows across the planning horizon.

(b) Constraint Method:

The constraint method is in a sense the dual of the weighting method which follows directly from the Kuhn-Tucker conditions for noninferiority (Willis & Perlack, 1980). The essential idea of this method is optimizing one objective function while representing all other objectives as constraints. Next after getting the optimal points for one objective, the objective and constraints need to be switched to acquire the optimal points for the next objective and it needs to be repeated for all objectives. Suppose we need to optimize k objective functions denoted as g, for a set of objectives Y. Mathematically:

Optimize: $Y= g_1 (X), \ldots, g_k(X)$, where k is the number of objectives.

Subject to: constraints on X

In constraint method,

Optimize: Max $Y= g_1 (X)$

Subject to: $g_2 (X), \ldots, g_k(X)$ and the original set of constraints on X

The main advantage of this method is its systematic way of generating the noinferior solutions for all the objectives where the major disadvantage is that it can be tedious and expensive to simulate and often could result in infeasible solutions when there are three or more objectives (Neufvill, 1990).

Cohon and Marks (1973) used a constraint method to show a tradeoff between net national income benefits from power, irrigation, and regional equity from an equal regional water distribution. In their paper, Romero et al. (1987) show how they solve an agricultural planning problem comprising of three objectives: employment, seasonal labor, and business profitability using a multi objective constraint tradeoff analysis. Leung et al. (2001) illustrated a special version of the constraint method trade-off analysis in which they reveal various optimal plans for quota allocation of cod fish among vessel groups in the Barents Sea. ReVelle et al. (2003) in Chapter 5 of his book illustrates some examples of the constraint method.

The major weakness of both the weighting and constraint methods is their computational efficiency when there are several objectives. To mitigate this, many other methods have later been developed as discussed by Cohon & Marks (1973). Recent modifications to the constraint method were introduced, such as the multi-population objective genetic algorithm tradeoff technique (MPGA & MOGA) by Cochran et al. (2003) which can solve multi-objective problems using parallel computers.

2.5 Decision Analysis Framework

A Decision Analysis Framework (DAF) is a structure in which the inputs will be specified at all the decision elements, utility functions, and tradeoff functions, and the output will be ranked decision alternatives for a decision maker to choose from. All the inputs in the procedure must be accepted by the people who are involved in the problem and the management team involved. An interesting definition of Decision Analysis Framework may be "a framework that is the combination of MCDA and Decision Support system (DSS) and the outputs will be the decision alternative". Shawwash (2000) shows an interesting flow chart (Figure 2) of typical Human-Machine interface for decision making.

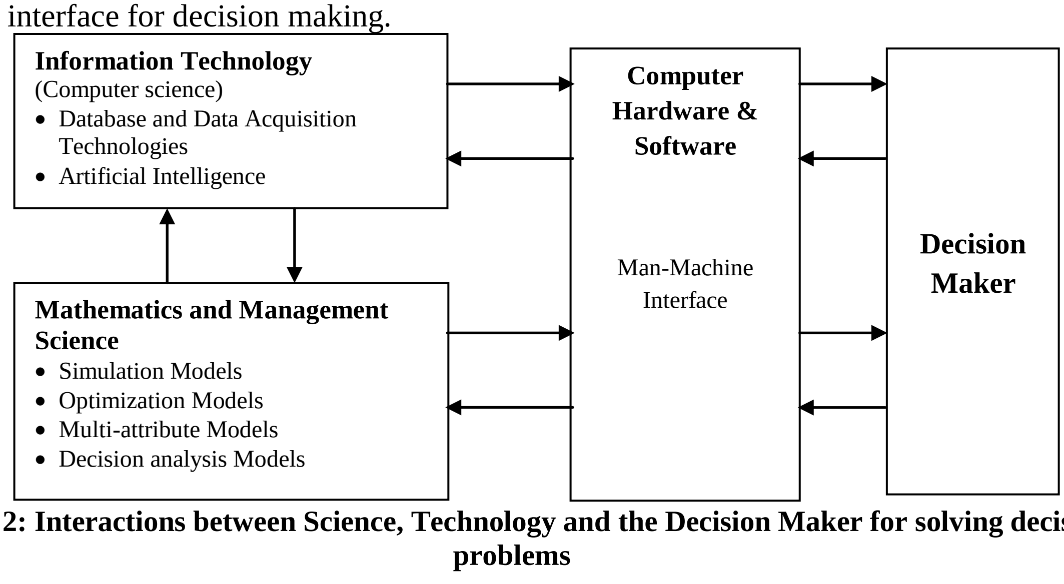


Figure 2: Interactions between Science, Technology and the Decision Maker for solving decision problems

Adapted from Shawwash 2000

The effectiveness of these frameworks and the availability of current high technologies make the whole decision analysis procedure much easier so that many researchers around the world are developing these kinds of frameworks using tools. Some of the examples of these types of frameworks are described below.

'STRIVER' was a three year European commission (EC) (2006-2009) funded organization that developed a strategy and methodology for improved IWRM - an integrated interdisciplinary assessment of European and third world country's river basins (STRIVER website, 2010). Through the process, they developed an interesting methodology for performing the multi criteria decision analysis and they named the framework 'Pressure Impact Multi Criteria Environmental Flow Analysis' (Nhung et al., 2008). At the end they used the contour curves in a multi criteria analysis (MCA) software tool to perform the decision analysis. The example given in this paper is of the Sesan River which has multi-sectoral interests and is regulated by a series of hydropower projects; the framework was developed after the joint consideration of multiple stakeholder interests.

In their research, Reichert et al. (2005) demonstrate, for a river rehabilitation project, how a Decision Analysis Framework can provide support in structuring the decision and stakeholder involvement processes and that can express the scientific assumptions, their consequences, and social preferences explicitly.

Pahlow et al. (2008) describe their research methodology for developing an integrated and interdisciplinary flood risk assessment methodology by considering the risk involved and by applying decision analysis techniques.

The US Army Corps of Engineers (Dunn & Deering, 2009) developed a tool for evaluating the full range of possible inflow uncertainties during flood flow seasons for planning purposes and for risk management decision making. The tool used is HEC-FRM (HEC-Flood Risk Management).

In next few chapters a Decision Analysis Framework has been developed for river systems in BC which can be used in the high inflow events to operate the dams into it. On the mean time to develop this framework, the components (contents) are described in to this literature review has been used for that river system.

Chapter 3: Decision Analysis Framework (DAF) and Modeling Methodology

This chapter summarizes the responsibilities of the Operation Planning Engineers Department of BC Hydro. This is followed by a presentation of the current procedures for dam operations, with reference to the importance and the need for a DAF tool for operations. The methodology used in this research is explained with the main topics on development of the cumulative distribution functions for damages, optimization modeling, which is used to obtain the value of damages, and the tradeoff analysis. Finally, the selection of the software package and a short description of the criteria used are provided.

3.1 Decision-Making Environment

3.1.1 Operation Planning Engineers (OPEs) Responsibilities at BC Hydro

The Operation Planning Engineers Department is one of seven departments within the Generation Resource Management division of BC Hydro. The others departments are: System Optimization; Planning, Scheduling and Operations (PSOSE); Hydrology and Technical Services (H&TS); Reliability and Planning; Water Resources and Licenses; and Coordination Agreements.

The OPEs have different responsibilities depending on the type of generating facilities (such as: hydro or thermal), and as the resource coordination. OPEs need to operate and plan the hydro system after considering many constraints, like water licenses for operating the hydro facilities, and must also consider the laws, regulations and guidelines of the provincial and federal authorities and other stakeholders. Typically, the constraints are related to target, minimum and maximum reservoir elevations and target, minimum and maximum flow releases at various times of the year as agreed to during the Water Use Planning (WUP) process most hydro facilities have gone through. Water license orders also require special operations and to facilitate monitoring for water use requirements or for the installation of physical works. Legislation, such as the Fisheries Act or the Heritage Act, for example, may restrict how projects may be operated.

Special operations may be required for dam safety, or for environmental, social or to meet other requirements.

Most projects operate within normal operating limits; however, during emergencies or special circumstances, extraordinary operations may be required. OPEs plan operations with input from a number of other departments and other lines of business. The regional offices or field operations identifies the requirements for plant maintenance or special operations. Powerex provides market advice and incentives to buy or sell power in the market and along with PSOSE identify opportunities that arise in long-term, day-ahead and real time operations. Dam safety provides guidance on operations and can impose temporary or permanent constraints. Departments outside of Generation Resource Management, such as the Bridge Coastal Restoration Program, for example, may require operational support that the OPE must plan for. BC Hydro Grid Operations may also request transmission outages from time to time for system reliability that may impact normal operations. At times, operations are coordinated with other electricity providers, such as Fortis BC, ALCAN, SCL and BPA.

The following list summarizes specific tasks that the OPEs must consider for maintaining a well functioning and efficient Hydro system operation:

- Provide PSOSE with the daily Generation Schedule for each facility, a short-term generation and water conveyance set of instructions, including those that may deviate from the specifications in the Generating Operating Orders (GOO);
- Given maintenance requirements, operating alternatives must be identified and optimized to achieve triple-bottom-line results;
- Assess the impact of reservoir operation on dam safety, fish, recreation, wildlife, communities and other non-power interests;
- Assess the energy costs and benefits of alternative operations;
- Assess the economic value of water in the reservoirs;
- Plan and track non-power releases of water to meet regulatory requirements for fish flows;
- Report any violations of the Water Licence requirements to the Comptroller of Water Rights;
- Track and approve maintenance outages using Commercial Management software;

- Liaise with BC Hydro Grid Operations to minimize generation's losses due to transmission constraints;
- Assess and approve Reliability-Must-Run, as required by BC Hydro Grid Operations ;
- Route flood events through the reservoirs;
- Manage ice jam flooding, where applicable;
- Manage power and other operating and coordination agreements or contracts;
- Maintain and update Generation Operating Orders;
- Recommend specifications for Water Licence compliance;
- Participate on operating committees, as required;
- Participate on environmental committees, as required;
- Participate at public meetings and for public consultation, as required;
- Co-ordinate IPP operations;
- Provide operational input and advice to engineering and other studies, as required;
- Document and communicate significant operational decisions; and
- Provide information and expert advice to stakeholders on hydro operations.

OPEs use different tools/software for the operations planning. The following list shows the available software packages and tools that can be used (from BC Hydro intranet and from personal communication with OPEs):

Software:

- Operational Information (OI) / Plant Information (PI) Processbook and Datalink;
- Commercial Resource Optimization (CRO) Database;
- CRO;
- Commercial Management (CM) Database;
- CM; and
- Time Studio.

OPEs use different tools for establishing the operating plans and for scheduling, with the following software packages:

- Plant-Specific Reservoir Routing Models, developed by OPE, for each plant (using MS-Excel (Simulation model);

- Operational Planning Tool (OPT) (Optimization model);
- UBC Reservoir Routing Model (Simulation model);
- Water Compliance Tool (WCT);

3.1.2 Limitations of the OPEs Tools

The above operation-planning tools such as the reservoir simulation models have limitations for their use in the high inflow (extreme event) periods. Most of the OPEs use one of the simulation models listed above for the daily operation of the hydro-facilities (personal communication with the engineers) and none of them directly/explicitly deal with the inflow uncertainty or tradeoffs between the operating objectives, such as: maximizing power revenue, up/downstream flood control, environmental/social impact etc. Again, one of the main problems in operating most of the hydro-projects during the high inflow seasons is the change in operation plans as inflow forecasts are updated by the H&TS Department.

According to BC Hydro's guidelines (BC Hydro Triple Bottom Line (TBL) Guideline, 1999), safe and continuous electricity must be supplied to the province that must meet the environmental, social, and economic value judgments of stakeholders. To properly incorporate the TBL guidelines within the operation planning tools during high inflow periods, the OPEs must change some of the operating rules for the normal operations.

Another shortcoming of the current operating and planning practices is the lack of record-keeping or documentation of the operating decision process during high inflow events, which could be helpful when updating or revising future strategies.

3.1.3 Value of the Proposed DAF Tool as an OPE Tool

After considering the factors described above, the value of a Decision Analysis Framework tool in the OPE operation tool packages becomes apparent. These kinds of decision support tools offer many advantages for maintaining a database with multiple-objectives or goals, providing impact measures and the latest and seasonal preferences for utility curves, and to define value tradeoffs for each river system. The parameters in such a tool can be updated and easily uploaded as necessary. The decision analysis tool incorporates the uncertainty of decision-making, like hydrology or the seasonal market price, and various non-power impacts like maintenance schedules, stakeholder participation, etc.

The decision analysis process is structured to communicate clearly about uncertainty, risk attitudes, and value tradeoffs, making it a quick and efficient way to evaluate operating alternatives by making tradeoffs among risks, costs, and other decision outcomes. Sensitivity analysis can also be accomplished quickly using such tools, which is a difficult task within the current state of art operation.

The most important advantage of the DAF is providing transparency, since the opinions of all levels of decision makers are accounted for, and this means that the company's TBL guidelines are incorporated into it. Thus, it would provide a valuable document for the Operations and Planning engineers for use in any future investigations about the operations during high inflow/extreme events periods.

3.2 Hydrology Inflow Forecast and Uncertainty

The UBC watershed model was developed by Dr. Michael Quick (Quick, 1977) for flood forecasting on the Fraser River in the 1970's. It was later adapted and modified by BC Hydro for calculating stream flow from mountainous watersheds and for forecasting inflows.

Five-day (or seven-day) inflow forecasts are issued in the morning of each working day (Figure 3). A forecaster runs the RFS using current basin conditions and precipitation and temperature forecasts, which may be further adjusted by a BC Hydro meteorologist. Forecasters sometimes apply post-model adjustments to the forecasted inflows to account for temporary model inaccuracies. During the high inflow events, they can provide three 5/7 day inflow forecast sequences each day with the following approximate exceedence probabilities attached to them: 25%, 50% and 75%. Figure 3 is an example of H&TS Department forecast for Cheakamus basin on October 14, 2003 and the actual observed inflow at that period; this clearly shows that this particular forecast underestimated the observed inflow.

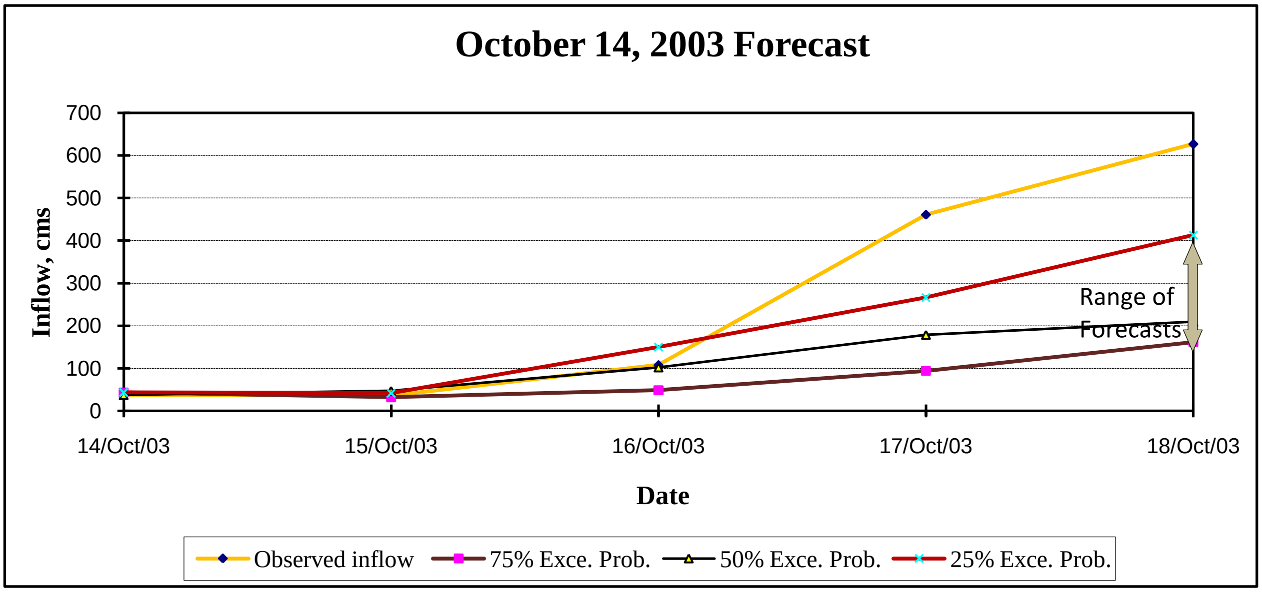


Figure 3: Five-day forecast issued by the H&TS Department (October 14, 2003, morning).

Even the highest probable forecast (25% exceedence probability) did not capture the inflow for that period. The current forecast can only provide three points of the probability distribution function each day (point distribution), and does not provide a good representation of the entire distribution and this creates difficulties for the OPEs when they try to capture the uncertainty in the reservoir inflows.

3.3 Development of Inflow Scenarios

The main problem with the current forecast is that it cannot capture the full distribution of the inflow during periods of high inflows. Consequently, a fitted volume distribution method is used using the Log Pearson Type III distribution function to adapt the current forecast and create a probability distribution function that can be used in the decision analysis process described herein. To accomplish this, the EasyFit – Distribution Fitting Software (MathWave website, 2010) is used. Forecasts created by the H&TS Department have excedence probabilities of 25% (high forecast), 50% (regular forecast) and 75% (low forecast). For research purposes, the H&TS Department generated one more forecast with 10% excedence probability (October 14, 2003, morning) for the October 14, 2003 event. The proposed method that was used to create the inflow scenarios for this research project is summarized below.

The volume of the five-day flood inflow forecast was with four exceedence probabilities of 10%, 25%, 50%, and 75% as shown in Figure 4 and listed in Table 1, to fit a Log Pearson Type III distribution for the total forecast volume as a function of the exceedence probability curve. The shape of the five-day inflow forecast for each exceedence probability was also calculated. The volume curve-fitted function and the shape are then used to calculate the five-day inflows for a number of exceedence probabilities (ranging from 2.5% to 99.5%). Figure 4 shows the curve-fitted flood forecast volume for the 2003 flood event.

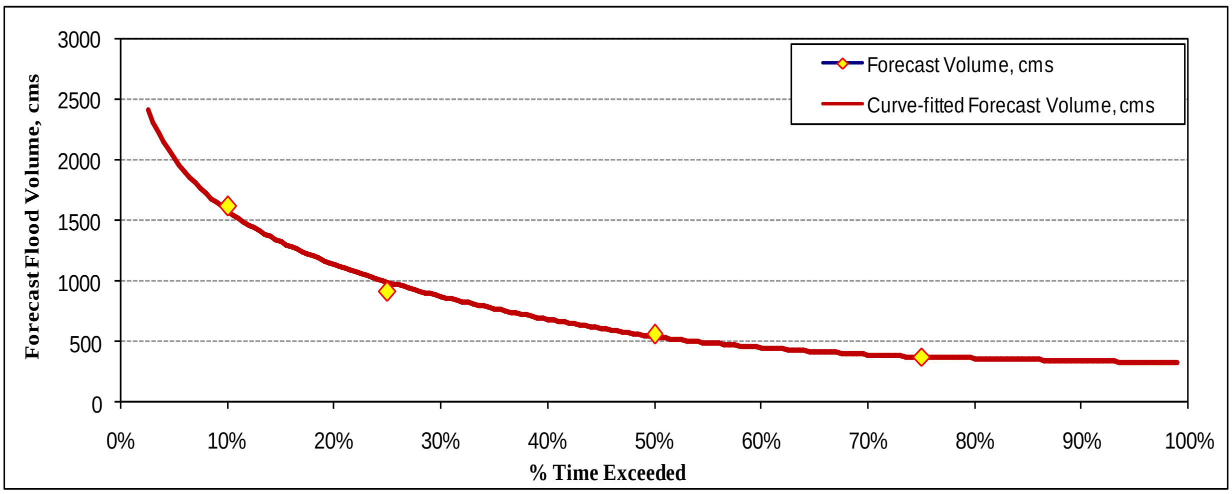


Figure 4: Extended exceedence probability distribution for forecast days.

Table 1: Cheakamus inflow, volume forecast and shape (October 14, 2003).

% Exceedence Probability & Shape	14-Oct-03	15-Oct-03	16-Oct-03	17-Oct-03	18-Oct-03	Forecast Volume, cms
10%	44	56	284	492	743	1619
10% Shape	3%	3%	18%	30%	46%	100%
25%	44	42	150	267	413	916
25% Shape	5%	5%	16%	29%	45%	100%
50%	37	37	102	179	209	564
50% Shape	7%	7%	18%	32%	37%	100%
75%	43	32	49	94	162	380
75% Shape	11%	8%	13%	25%	43%	100%

The fitted function and forecast inflow shapes are used to sample or generate a number of scenarios (in this case, 195 in total) for the five-day forecast. The generated scenarios should cover the entire range of the exceedence probabilities at low resolution (e.g., randomly generated or at 0.05% equally spaced increments). The same process is repeated for the tributary inflow forecast. If the forecast is not available, it can be calculated using a certain percentage of the Cheakamus inflow forecast (e.g., in this case 50%). Figure 5 shows the Cheakamus inflow scenarios generated using the fitted curves for the 2003 flood event.

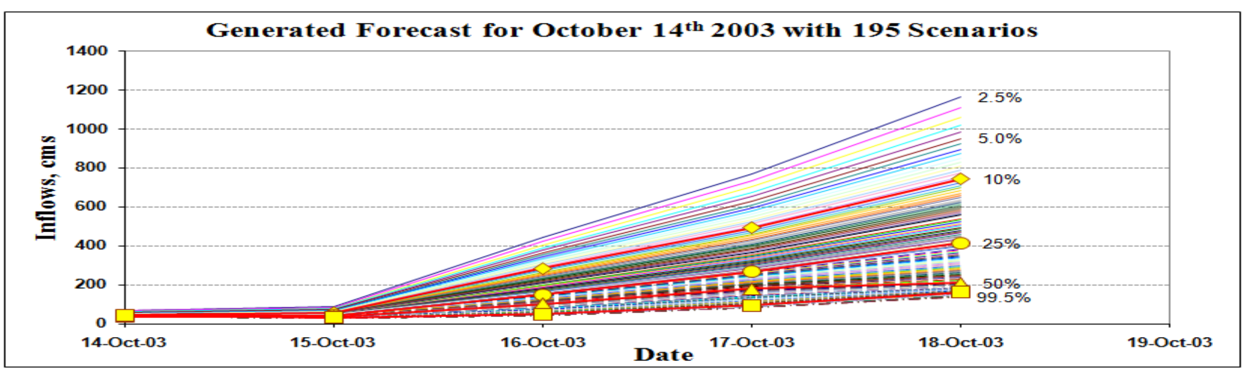


Figure 5: CMS volume-generated inflow scenarios.

3.4 Elements of the Decision Analysis Framework

Some common elements can be found in the decision analysis process, which are necessary for capturing the uncertainty and for making the trade-offs analysis. The objectives (interests, values, concerns, fears, and aspirations) (Hammond et al., 1999), and measurements of the objectives are crucial, since the performance measurements determine the uncertainty of the decision process and determine which alternatives should be chosen by the decision maker. For this research, the key elements of the problem are summarized by the consequence table (Table 2):

Table 2: Consequence table for the Project.

Goal	Objectives	Measures	Performance Measurement
Best Flood Routing Operation	Maximize Revenue Generation	Revenue Gain or loss	Million Dollar (M$)
	Minimize Flood Damage	Flood Damage	Million Dollar (M$)
	Minimize Environmental Impact	Damage to the Spawning Channels	Impact Units
	Minimize Reputation Impacts	Corporate Risk Matrix Scale	Qualitative Measures

The goal chosen for this research is to select the 'Best Flood Routing Operation,' and based on the dam operation alternatives that are suitable for high inflow periods. After discussing and interviewing the OPEs and planners, and reading through the operation materials for previous events, three operating alternatives are considered for this research:

Alternative 1: Normal Operation

Normal operation mainly defines the regular operation based on expected (50% probability) inflow sequence where satisfying system needs is the priority.

Alternative 2: Power Maximization Operation

Power maximizing operation describes running the turbines at full load to generate power in anticipation of high inflows, with the next priority being given to spilling water through the spillways to control the reservoir level.

Alternative 3: Pre-Spill Operation

Pre-Spill operation allows water to spill through the spillways prior to spill during the high inflow and prior to filling of the reservoir. This operation is the most conservative and allows some extra room to be made in the reservoir for attenuating the potential high inflows at the peak of the flood.

3.5 Impact Curves and Utility Curves

Impact functions represent a fundamental concept in assessing flood damage; e.g., structural damage due to inundation, fish spawning channels or forest damage, loss of lives, revenue loss due to dam operations, the corporation's public image, etc. In deriving the damage curves, historical data must be continuously collected and analyzed and a regional extension of the available flood damage data and curves may also be fruitful. The curves are used to estimate the expected losses of the proposed best operation plans using risk and uncertainty analysis (National Academy Press, 2000). From the literature, many different ways are available for developing the damage/impact curves. Some of the most applicable and practiced methods in the literature include:

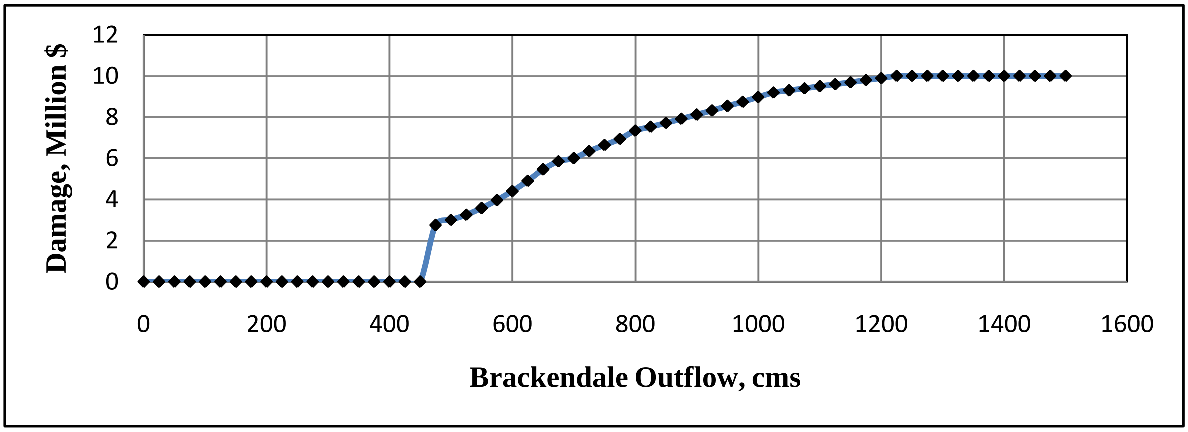
- High Level Expert's Opinion (Messner et al., 2006);
- Historical Records (USACE Manual No. 1110-2-1619);
- Field Works (Prettenthaler et al, 2010); and
- Hydraulics, Hydrological and Mathematical Modeling (Luino et al., 2009).

The damage functions typically have three key elements (USACE Manual No. 1110-2-1619):

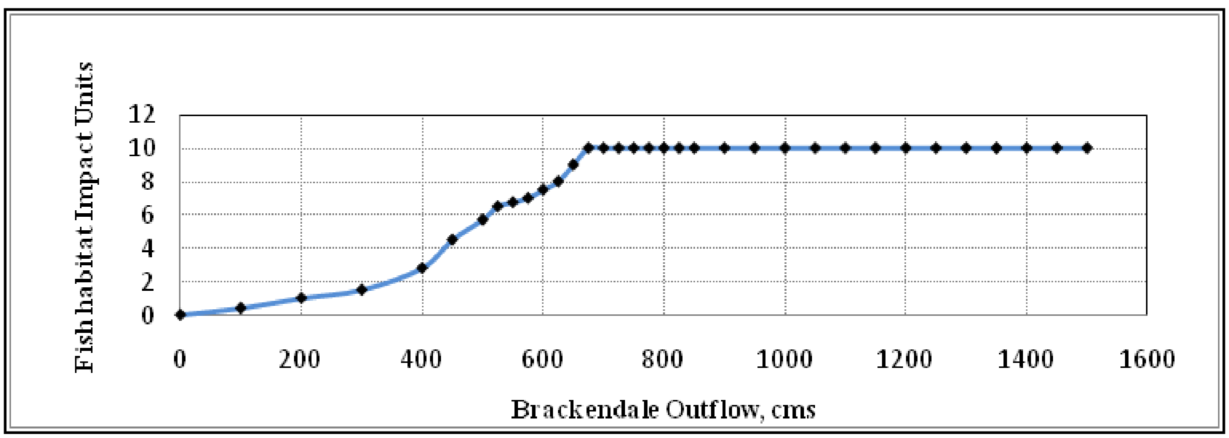
- Threshold at which the damage starts,
- Rate at which the damage increases, and
- The maximum level of damage.

The last point is especially important for capturing the whole uncertainty in the decision-making process and can be explored through value tradeoffs. In addition, a sensitivity analysis of the three points reveals: 1) their role in decisions; and 2) the value of gathering better information.

In this research, damage curves were developed using experts' opinions. The OPE experts for the Cheakamus system and experts from other departments on flood impacts and economic analyses (like Hydrology, Engineering, Reliability and Planning, Environmental and the Water Resources and Licensing groups of BC Hydro) were interviewed several times before refining two damage/impact curves for two different objectives (flood damage, Figure 6a; and environmental impact, Figure 6b). A revenue generation curve was developed by using the optimization model according to the constraints and the water flow through the turbines. The public image impact (Table 3) was derived from the discrete qualitative impact point index, using the flood damage curve and the BC Hydro risk matrix (BC Hydro intranet). All of the damage/impact curves were based on the river flows at the Brackendale gauging station.



(a) Flood damage curve.



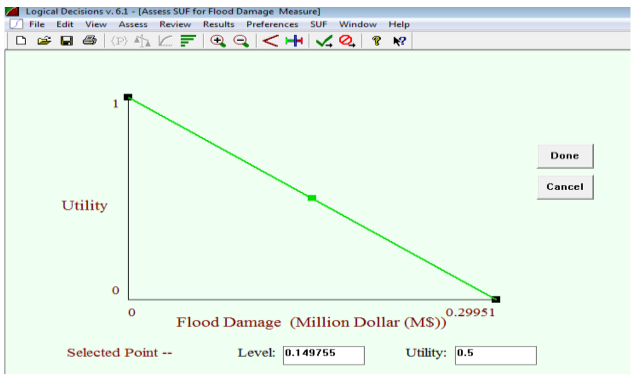
(b) Environmental impact curve.

Figure 6: Damage/Impact curves

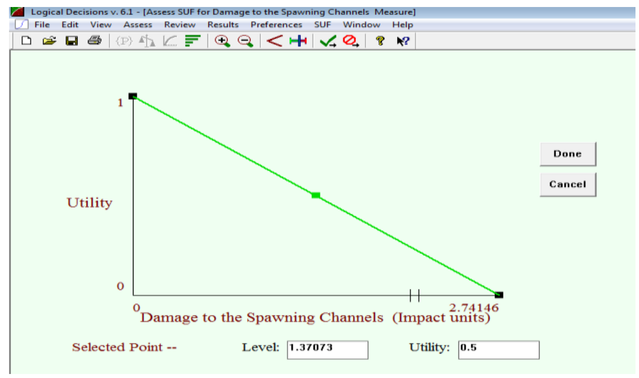
Table 3: Risk matrix levels for the public image.

Risk Matrix Level	Media/Opinion Leader's Response
S1	No Coverage
S2	Brief negative or mixed local media coverage
S3	Possible isolated "one-off" major media coverage
S4	Some negative media coverage at provincial level
S5	Widespread and sustained negative media coverage
S6	Opinion leaders nearly unanimous in public criticism. Sustained and very negative media coverage. National media coverage

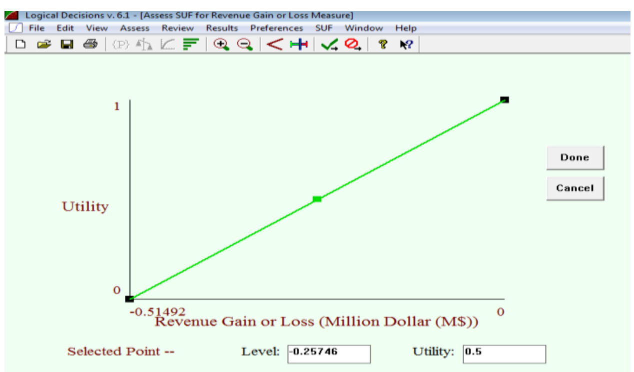
A utility function transforms the usefulness of an outcome into a numerical value that measures the personal worth of the outcome. The utility of an outcome may be scaled between 0 and 100, converting the monetary matrix into the utility matrix. This utility function may be a simple table, a smooth continuously increasing graph, or a mathematical expression of the graph. For this research, the opinions of experts were used to develop the utility functions for different measures, where the 'Single Utility Function (SUF)' method was used for Flood Damage, Environmental Impact, and Revenue Generation measures, and the 'Direct Assessment' method was used for the Public Image measure. The decision analysis software package, Logical Decisions, is able to develop the utility function on the basis of the information provided, like the maximum utility for this measure, the minimum utility for this measure, and the preference for the intermediate point of the utility. Experts were asked for the information, which was used to generate impact curves (Figure 7; Figures 7a-7d are taken directly from the DA software).



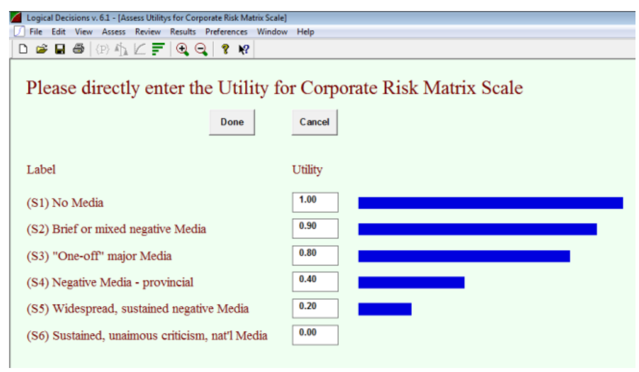
(a) Flood damage utility curve.



(b) Environmental impact utility curve.



(c) Generation revenue utility curve.



(d) Public image impact utility curve.

Figure 7: Utility curves for the measures.

3.6 Optimization Model

The main objective of this component is to operate the hydro facility in a suitable way during the flood seasons after fulfilling the following objectives:

- Maximize economic returns from power generated by the Hydro Generating System;
- Minimize adverse effects from flood events through operation of the Hydro Generating System;
- Protect the integrity of the river bed at First Nation's heritage sites and the cultural values, while maximizing wild fish populations used for food;
- Minimize environmental impacts, such as fish spawning channels downstream; and
- Minimize the public image impact.

The optimal solution must consider multi-objective optimization problems, while considering the above objectives. Some uncertainties are present including inflow forecasts, market prices with seasonal variability. As the operation is for a very short duration, market prices are set at a fixed value. Considering the above factors, the OPT model (Penner et al. 2008) was extended to formulate a Stochastic Linear Programming Optimization model is used for the optimization. The question as to how the alternatives should be considered in the model, in terms of their outputs, is dealt with separately, in developing the damage CDFs for the DA software. To solve the problem, a 'Penalty Function' based methodology (Sigvaldason, 1976) was applied in the model. The penalty functions (using monetary values) mainly concern the reservoir elevations and discharges from each release facility (Figure 9) and/ or for the total discharge. Penalty functions are used in the objective functions and may be violated if needed (soft constraint) to create different alternatives in the model. The OPEs suggested the values for the penalty functions for the three alternatives described above, and each time the model was run to obtain output values. Most of these objective functions were described in the Water Use Plan (WUP, 2005) and in the water license for Cheakamus river system. The system constraints (i.e., dam safety issues, reservoir capacity, turbine flow, etc.) were described in BC Hydro's System Generation Operating Order (GOO, BC Hydro intranet) and in BC Hydro's System Local Operating Order (LOO, BC Hydro intranet). In the optimization model, the damage curves were formulated as a piece-wise linear function (Fourer, 2003), so the model can calculate the damages from outflows of the different release points and for all scenarios (5 days x 195 scenarios for each day). Figure 8 illustrates an example of the release points for the Cheakamus facility.

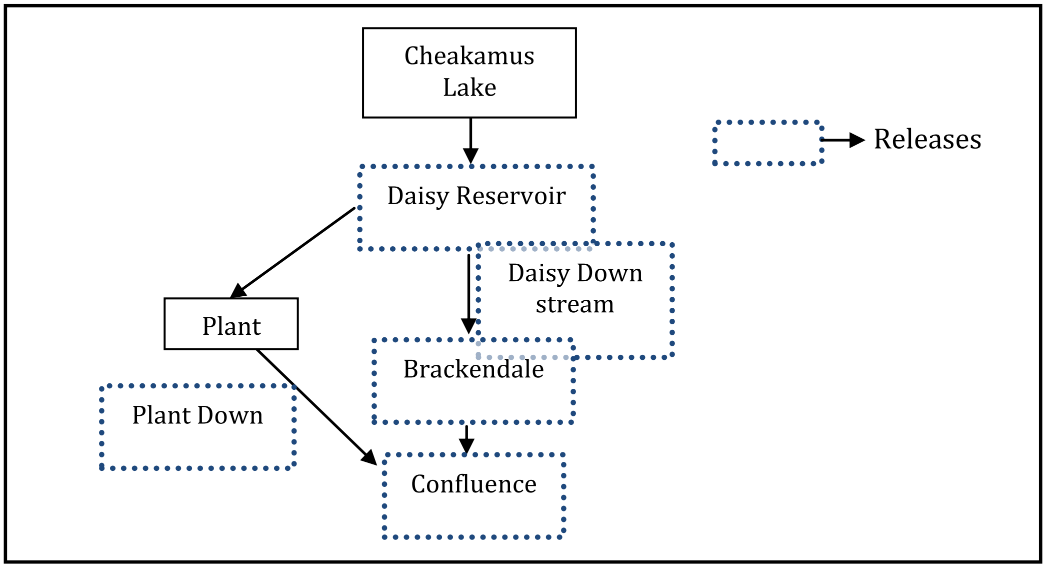


Figure 8: Cheakamus schematic for the optimization model.

Another purpose of the optimization model was to develop the tradeoff curves for the various objectives. Basically, this stochastic linear model was an extended step for the tradeoff analysis. In the second step, a multi-objective 'weighting method' technique was used to develop the tradeoff curves for the three objectives (Flood Damage, Environmental Impact, and Revenue Generation).

The mathematical programming techniques and to formulate the model equations as discussed below, AMPL modeling language (Fourer et al., 2003) software was used, while the IBM ILOG CPLEX optimizer (IBM website, 2010) solver was used to solve the optimization problem.

3.6.1 Stochastic Linear Programming Model

3.6.1.1 Objective Function

In the objective function, penalty functions were added in terms of preferred ranges of reservoir elevations and discharges. Deviation outside this range is not desirable and was penalized and the greater the deviation the less desirable the operation becomes. A zone of preference was established around the preferred range. Deviations outside the preferred range were penalized; the greater the deviation, the greater the penalty. Again, the objective function optimizes the values of the inflow forecast (195 scenarios), with associated probabilities within the forecasted period. The objective function mainly minimizes the loss of money from the operation after considering the penalties. Mathematically it can be presented by the following expression:

Minimize Penalties:

$$Min(Z) = \sum_{i=1}^{scen} \sum_{t=1}^{forecast} \{ (-\underbrace{f_{\mathrm{Rev}} + f_{\mathrm{Re}l1} + f_{\mathrm{Re}l2} + f_{\mathrm{Re}l3} + f_{\mathrm{Re}s} + f_{\mathrm{previousday/weekinflow}}}_{\text{PENALTIES (soft constraints)}}) \times P_{i,t} \}$$

Where,

scen = Number of inflow scenarios,

forecast = Period of forecast (for model, start to end study period),

$P_{i,t}$ = Probability associated with the forecasted scenario; $\Sigma P_{i,t}=1$,

f_{Rev} = Power generation revenue

f_{Rel1} = Diversions through reservoir release structures penalties

f_{Rel2} = Diversions through other release nodes penalties

f_{Rel3} = Diversions through power plants penalties

f_{Res} = Reservoir Elevation Requirement penalties

$f_{\text{Prev. Day or Week Inflow}}$= Releases as a function of previous day(s) inflow penalties

3.6.1.2 Decision Variables

var $V_{p,t,g}$ = reservoir ‘p’ storage (volume) at time ‘t’ and scenario ‘g’,

var $El_{p,t,g}$ = reservoir ‘p’ storage (elevation) at time ‘t’ and scenario ‘g’,

var $spilQ_{p,t,s,g}$ = reservoir ‘p’ diversions through the reservoir release structures ‘s’ (spillways, outlets, valves, …) at time ‘t’ and scenario ‘g’, and

var $turbQ_{p,t,s,g}$ = reservoir ‘p’ turbine flow through the reservoir power plant release ‘s’ at time ‘t’ and scenario ‘g’.

3.6.1.3 Constraints

Continuity Equation:

$V_{p,t,g=}$ $V_{p,t-1,g}$+ ($QIR_{p,t,y,g}$ +$QturbINF_{p,t,g}$ +$QspillNF_{p,t,g}$ -∑$turbQ_{p,s,t,g}$ -∑$spillQ_{p,s,t,g}$)* HoursInDay*SecIn_Hr

Where:

$V_{p,t-1,g}$ = volume of reservoir ‘p’ at time ‘t’ and scenario ‘g’,

$V_{p,t-1,g}$ = volume of reservoir ‘p’ at time‘t-1’ and scenario ‘g’,

$QIR_{p,t,y,g}$ = natural inflow to reservoir ‘p’ at time ‘t’ and scenario ‘g’ of year ‘y’,

$QturbINF_{p,t,g}$ = inflow to reservoir ‘p’ by power plants from other power plants at time ‘t’ and scenario ‘g’,

$QspillNF_{p,t,g}$ = inflow to reservoir ‘p’ by releases from other power plants at time ‘t’ and scenario ‘g’,

∑ $turbQ_{p,s,t,g}$ = total turbine flow from the reservoir ‘p’ to the downstream at time ‘t’ and scenario ‘g’, and

∑ $spillQ_{p,s,t,g}$ = total spill flow from the reservoir ‘p’ to the downstream at time ‘t’ and scenario ‘g’.

Minimum and Maximum Elevations in the Reservoirs:

$MinEl_p <= f(El_{p,t,g}) <= MaxEl_p$

Where:

$MinEl_p$ = minimum elevation level for the reservoir 'p',

$f(El_{p,t,g})$ = a function to calculate the minimum and maximum turbine limits as a function of the elevation of the reservoir 'p' at time 't' and scenario 'g', and

$MaxEl_p$ = maximum elevation level for the reservoir 'p'.

Minimum and Maximum Release Flows:

$MinSpillQ_{p,s} <= SpillQ_{p,s,t,g} <= MaxSpillQ_{p,s}$

Where:

$MinSpillQ_{p,s}$ = minimum spill flow through the 's' release structure of reservoir 'p',

$SpillQ_{p,s,t,g}$ = spill flow through the 's' release structure from the reservoir 'p' to the downstream at time 't' and scenario 'g', and

$MaxSpillQ_{p,s}$ = maximum spill flow through the 's' release structure of reservoir 'p'.

Minimum and Maximum Flows that are Directed Through the Power Plants:

$MinTurbQ_{p,s} <= TurbQ_{p,s,t,g} <= MaxTurbQ_{p,s}$

Where:

$MinTurbQ_{p,s}$ = minimum turbine flow through the 's' release structure of reservoir 'p',

$TurbQ_{p,s,t,g}$ = turbine flow through the 's' release structure from the reservoir 'p' to the downstream at time 't' and scenario 'g', and

$MaxTurbQ_{p,s}$ = maximum turbine flow through the 's' release structure of reservoir 'p'.

Water License for Power Generation:

$\sum turbQ_{p,s,t,g} <= License\_Allocated_p * 1000000/(dT * HoursInDay * SecIn\_Hr)$

Where:

$\sum turbQ_{p,s,t,g}$ = total turbine flow from the reservoir ‘p’ to the downstream at time ‘t’ and scenario ‘g’, and

$License\_Allocated_p$ = the water license is related to the total plant diversion in a reservoir.

Minimum and Maximum Storage in the Reservoirs:

$StorMin_{p,t} <= V_{p,t,g} <= StorMax_{p,t}$

Where:

$StorMin_{p,t}$ = minimum storage capacity of the reservoir ‘p’ from the storage vs. elevation curve,

$V_{p,t,g}$ = volume of reservoir ‘p’ at time ‘t’ and scenario ‘g’, and

$StorMax_{p,t}$ = maximum storage capacity of the reservoir ‘p’ from the storage vs. elevation curve.

Releases through the Spillways from the Rating curves:

$spill_p = spilQ_{p,s,t,g}$

Where:

$Spill_p$ = spill from the reservoir ‘p’ for both ‘free’ and ‘controlled’ gateway from the release structure rating curves, and

$SpilQ_{p,s,t,g}$ = spill flow through the ‘s’ release structure from the reservoir ‘p’ to the downstream at time ‘t’ and scenario ‘g’.

Minimum and Maximum Turbine Flow from the Rating Curves:

$TurbMin_{p,s,t} <= El_{p,t,g} <= TurbMax_{p,t}$

Where:

$TurbMin_{p,s,t}$ = minimum turbine flow capacity through the ‘s’ release of the reservoir ‘p’ from the turbine flow vs. elevation curve,

$f(El_{p,t,g})$ = a function to calculate the minimum and maximum turbine limits as a function of the elevation of the reservoir 'p' at time 't' and scenario 'g', and

$TurbMax_{p,s,t}$ = maximum turbine flow capacity through the 's' release of the reservoir 'p' from the turbine flow vs. elevation curve.

3.6.1.4 Alternatives and Penalty Functions

The major penalty functions for the model variables are defined by: 1) releases and 2) elevations in reservoirs.

The impact of the releases and elevations on the objective function is introduced by the three-dimensional penalty functions. Mathematically, a penalty function is expressed as: Penalty = F (time, flow, or elevation). As the linear programming cannot deal directly with non-linear functions, the penalty functions are presented as piece-wise linear functions. Non-linear functions are transformed to a series of linear functions connected by brake points. The co-ordinates of the breakpoints define the piece-wise functions. An example of a release flow penalty function for the outflow from a particular point of the system on the October 14 is given in Figure 9. Similarly shaped penalties can be defined for each day within a year, if required.

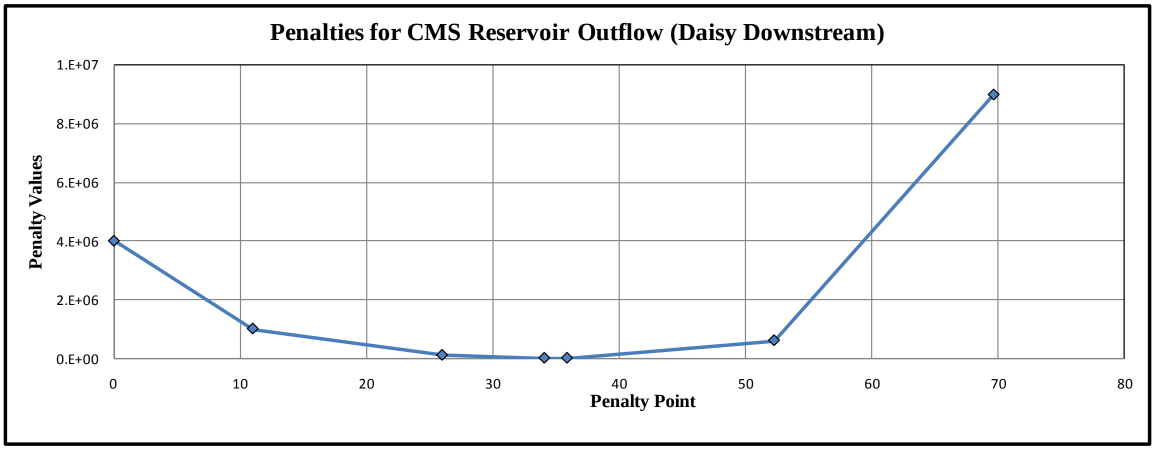


Figure 9: Penalty function for release.

The x-axis represents the flows (or elevations, for elevation penalties), while the y-axis represents the penalty values. The penalty function (shown in Figure 9) indicates that the flow regime between 34.1 and 35.9 m^3/s is preferred (zero cost between the two flows). The cost increases according to the penalty function, when flows are greater than 35.9 m^3/s and less than 34.1 m^3/s.

The piecewise linear curves used for penalties or rating curves have to be consistent with the rules of linear programming. They must be convex for minimizing problems and concave for maximizing problems. Since the model features a minimizing objective function, the piece-wise penalty function must be convex; i.e., the pieces must have increasing slope (increasing first derivative).

By providing penalty values for elevations and releases, the model can be directed to either staying within certain reservoir zones, flow regimes, or maximizing power revenues or making a balance for each requirement. By doing so, the OPEs can create different alternatives from experience, and run the model for outputs. For this research project, we created three sets of penalty functions for the three different alternatives, using the experience of the OPEs.

3.6.2 Multi-Objective Tradeoff Analysis

One of the main purposes of this research was to develop the tradeoff curves for the different objectives. Hence, a multi-objective optimization tradeoff analysis was conducted using the weighting method. Three objectives (revenue generation, flood damage, and fish damage) were used in the objective function, and the stochastic linear programming model was optimized to perform the multi-objective analysis.

3.6.2.1 Objective Function

Maximize Money:

$$Max(Z) = \sum_{i=1}^{scen} \sum_{t=1}^{forecast} \{(w_1 f_{\mathrm{Rev}} - w_2 f_{flooddamage} - w_3 f_{fishdamage}) \times P_{i,t}\}$$

Where, scen	=	Number of inflow scenarios,
forecast	=	Period of forecast (for model, start to end study period),
$P_{i,t}$	=	Probability associated with the forecasted scenario and $\Sigma P_{i,t}=1$, $\Sigma w_i=1$,
f_{Rev}	=	Revenue gain,
$f_{flooddamage}$	=	Flood damage (M$), and
$f_{fishdamage}$	=	Fish impact (Units).

3.6.2.2 Decision Variables

The decision variables are the same as described in the Section 3.8.1.2

3.6.2.3 Constraints

The constraints are same as described in the Section 3.8.1.3

3.6.3 The Optimization Algorithm Flow Chart

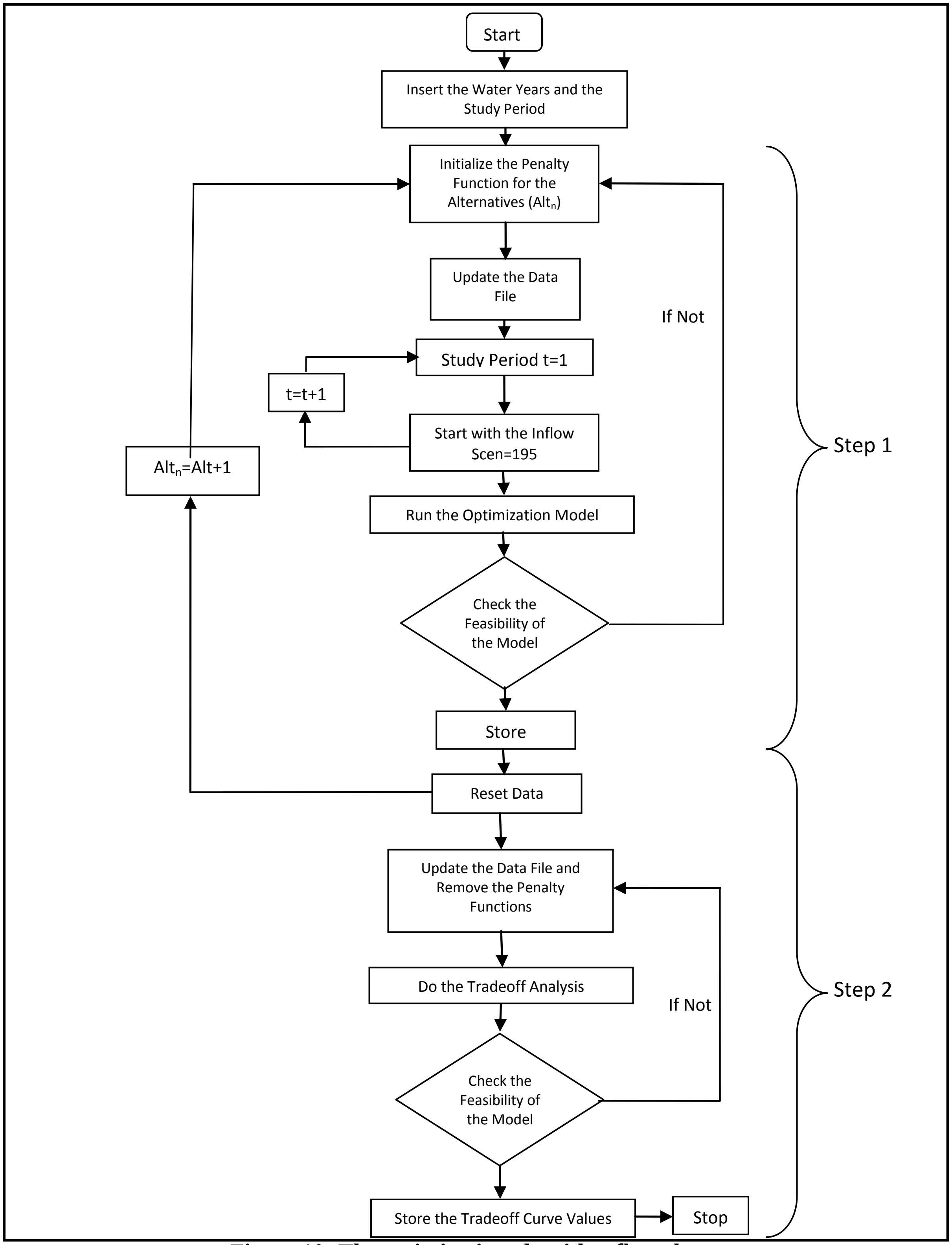


Figure 10: The optimization algorithm flow chart.

3.7 Developing the CDF Curves

To identify the differences among the alternative damage values, a frequency analysis was done for each impact/measure, and for each alternative, a Cumulative Distribution Function (CDF) was derived for the event (for each respective measure), thus capturing the probabilistic uncertainty for all relationships (USACE Manual No. 1110-2-1619). The CDFs are one of the main inputs for the DA software.

3.8 Decision Analysis Software Choice and Inputs

To achieve the goal of this research, the DA software was used with the results of the above analysis, to capture the best alternative for the decision-maker and to provide easily accessible documentation that could be used in the event of further complications or analysis. Due diligence in selecting a package should involve the following critical questions, in addition to cost considerations:

- Is there a single decision-maker or are there multiple decision-makers (stakeholders)?
- Will the decision-maker(s) participate in the decision analysis (decision conference), or will they be periodically presented with results (dialog decision process)?
- Does the decision situation involve only one alternative or a portfolio of alternatives?
- Do stakeholders have multiple, conflicting objectives for consideration?
- Is there significant uncertainty in the events that affect decision outcomes?
- Is it a single decision or a decision strategy (a sequence of decisions over time)?

To answer these questions and guide the selection of the decision analysis software, several multiple-objective decision analysis software packages were examined. They were divided into two categories: computer-installed (non-web-enabled or local software) and web-based (web-enabled and shared) packages. The list of software packages and links to their developers' websites are given below:

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).

The next question is concerned with how the software can deal internally with the following issues:

- **Incorporating Uncertainty** – A fundamental part of making decisions in the face of extreme flows is the role of uncertainty. The ability to incorporate uncertainty among the multiple objective decision outcomes is the main criterion for selecting a software package.
- **Range of Impacts** – Sensitivity to the range of impacts is a key theoretical issue that was used for a pass/fail rating for these software packages. As an example, cost may be an issue when buying a car, but the "decision weight" assigned to the issue will differ across the range for models, depending on whether it is $900 or $9,000.
- **Consequence Table –** The consequence table is a fundamental aspect to good decision-making and a key reporting tool for multiple objective decisions. The matrix clearly lays out the decision options, the objectives that will be used for comparing the options, and the estimated impacts of each option for each objective.
- **Tradeoff Analysis –** The tradeoff analysis must be for different kinds of methods. When assessing decision weights, the implied tradeoff between the objectives is a key check for the research.

- **Input of the Qualitative Measures** – In some cases, no quantitative measures exist. For these impacts (such as reputation or public image), qualitative measures need to be built and tested with upper management to ensure their usefulness during extreme flow events.

After considering the above issues, the Logical Decisions for Windows (LDW) Version 6.1 (later upgraded to Version 6.2) was selected for this research. Some of the inputs for the software are described below:

<u>Defining the Probabilistic Level</u>

Probabilistic levels are those with uncertainty. In the software, uncertainty is defined with a probability distribution for the level. For this research, the developed CDFs will be the distribution inputs for the measures and alternatives. Figure 11 shows an example of an input of the probabilistic level for the software.

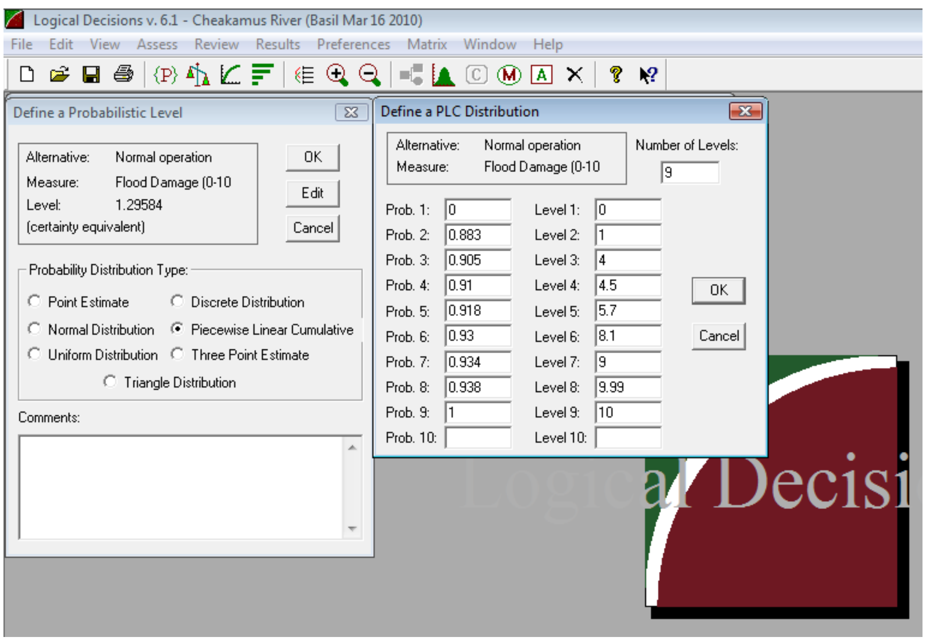


Figure 11: Probabilistic level input window for the measures.

Assessing Common Units

The second major step in the LDW analysis is to assess preferences. The preferences for LDW must be defined for converting the measures to common units and for computing weights of the measures and goals. The common units for assessment in the software are:

- Single Utility Function (SUF) Assessment,
- Analytic Hierarchy Process (AHP) Assessment,
- AHP SUF Assessment,
- Adjusted AHP Assessment,
- Ideal AHP Assessment,
- Direct Assessment.

Figure 12 shows an example of SUF input in the software.

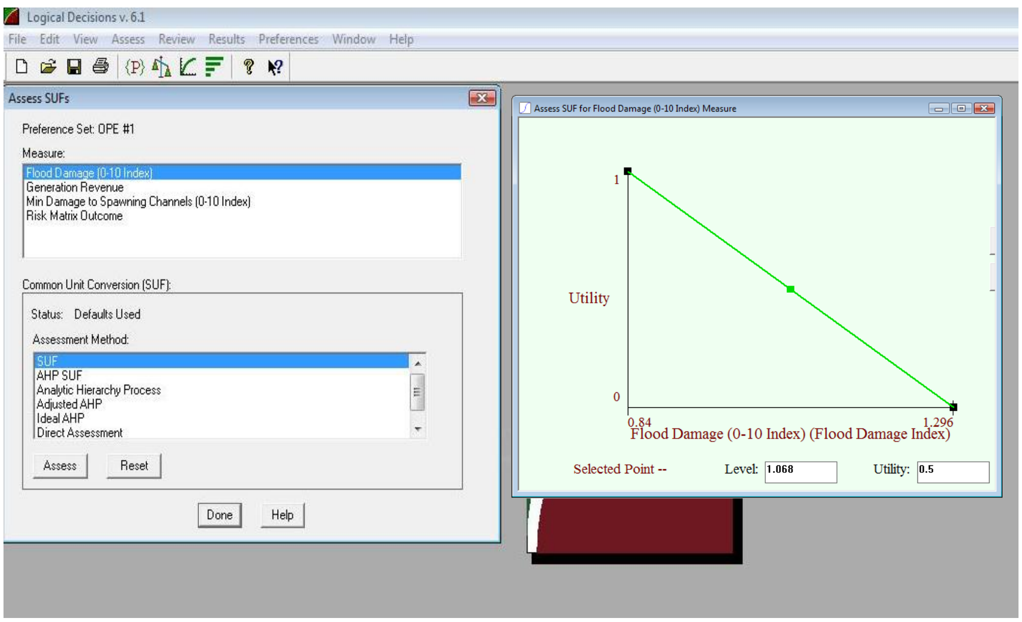


Figure 12: Window to define utilities among the measures.

Assessing Weights

The third major step is defining the weights in the preference set for the relative importance of the measures and goals in the analysis. Technically, these form the scaling constants for the

Multi-Measure Utility Functions (MUFs) for the LDW to compute the utilities for the alternatives of the goals. The weights in the software are assessed by the following:

- Tradeoffs Method,
- Direct Entry Method,
- "Smarter" Method (Rank Order),
- "Smart" Method (Swing Weights),
- Pair-wise Weight Ratios Method, and
- Analytic Hierarchy Process (AHP) Method.

Figure 13 shows an example of the Tradeoffs Method input in the software.

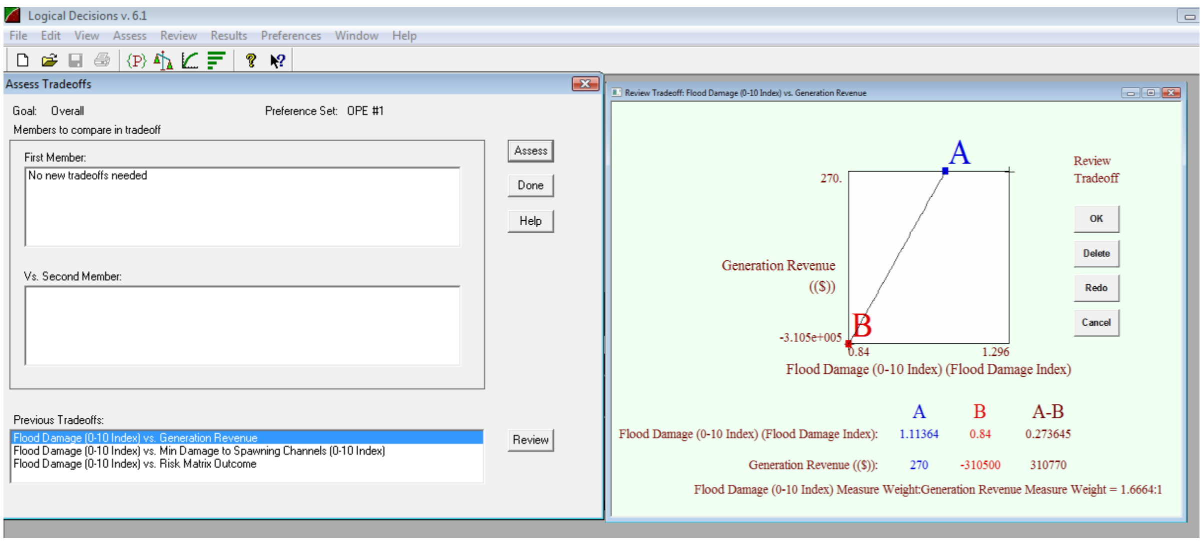


Figure 13: Window to define weights between the measures.

<u>Goals Hierarchy</u>

In LDW, the organization of the goals and measures fall into a tree-like structure called the goals hierarchy, which is a broad structure with the highest order goal decision at the left and more specific goals to the right as shown in Figure 14. The evaluation measures are at the lowest level of the goals hierarchy.

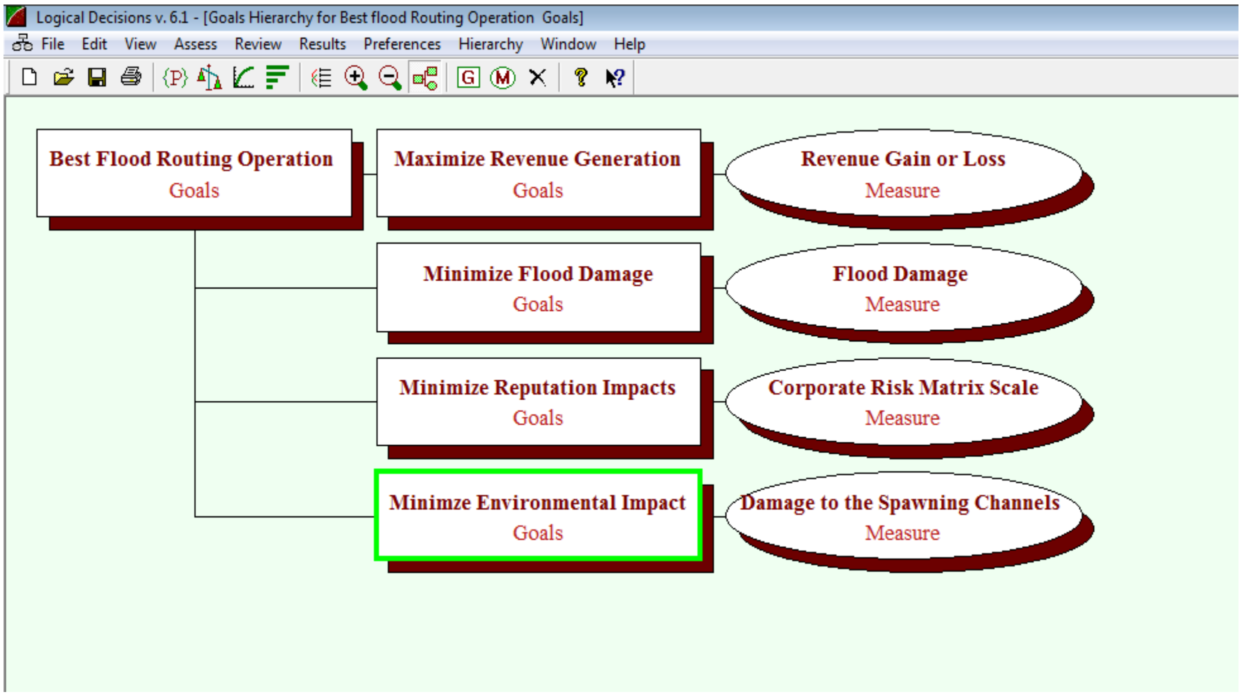


Figure 14: Goal hierarchy window for the project.

3.9 Summary of the Methodology Used in the DAF

Figure 15 summarizes the methodology used in this research. Once a forecast is issued for a high inflow event, a number of simulation and optimization models are used to derive the response of the system under different operating strategies or alternatives. The output of the models is then used to prepare CDFs for the various damages and using the predefined utility and trade-off functions and then the CDFs are read by LDW software and the software is run and the results are then summarized and documented. If the alternative does not provide a good strategy to manage the event, a new set of alternatives are prepared and the process is repeated.

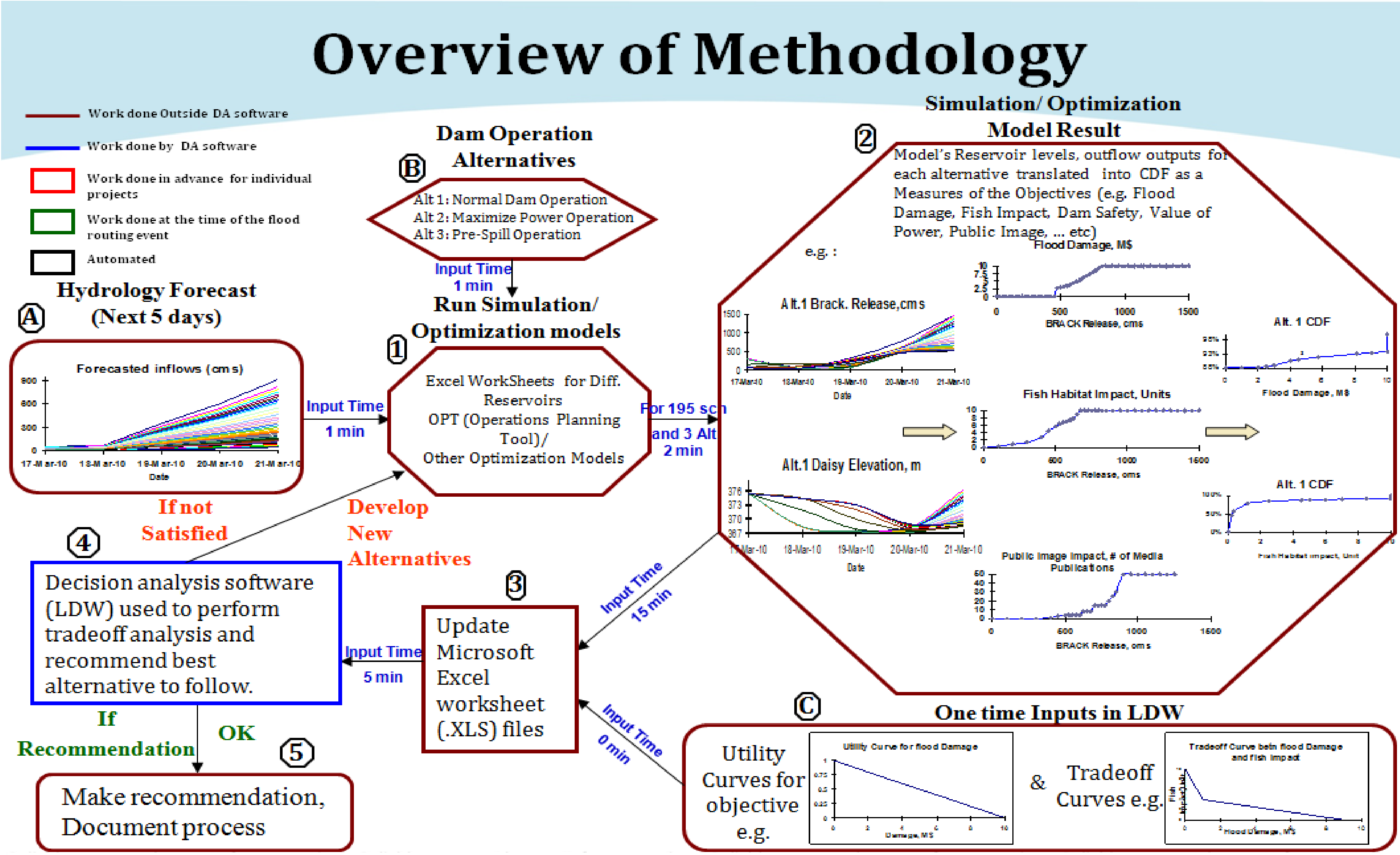


Figure 15: Methodology of the research at a glance.

Chapter 4: Case Study and Results

The Cheakamus flood event of October 2003 was chosen as a case study for this research. This was a fifty years return period flood event, which caused significant damage and property loss in that area. Because of its location on the Squamish River, BC Hydro's Cheakamus Power House facility diverts water from the Daisy Dam, but the relatively small amount of turbine flow did not significantly improve the flooding conditions in the area between the Daisy Reservoir and the confluence with the Squamish River. At the end of this chapter, the results of the decision analysis framework are presented.

4.1 Case Study Description

4.1.1 Cheakamus River Area

The Cheakamus River is a tributary of the Squamish River, originating in the Fitzsimmons Range of the Coastal Mountains in Garibaldi Provincial Park, about 25 km southeast of Whistler, BC. Its watershed has an area of 1,070 km^2 and an elevation ranging from 30 m above sea level, where it meets the Squamish River, to 2,300 m above sea level at its headwaters.

The Cheakamus flows 70 km in a northwesterly direction into and out of Cheakamus Lake, southeast of Whistler, before turning south into Daisy Lake, alongside Highway 99 (Sea to Sky Highway) between Vancouver and Whistler. The Cheakamus continues south out of Daisy Lake and through Cheakamus Canyon, creating strong rapids and a waterfall before emptying into the Squamish River at the community of Brackendale, immediately north of Squamish. A portion of that water is released from the Daisy Lake Dam down the 26 km stretch of the Cheakamus River to its confluence with the Squamish River. The remainder of the water in the Daisy Lake Reservoir is diverted through a tunnel that runs through Cloudburst Mountain to the Cheakamus Generating Station, located on the left bank of the Squamish River.

The Cheakamus watershed is transitional between the milder Pacific Coast and colder interior, climatic regimes. The valley is oriented such that it receives the predominant winter southwesterly winds that transport moist air up Howe Sound and far up the valley. A series of fall and winter storms commonly occur from late-September until March. Summer storms also occur but are usually small, though intense. Infrequent, large summer storms can produce extreme flooding. Annual precipitation tends to decline along the valley bottom moving inland where a greater proportion also falls as snow due to the colder inland climate and higher elevations. At Garibaldi and Alta Lake climate stations, over half the annual precipitation falls between October and January. Approximately 75% of the total inflow to the Cheakamus River originates upstream of the Daisy Lake Dam.

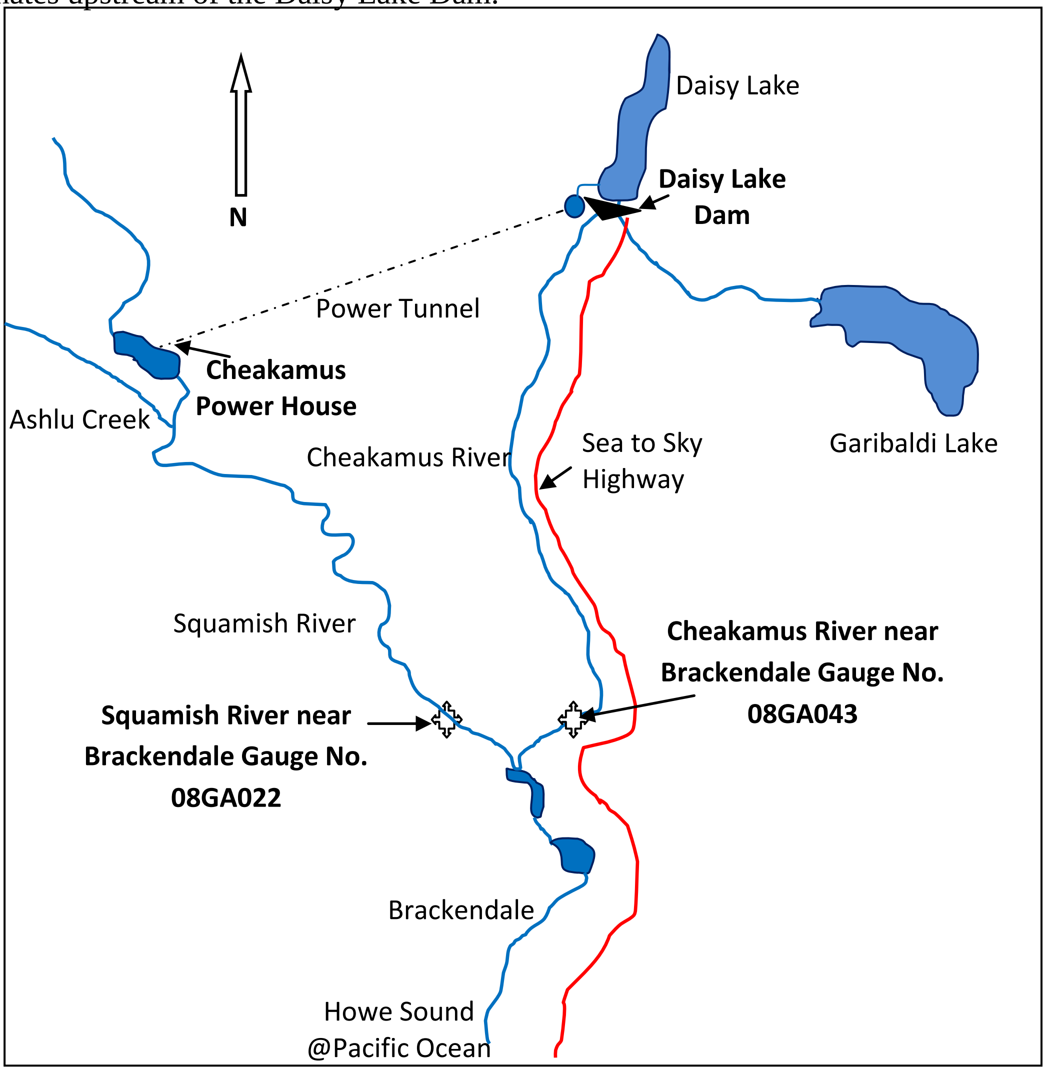


Figure 16: Map of the Cheakamus River area.

4.1.2 Cheakamus River Hydroelectric Facility

The Cheakamus generating system was completed in 1957 and is comprised of the Daisy Lake Dam and Reservoir, the 157 MW Cheakamus Powerhouse in the Squamish Valley, and a connecting tunnel through Cloudburst Mountain.

During normal operations, the Daisy Lake Reservoir has an operating range from 364.90 m to 377.25 m above sea level, a fluctuation of 12.35 m. The reservoir can store approximately 55 million cubic meters of water, which is only 3.5% of the average annual inflow.

Water for generating electricity is drawn from the Daisy Lake Reservoir via a canal under the Sea-to-Sky Highway into Shadow Lake where it enters a 5.5 m diameter, 11 km long tunnel that runs through Cloudburst Mountain to the Squamish Valley. Twin penstocks carry the water from the tunnel exit to the Cheakamus generating station, after which it is discharged into the Squamish River. The maximum flow from the generating station is 65 m^3/s, with a 340 m head difference in the elevation between Shadow Lake and the generating station.

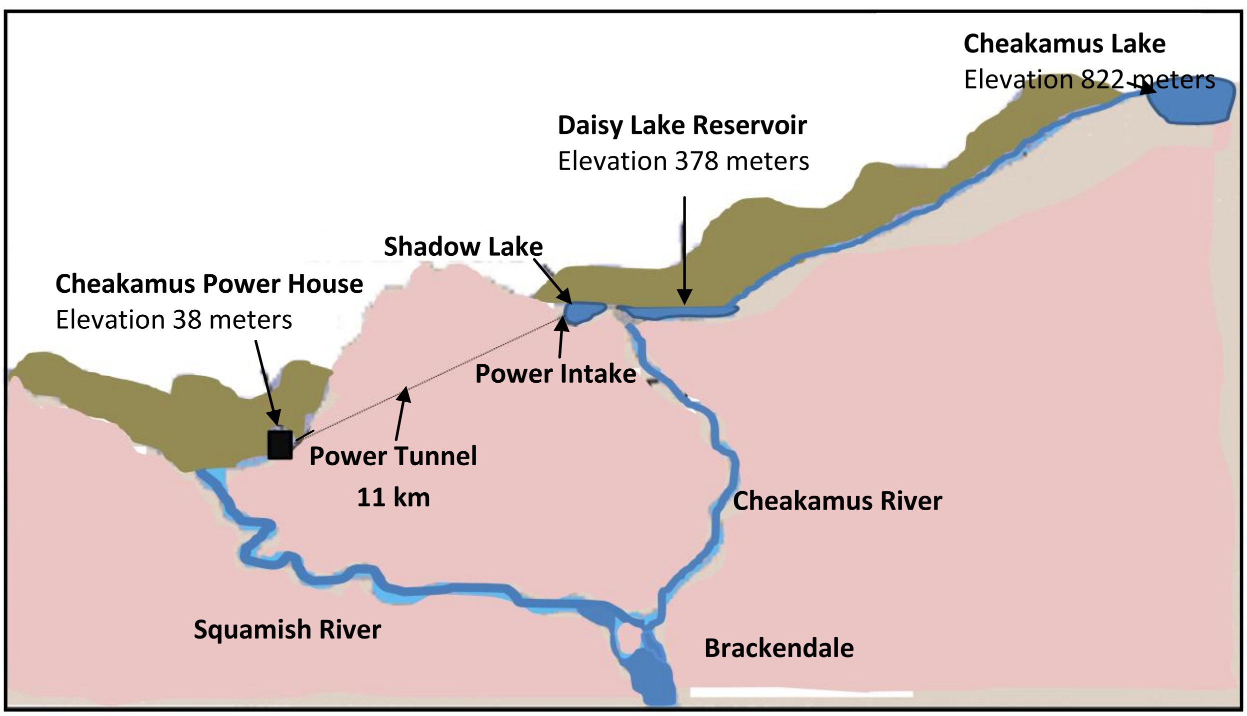


Figure 17: The Cheakamus system

The Cheakamus facilities currently generate approximately 590 GWh/year through the two turbines, which is approximately 1.5% of BC Hydro’s total system production. Under an order issued April 6, 1999, BC Hydro is required to release through the spill gates downstream into the Cheakamus River the greatest of 5 m^3/s or 45% of the previous 7 days average inflows to the reservoir (within a range of 37 to 52%). Later, in February 17, 2006, according to the new Water Licenses & Order, the rule was changed, and flows must be released from the Daisy Lake Dam to meet the following minimum flows at downstream Brackendale station of Cheakamus River:

- 3 m^3/s from 1 November to 31 December,
- 5 m^3/s from 1 January to 31 March, and
- 7 m^3/s from 1 April to 31 October.

The operators of the Cheakamus River system need to fulfill the following requirements/constraints for dam operations during the high inflow periods to mitigate the flood impacts to the river:

- The Cheakamus Project is designed to pass the Probable Maximum Flood (PMF) without failure of the dam. The peak 6-hour inflow to the Daisy Lake Reservoir during the PMF is estimated to be 4,129 m^3/s and the maximum PMF level equal to El. 381.59 m. At the maximum PMF level of 381.59 m, about 600 m of the highway and railway adjacent to the power intake canal may be inundated.
- The Cheakamus River channel downstream of the Daisy Lake Dam is mobile, and as a result, the bankfull discharge changes with time. The latest bankfull discharge estimate (October, 1997) is 450 m3/s or 15,800 cfs at the Brackendale gauge.
- A spill of 230 m3/s from the Daisy Lake Dam will likely result in a bankfull discharge of close to 450 m3/s at the Brackendale gauge.
- The Daisy Lake Reservoir must be operated to a maximum target elevation of 373.50 m between October 1 and December 31 to reduce the flood risk downstream of the Daisy Lake Dam when heavy and prolonged rainfall are the most severe.

In Figure 18, the potential flood zones of the Cheakamus River are highlighted. These flood zones consists of subdivisions that are heavily populated with a number of houses and farms.

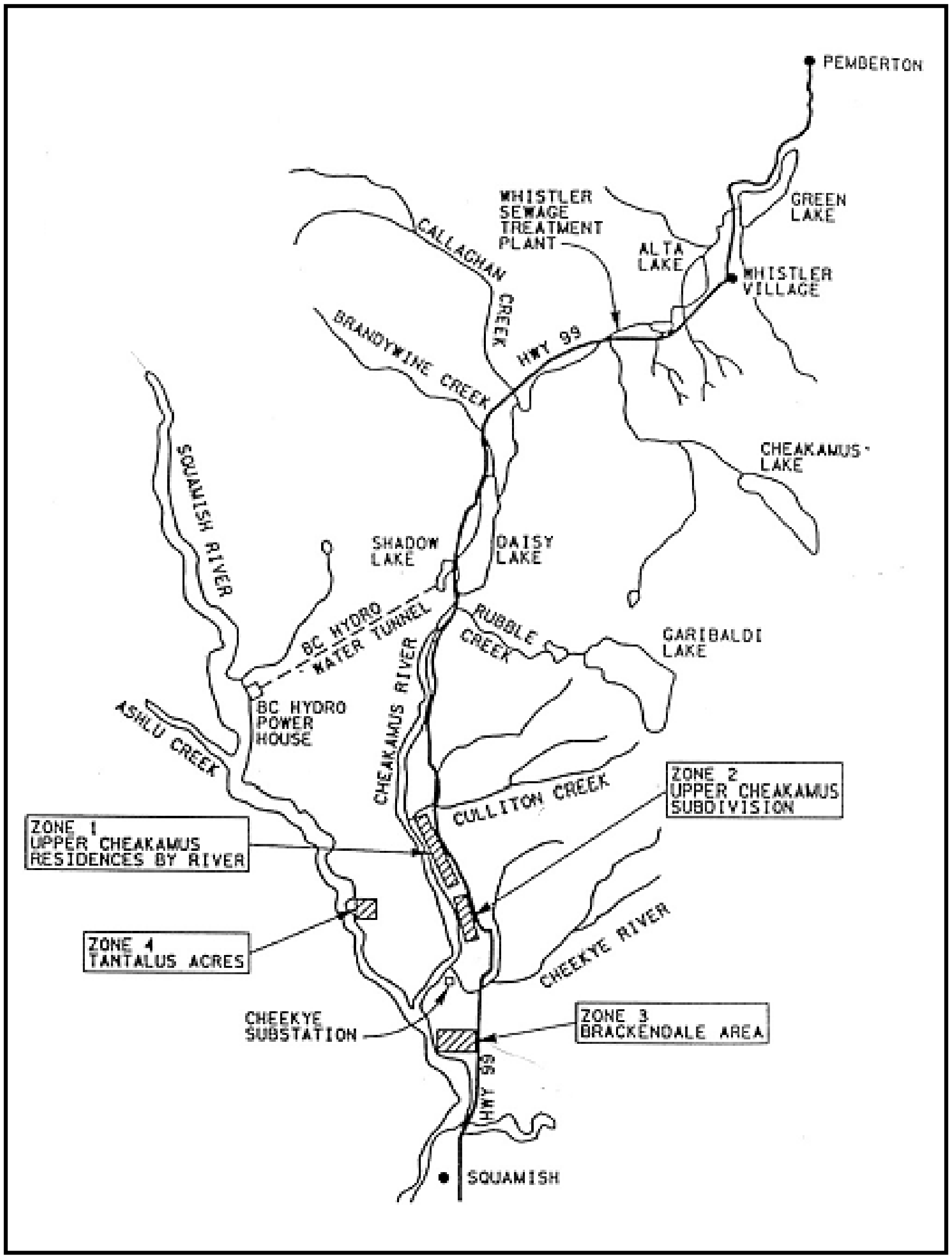


Figure 18: Cheakamus potential flood zones

Source: BC Hydro Intranet

4.1.3 Cheakamus Flood Event (October, 2003)

The Squamish area experienced a significant inflow event October 17-21 in 2003. The towns of Squamish and Pemberton and the areas in between experienced heavy rainfall from October 16-19, 2003, with resulting significant flooding and damage to private and public property. Because of its location, the BC Hydro's Cheakamus facility can affect flood conditions between the Daisy

Reservoir and Squamish. At Brackendale, releases from the dam account for about 90-95% of the total flow; at Squamish, the reservoir flows were further diluted to about 80-90% of the total flow below the confluence of the Squamish River. BC Hydro manages flooding in the corridor by targeting flow conditions at Cheakamus River near Brackendale with respect to bankfull flows of 450 m^3/s. Average daily inflow and cumulative inflow data are shown below in Table 4. Total inflows over the five days exceeded the total licensed storage in Daisy Reservoir by a ratio of 3:1.

Table 4: Inflow summary of Brackendale at October 2003

Date	Avg. Daily Inflow (m^3/s)	Cumulative Volume (m^3/s-days)
17-Oct	461	461
18-Oct	627	1088
19-Oct	404	1492
20-Oct	311	1802
21-Oct	219	2021

Hydrographs and Daisy Lake elevations are shown in Figure 19.

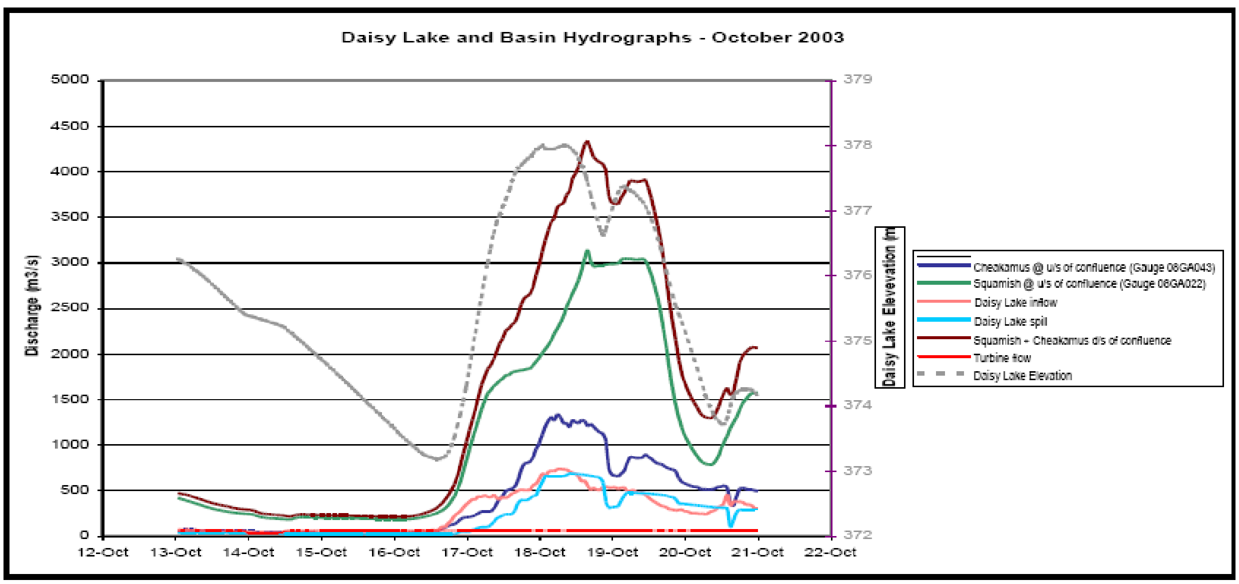


Figure 19: Cheakamus hydrographs at different releases and Daisy Lake elevations for the event.

Most of the flooding occurs to the town of Squamish, which is downstream of the confluence of the Squamish, Cheakamus, and Cheekye rivers. Figure 20 indicates that bankfull at Brackendale near Cheakamus was reached on October 17 at 12:00 PM. (The gauge at Brackendale on the Cheakamus River is upstream of the confluence of the Cheekye.) Figure 20 shows the sum of Brackendale and Squamish river inflows as well.

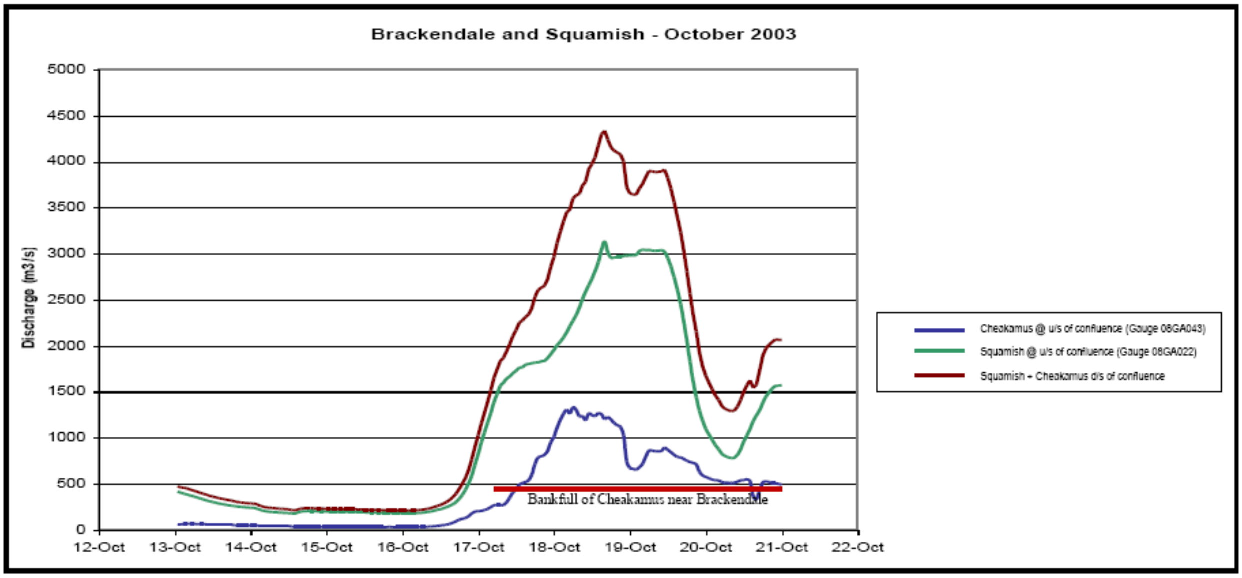


Figure 20: Comparison of the discharge between Daisy and Squamish for the event.

Inflow forecasts are issued every morning. Five-day forecasts (low: 75% exc. probability, regular: 50% exc. probability, and high: 25% exc. probability), starting from October 14, and comparisons with the actual inflow are shown in Figure 21.

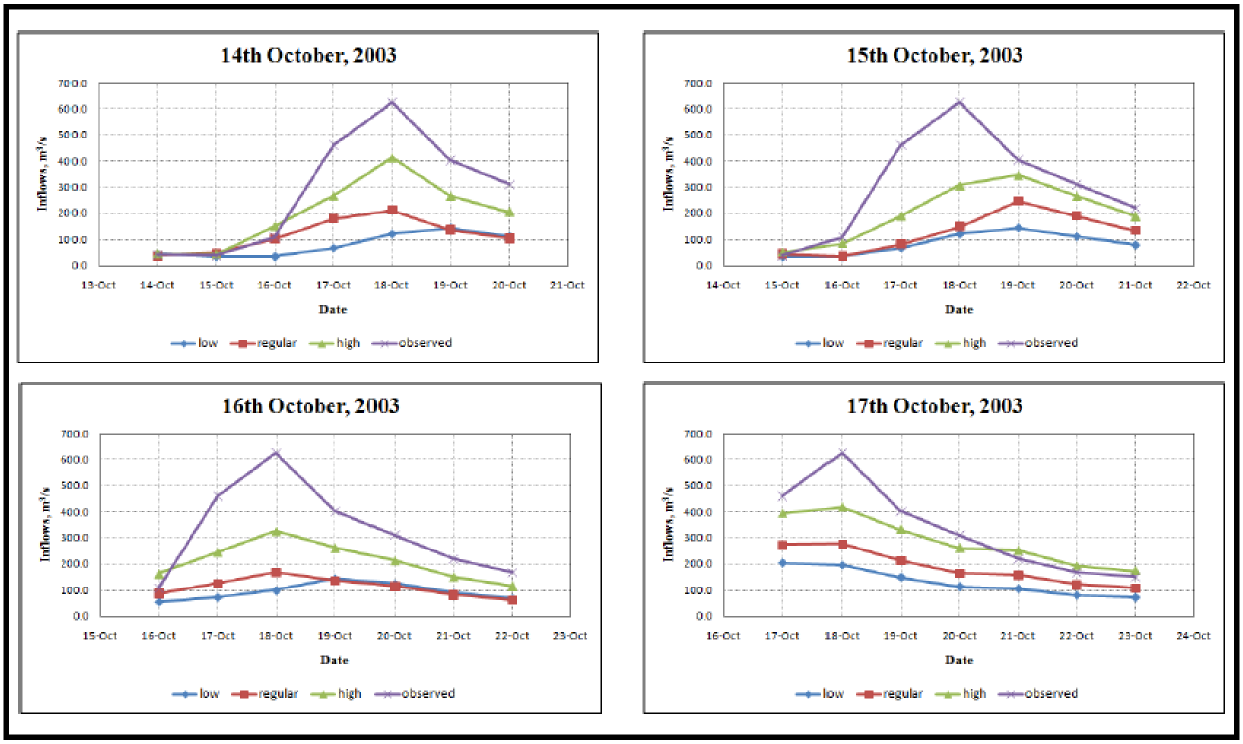


Figure 21: Inflow forecasts by the H&TS Department from October 14-17, 2003.

From Figure 21, the observed inflow was clearly much higher than the anticipated forecasts. Due to the small storage capacity, reservoir operations were not able to prevent downstream flooding at Brackendale and therefore prevent the subsequent damage to the residential area, and the farms, roads, bridges, railways, and downstream spawning channels. This flood caused significant flood damages and resulted in a major concern for BC Hydro with regard to public understanding of how much flood protection such small reservoirs can provide.

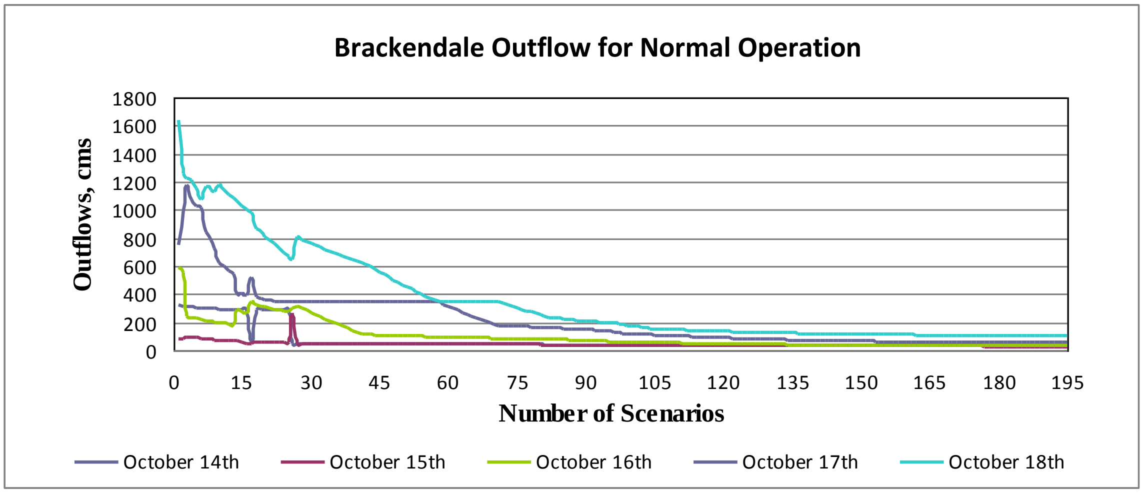
4.2 Results

4.2.1 Optimization Model Results

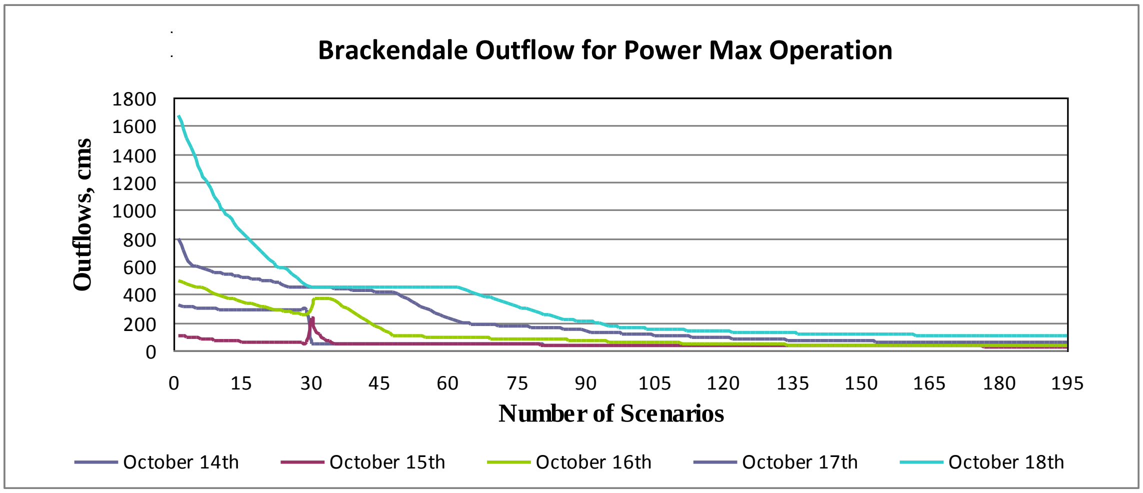
The adapted OPT model optimized the objective function for all 195 five-day inflow scenarios (October 14-18, 2003) and all three alternatives. To evaluate the case of the Cheakamus flood event (October, 2003), the decision making environment at the time was used in this exercise. The initial elevation of the reservoir (start of October 14, 2003) was 375.4 m for all inflow scenarios and operating alternatives.

4.2.1.1 Outflow at the Brackendale Gauging Station

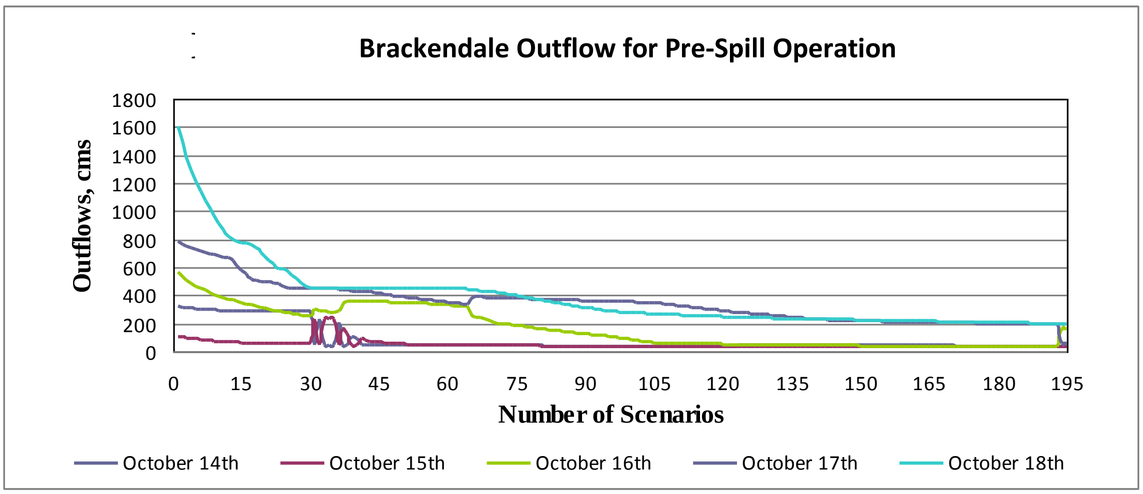
For the case of Cheakamus, the damage curves were developed with respect to the Brackendale gauge outflow results. The outputs from the optimization model for the three alternatives of the Brackendale outflows are shown in Figure 22.



(a) Normal operation outflow.



(b) Power maximum operation outflow.



(c) Pre-spill operation outflow.

Figure 22: Outflow in the Brackendale node.

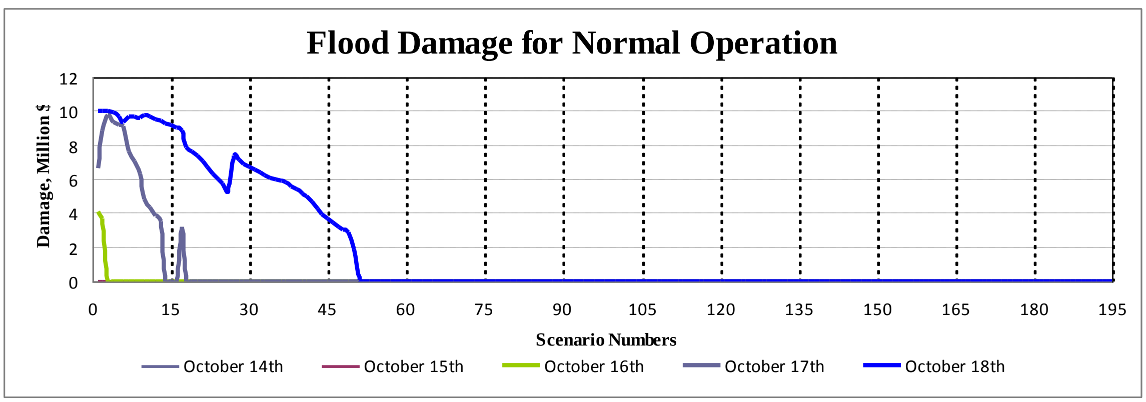
Figure 22 illustrates the optimization model outputs for the Brackendale outflow for different operations. Among the three operations, pre-spill operation discharges more water in total among the 195 scenarios; i.e., about 200,250 m^3/s in the five-day study period. The power max operation follows the pre-spill operation which is about 153,000 m^3/s, and the normal operation is about 149,000 m^3/s in total. The verity gives more room for the pre-spill option in the reservoir to store water at the end of the day on October 18, 2003. For the day-wise comparison, on the very first day (October 14, 2003), the maximum amount of discharge occurs in the pre-spill option, which is about 20,400 m^3/s, while the Power Max option is about 15,000 m^3/s and normal operation is about 10,500 m^3/s. The same thing occurs on the second day, too. The pre-spill operation causes the reservoir to store water on the third, fourth, and fifth day, which would be an advantage for these kinds of events.

4.2.1.2 Damage Values for Each Alternative

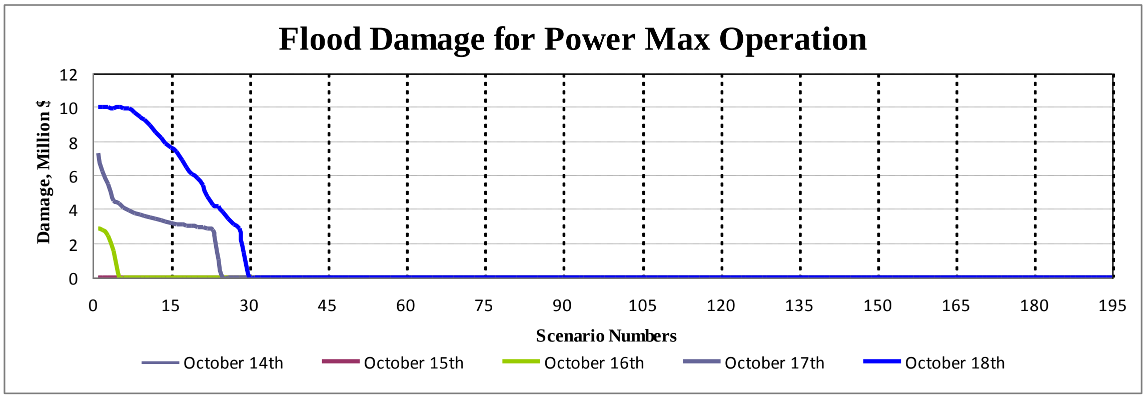
The optimization model calculates the damage values from the piece-wise linear functions for each objective, using the Brackendale outflows. This section describes the damage that would result from each operation and compares the damage values for the three alternatives, based on the three objectives: flood damage, environmental impact, and generation of revenue.

Flood Damage

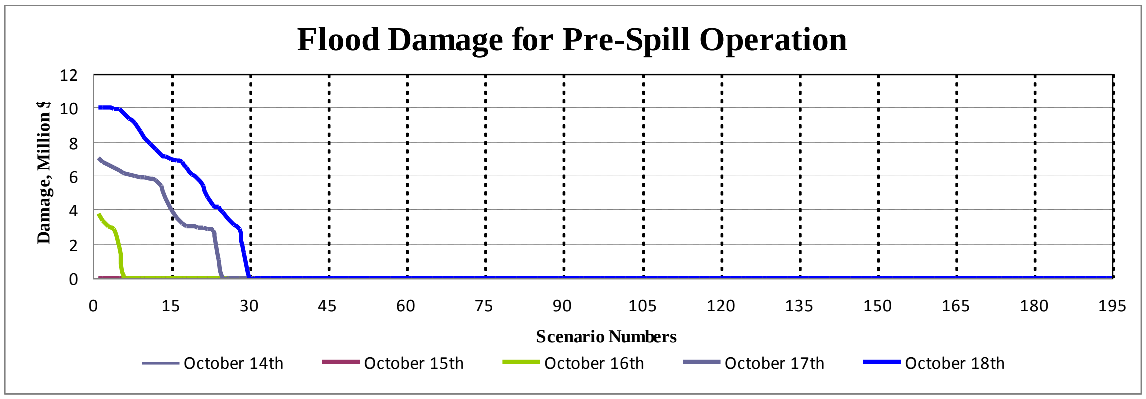
Figure 23 shows graphs for the flood damages for different operations. From the graphs, for the pre-spill operation, the damage values are shifted towards zero. Thus, the possibility of high flood damages occurring with the pre-spill option is lower than those of the other two options. By comparing day-wise, all of the alternatives have maximum damages in the final day (October 18, 2003). No flood damage would occur during the first two days, in any of the alternatives.



(a) Flood damage for normal operation.



(b) Flood damage for power maximization operation.



(c) Flood damage for pre-spill operation.

Figure 23: Flood damage values for the different operations from the optimization model.

In Figure 24, the comparison of flood damage is shown for the alternatives and the scenarios, with reference to the event (195 scenarios x 5 days). After the 70th event point, all operations have zero damage. The most damage would occur in the normal operation, and the same amount of damage would occur in the pre-spill and the power max operations. The total flood damage for the normal, power max and pre-spill alternatives would be \$448, \$304, and \$327 million, respectively.

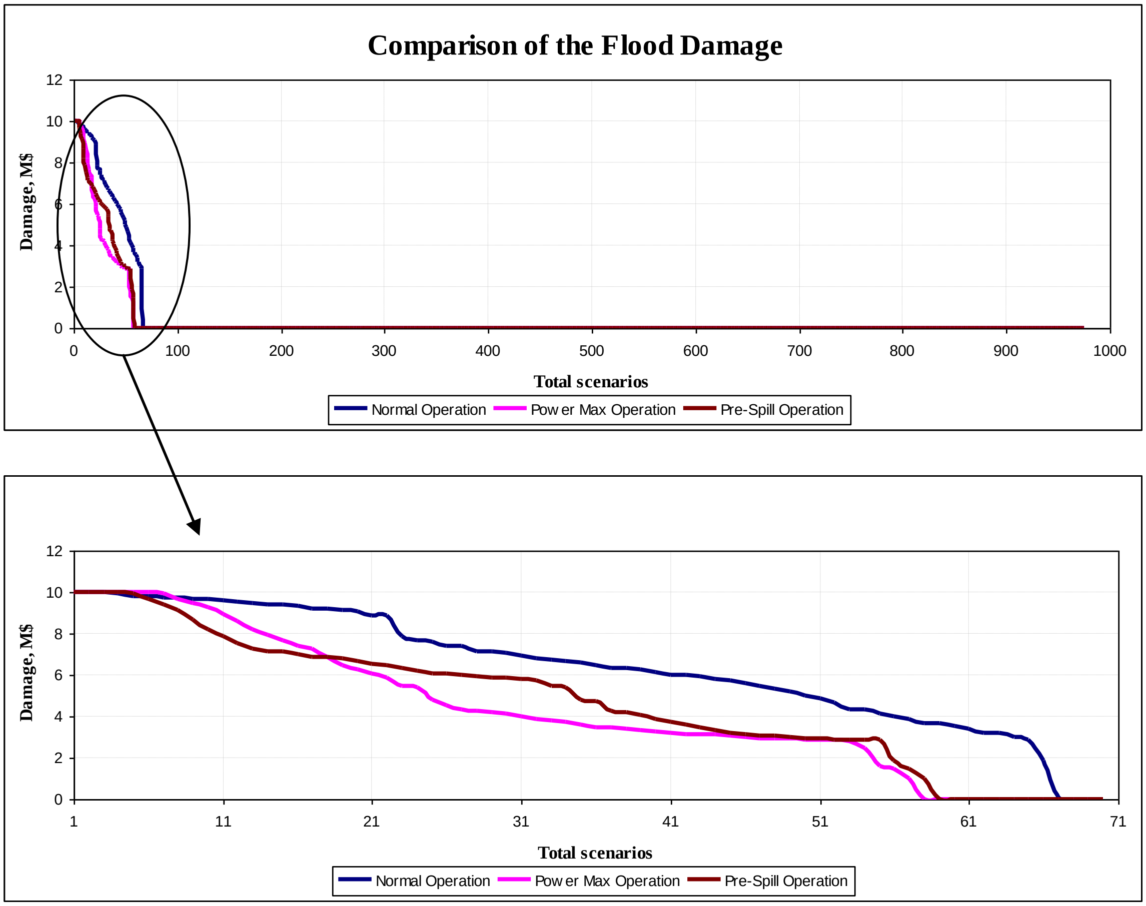
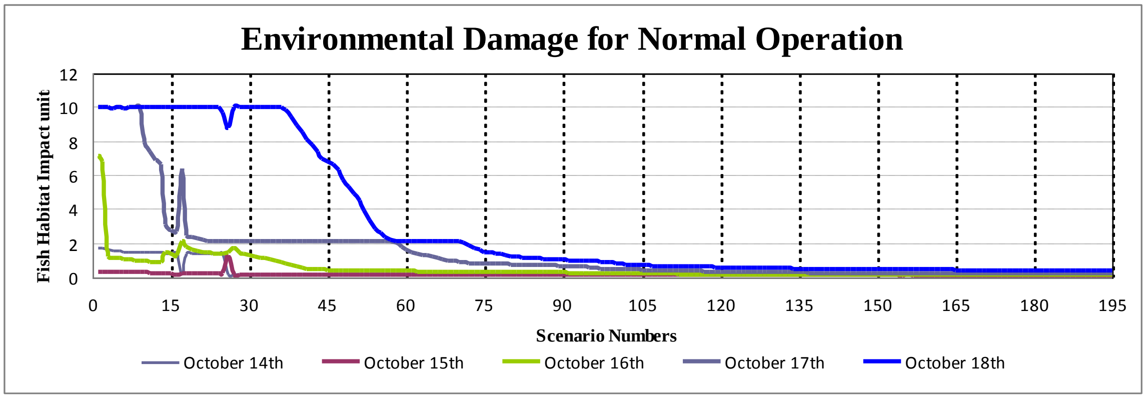


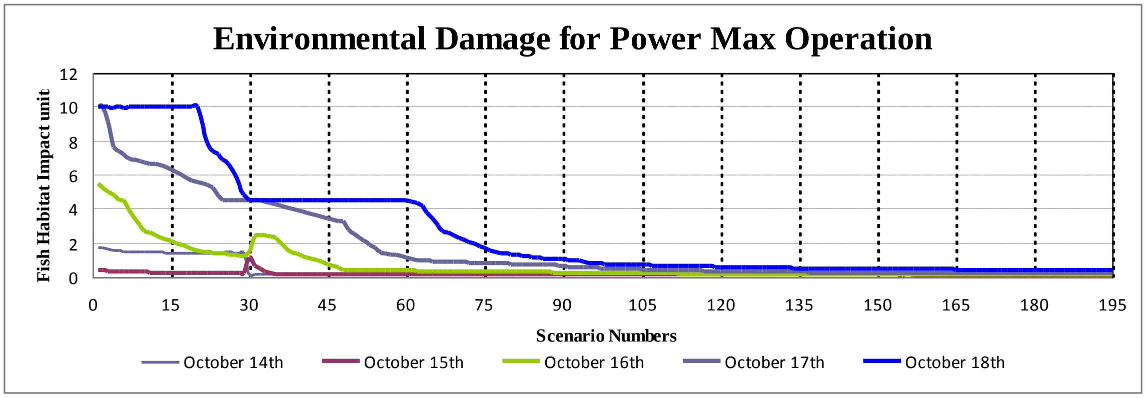
Figure 24: Comparison of flood damage for the alternatives.

Environmental Damage

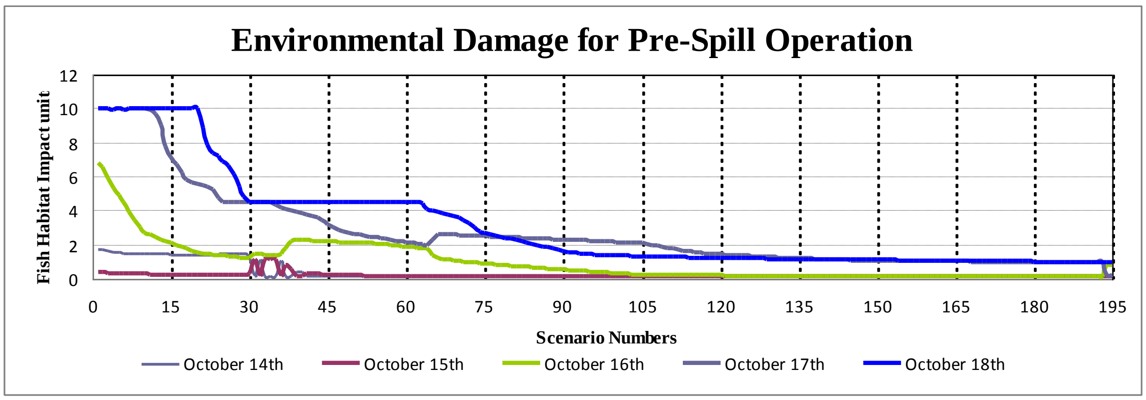
From Figure 25, in the normal operation, the maximum impact would be 10 units, which has much higher occurrence rate than that of the other two operations. For the power max and the pre-spill operations, the rate of maximum impact is very low, though they would still cause a minimum impact for the lower scenarios (which are almost zero in the normal operation). For the environmental impact, some value of impact occurs even for the very first day of the event.



(a) Environmental impact for normal operation.



(b) Environmental impact for power max operation.



(c) Environmental impact for pre-spill operation.

Figure 25: Environmental damage values for the different operations from the optimization model.

Figure 26 compares the alternatives for environmental damage for all scenarios. The graphs show that most of the environmental damage occurs in the pre-spill operation (about 1,450 units in total), followed by the power max operation (1,095 units) and the normal operation (1,075 units). Compared to flood damage, environmental impact would occur for three operations in all 975 scenarios (5 days x 195 scenarios).

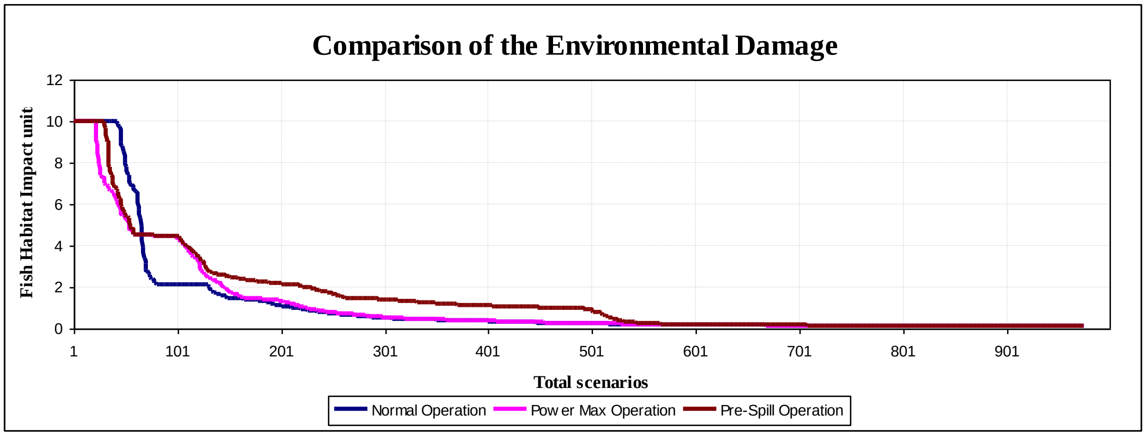
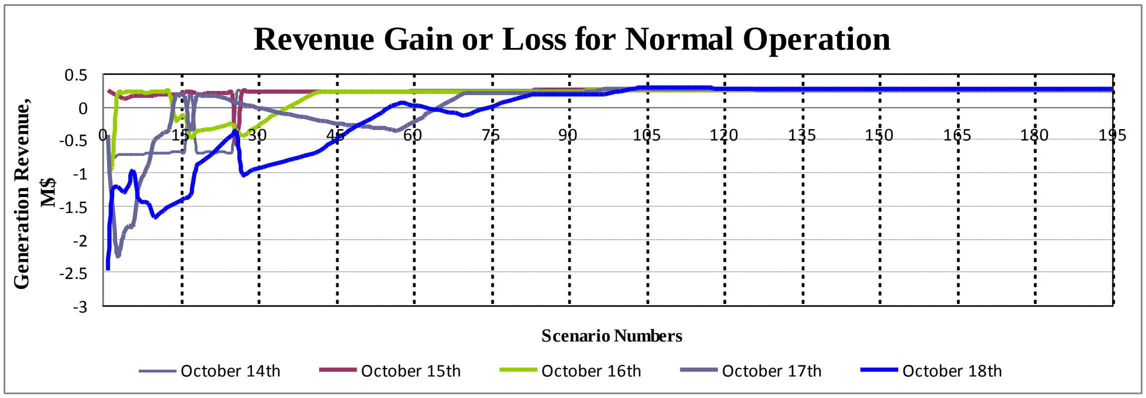


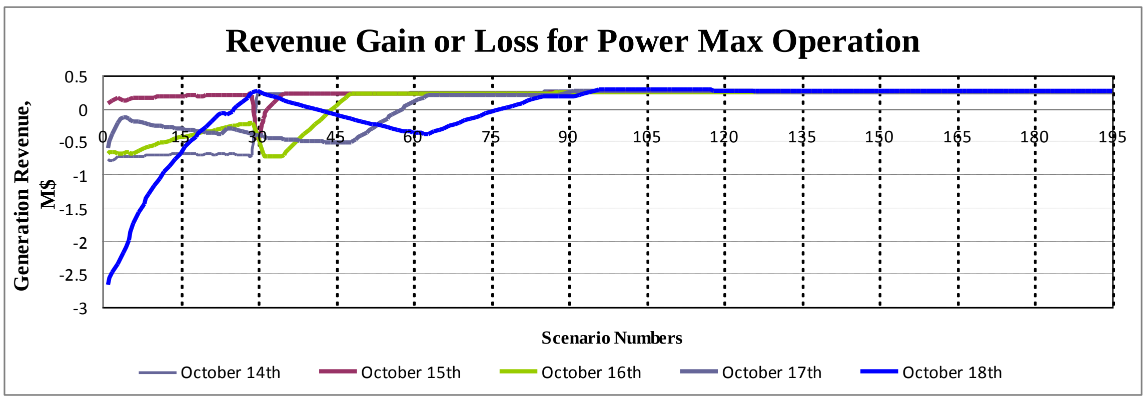
Figure 26: Comparison of environmental impacts for the alternatives.

Revenue Gain or Loss

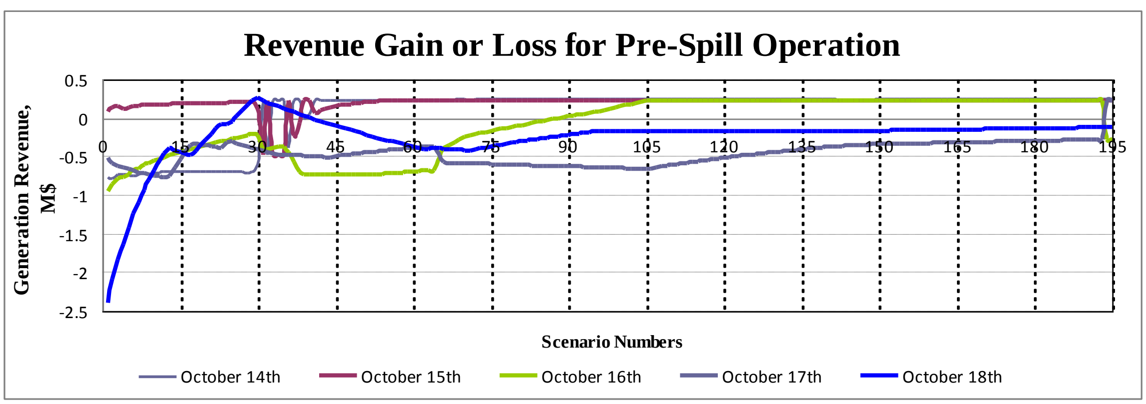
Figure 27 shows the generation power for the different operations for all scenarios, in a day-wise comparison. The power generation refers to the power generation by the turbines from operations, minus the water losses due to spilling, which otherwise could be stored for future use. The values are calculated in millions of dollars. The positive values mean that the revenue is a gain; while negative values mean that a loss in revenue occurs. From the graphs, no revenue loss will be caused by the normal or the power max operations, except on the final day of the event, if we sum total revenue for all scenarios for the day. Alternatively, pre-spill operation will cause a revenue loss from the third day of the event. The maximum revenue gain for normal operation is about $0.286 million, for power max operation about $0.29 million, and for pre-spill operation about $0.26 million, for a scenario. Alternatively, maximum revenue loss for the normal, power max, and pre-spill operations would be $2.48 million, $2.65 million, and $2.39 million, respectively.



(a) Generation of revenue for normal operation.



(b) Generation of revenue for power maximization operation.



(c) Generation of revenue for pre-spill operation.

Figure 27: Revenue gain or loss for different operations from the optimization model.

Figure 28 shows the total revenue generation (loss or gain), by alternatives, for all 975 scenarios (5 days x 195 scenarios). The shape of the curves for the normal and power max operations are the same for the majority of the scenarios at the beginning. Nevertheless, the shape of the curves for power max and pre-spill operations are the same for the last scenarios. The total generation revenue for all scenarios, and for the event, alternative-wise is normal ($96 million), power maximization ($94 million), and pre-spill (-$101 million), respectively. Thus, the pre-spill operation will cause revenue loss for the event while the other two operations will cause revenue gain for the event.

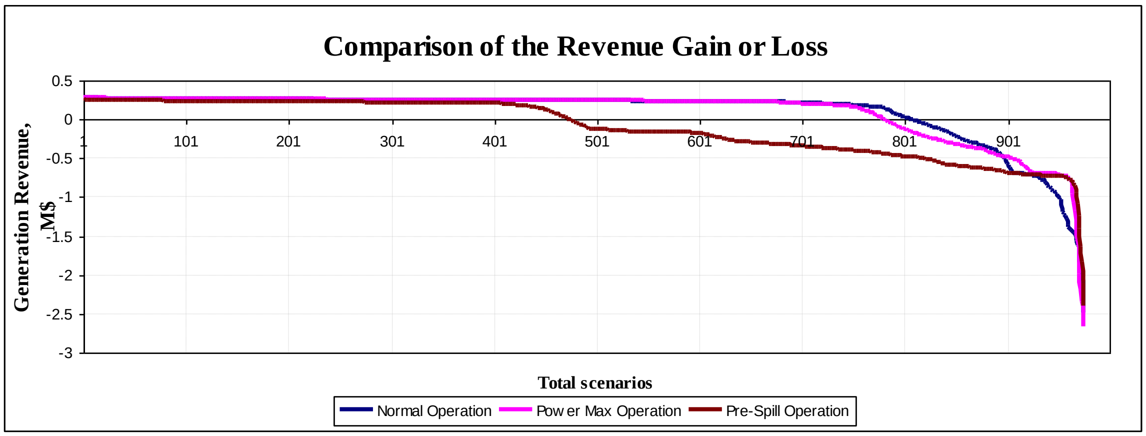


Figure 28: Comparison of the generation revenue among the alternatives.

4.2.1.3 Damage Cumulative Distribution Functions (CDFs)

Figure 29 shows the flood damage CDFs for the different alternatives, based on the statistical analysis on the damage values (described in the previous sections). From the comparison, the probability of higher damages (from $5-10 million) is greater for the normal operation (around 6%), compared to those of the other two operations (3.3% for power max, and 4% for pre-spill). The probability of zero damage is almost the same for all three alternatives. The maximum damage, which is $10 million, occurs most often in the normal operation (1.65%), while 1% in the power max operation and 0.7% in the pre-spill operation. From the shape of the curves, normal operation has a small downside at the beginning, suggesting that it has a lower probability in the small damage values, whereas, power max has a sudden change in the shape (at around $4-6 million damage) with a maximum probability. Pre-spill operation has almost a smooth probability of occurrences of damage.

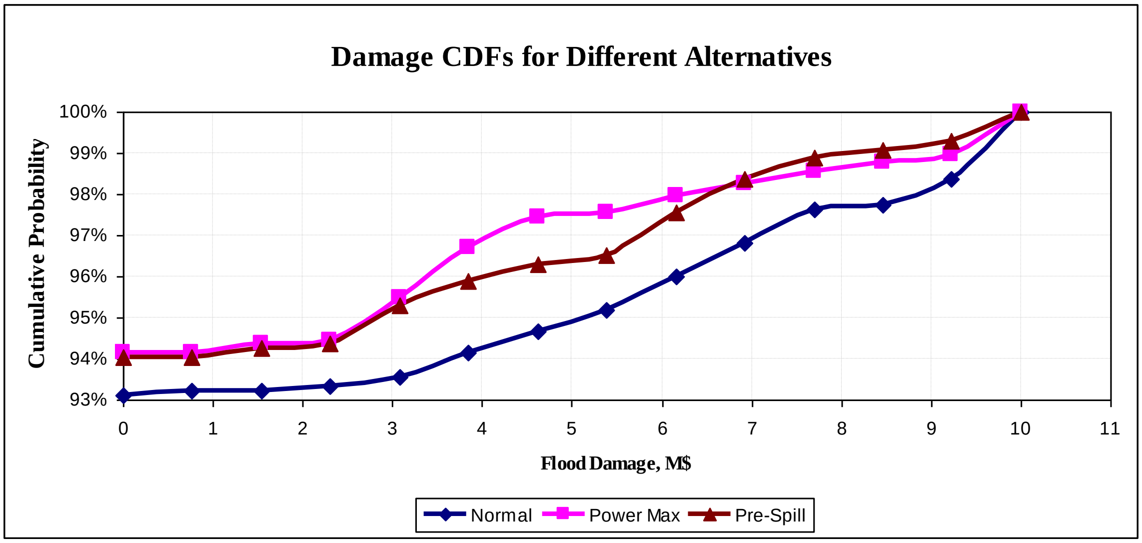


Figure 29: Damage cumulative distribution function for flood damage.

Figure 30 shows the environmental impact CDFs for the different alternatives from the statistical analysis on the impact values described in the previous sections. From the comparison, the probability of higher damages (from 5-10 units) is greater in the normal operation (around 6.8%), compared to the two other operations (5.5% for power max operation and 5.75% for pre-spill operation). The maximum damage (10 units) occurs most of the time in the normal operation (5.33%), and occurs 3% for the power max operation and 3.9% for the pre-spill operation. Inspection of the shape of the curves at the beginning, the normal operation and the power max operation have smooth increases in probability, in contrast to that of the pre-spill operation.

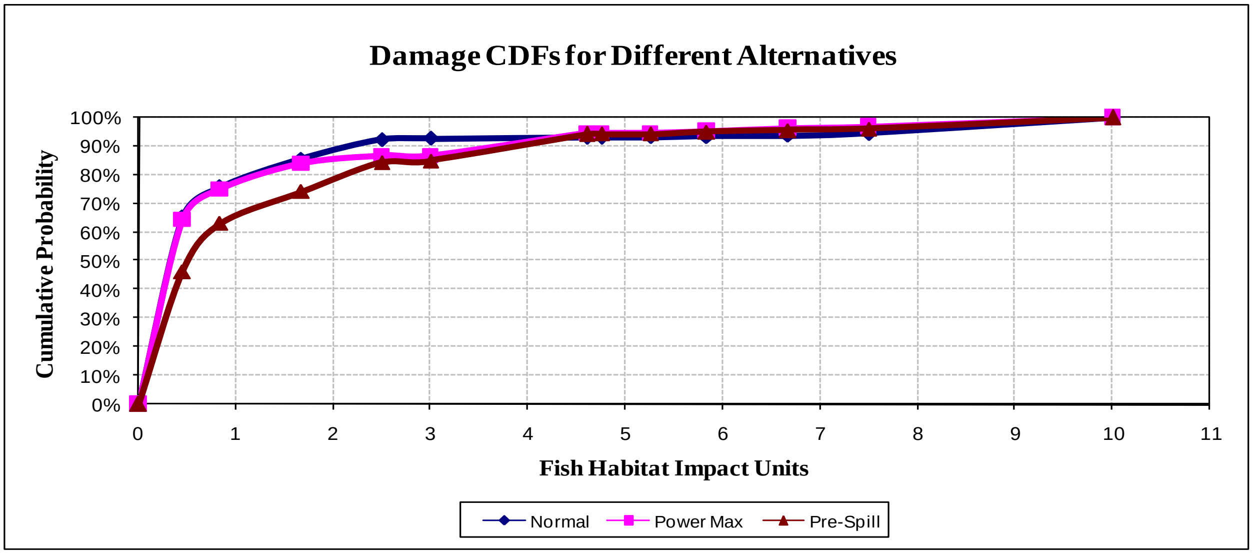


Figure 30: Damage cumulative distribution function for the environmental impact.

Figure 31 shows the CDFs for the generation revenue for all alternatives. The graphs show that most of the revenue gain takes place in normal operation (probability greater than 95%). Next, the power max operation has a probability of more than 90% for the revenue gain objective. The pre-spill operation has only a 60% probability for the revenue gain objective, based on the scenarios.

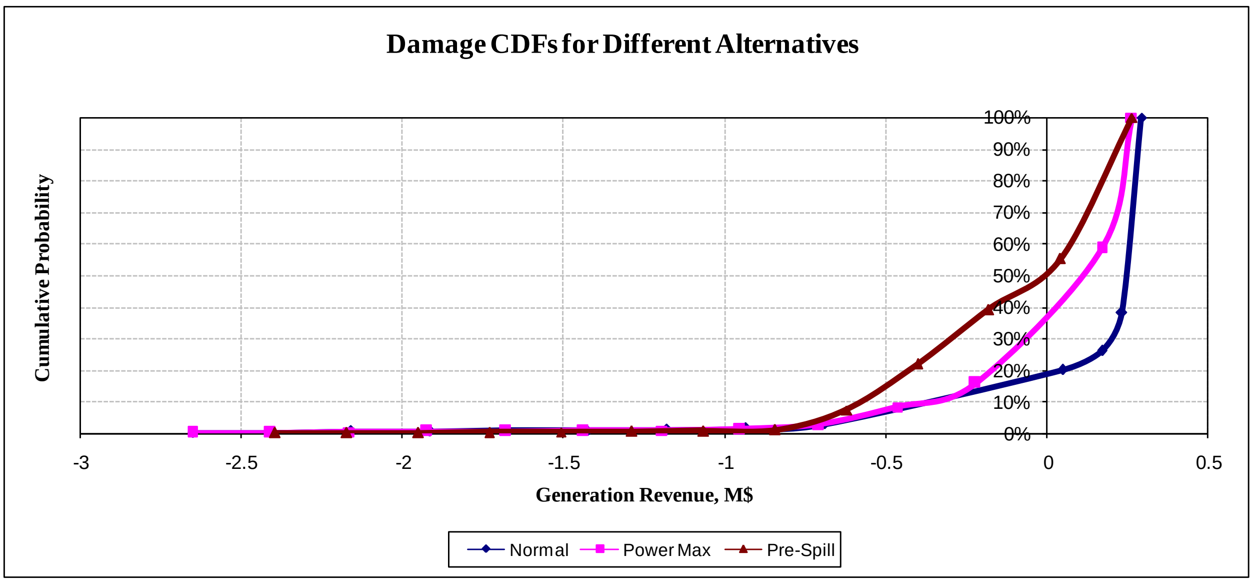


Figure 31: Damage cumulative distribution function for generation revenue.

The public image impact probability is defined from the experts opinion, the defined probabilities for different risk matrix measures, and the different alternatives (Table 5).

Table 5: Probability for the public image impact measure

Risk Matrix Level	Media/Opinion Leader's Response	Alternatives		
		Normal	Power Max	Pre-Spill
S1	No Coverage	0.881	0.881	0.942
S2	Brief negative or mixed local media coverage	0.002	0	0.001
S3	Possible isolated "one-off" major media coverage	0.001	0	0.056
S4	Some negative media coverage at provincial level	0.002	0.002	0
S5	Widespread and sustained negative media coverage	0.114	0.007	0
S6	Opinion leaders nearly unanimous in public criticism. Sustained and very negative media coverage. National media coverage	0	0.11	0

4.2.1.4 Trade-Off Curves

The Figure 32 below contains the summary of the tradeoff analysis from the Stochastic Linear Programming Multi objective weighting method optimization model. For different weights w1, w2 and w3 the tradeoff value of Revenue gain or loss, flood damage and fish spawning impact measures has been developed. The three dimensional tradeoff curve from the weights is shown in Figure 32.

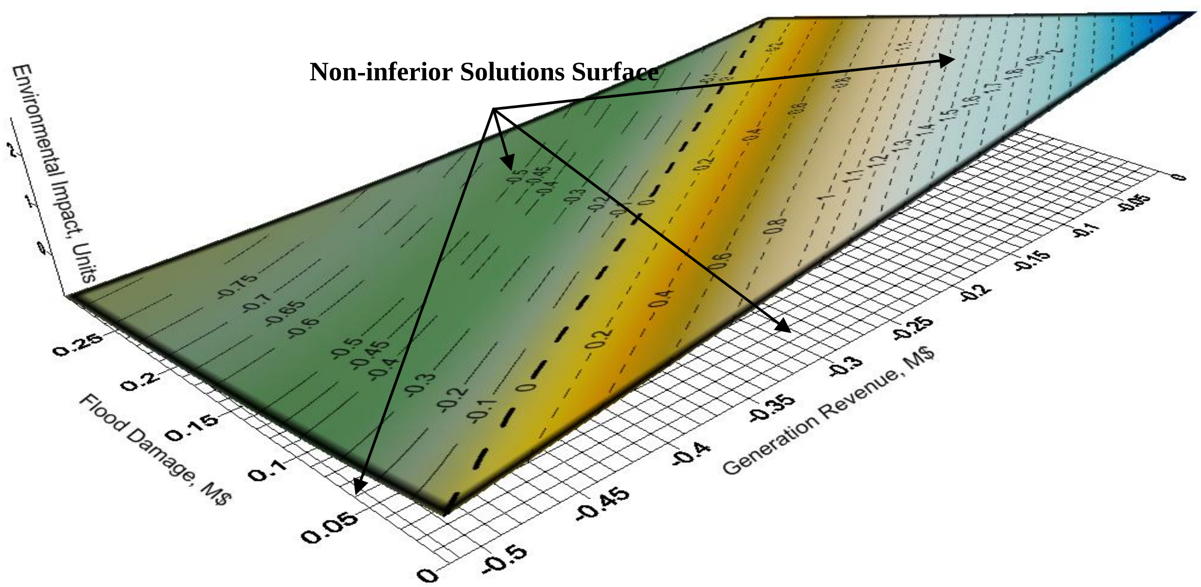


Figure 32: Tradeoff Curve in a contour map with non-inferior solution surface (Neufville, 1990)

The figure shows the trade off curve among the three measures in a contour map where the edge of the graph (bold black line) is the non-inferior surface for this tradeoff. The axis points for the non-inferior surface are 2.74 unit (for Environmental Impact), 0.3 M$ (for Flood Damage) and -0.51 M$ (for Generation Revenue).

The non-inferior surface has been taken as an input in the decision analysis software to perform the tradeoff analysis.

4.2.2 Logical Decision for Windows (LDW) Outputs or Results

As described in the methodology in Chapter 3, LDW software requires the user to input CDF damage curves, utility curves, and tradeoff curves for the decision analysis. All of the required parameters have been formatted for input to software, as described above, with respect to the different measures and alternatives. The LDW software outputs the results in different formats in a 'Results' tab. After performing the analysis LDW, the best operation for the event was found to be the power max operation alternative. Some of the result display options for the software are described below.

Ranking of Alternatives

Figure 33 shows that the power max alternative scores the maximum utility of 0.35 on all measures, compared to the other alternatives (pre-spill, 0.26; and normal operation, 0.25). The comparisons can also be done according to the objectives. In Figure 34, the maximum generation revenue objective for the normal operation scores the best utility (1.35), while the other values are 1.29 for power max and 1.01 for pre-spill operations.

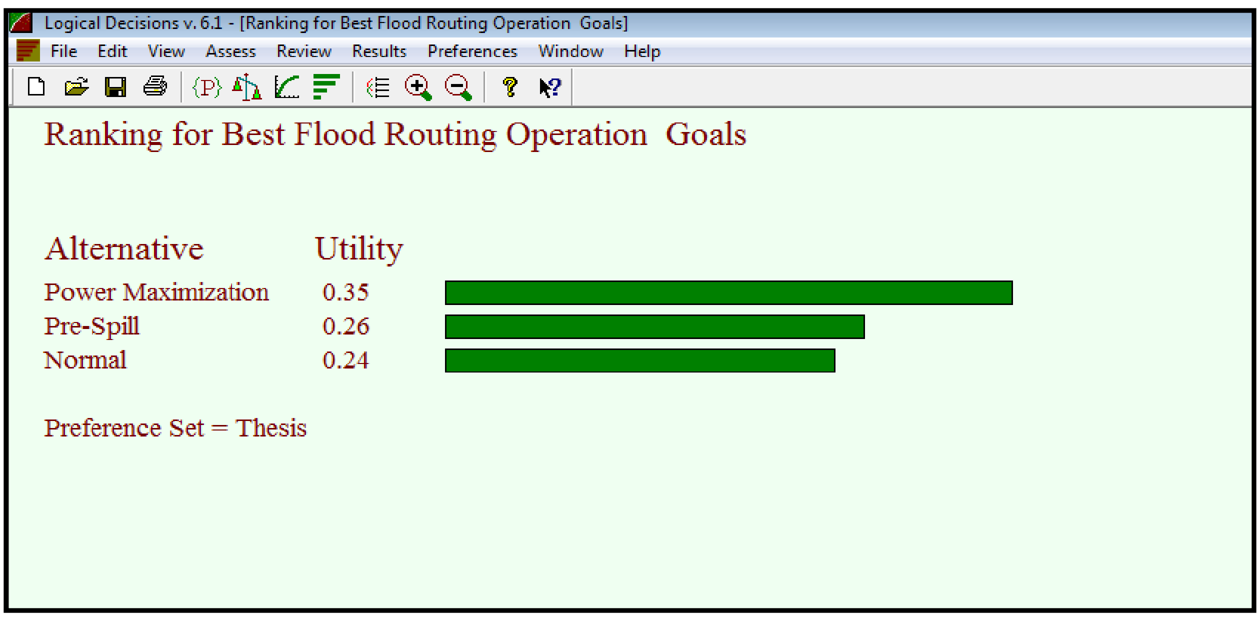


Figure 33: Ranking of the alternatives for the best flood routing operation goal.

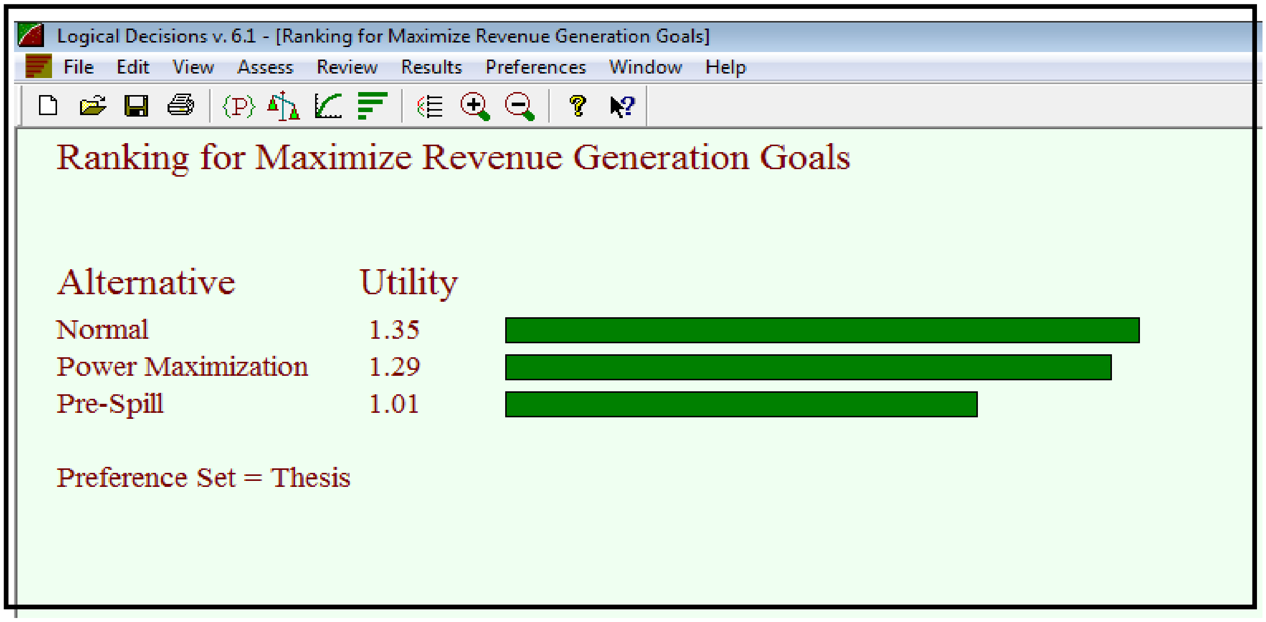


Figure 34: Ranking of the alternatives for the maximum generation revenue objective.

Stacked Bar Ranking

In this result option it can present the results on how the alternatives' utilities score on the lower level goals and measures affect of the utility on the selected goal. An alternative with a long bar indicate that the member is important and that the alternative scores well on the goal. If the bar is short, it means that the member is relatively unimportant or that the alternative scores relatively poor on the goal.

Figure 35 shows that the "Maximize Revenue Generation" power max alternative utility contribute highest to the objective while the contribution of the 'Minimize Reputation Impact' objective is minimal. The "Minimize Flood Damage" objective does not make any contribution to the normal alternative utility, which indicates that this operation will not be helpful in the event for minimizing flood damages.

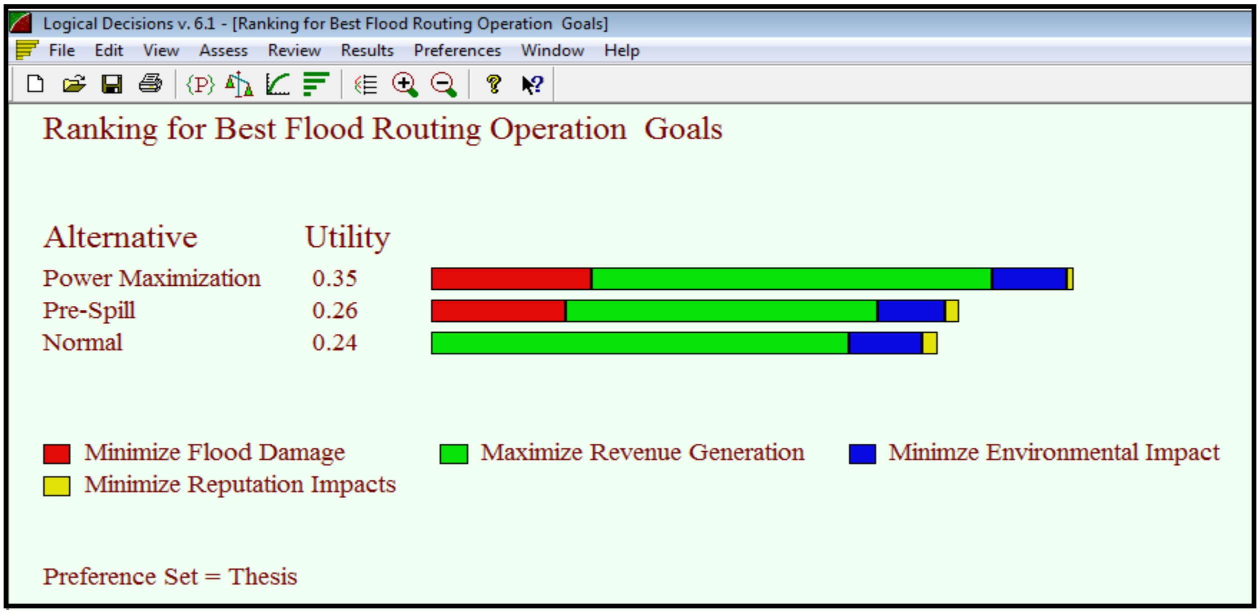


Figure 35: Stacked bar ranking of the alternatives for the goal.

<u>Measure Equivalents Ranking</u>

The Measure Equivalents Ranking option displays an overall ranking of the alternatives along with the levels of a particular measure, for the same overall utilities as if all other measures were at their most preferred level.

Figure 36 shows that each equivalent in the figure represents the flood damage for an “equivalent” operation that would be preferred equally to the alternative if the equivalent operation was at the most preferred level (for all measures other than flood damage). Thus, power max should be preferred (with a damage of $0.345 million, from the CDFs) as an operation with the most preferred levels for each measure, except for the flood damage of $0.776123 million.

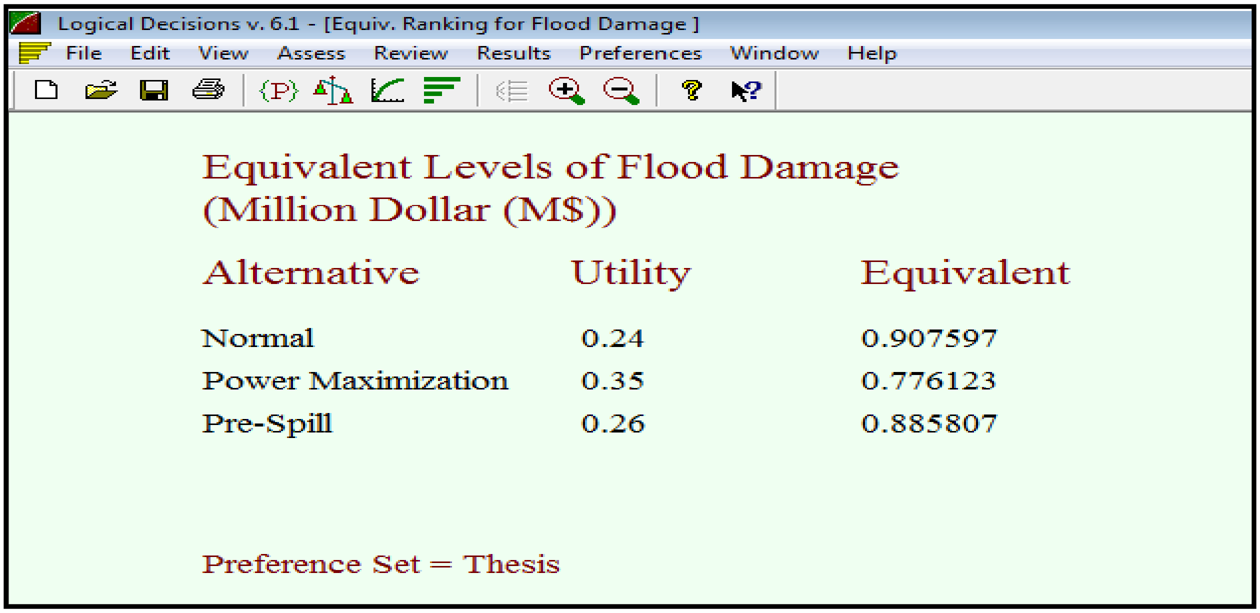


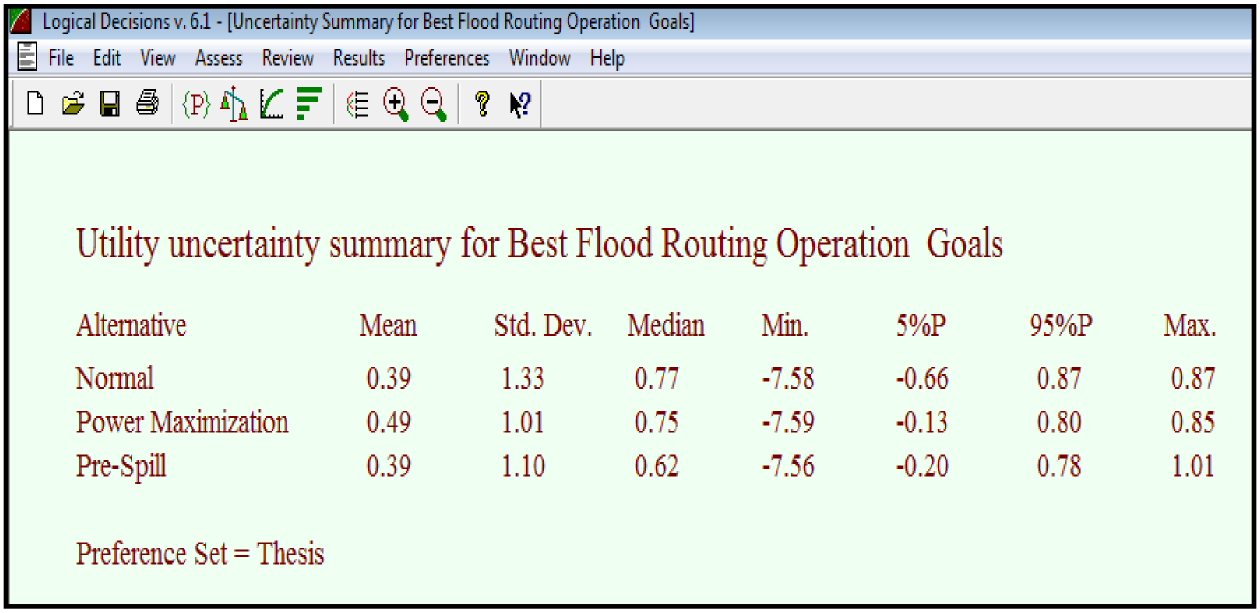
Figure 36: Flood damage measure equivalent ranking for alternatives.

Uncertainty Summary

The Uncertainty Summary option shows a table that summarizes the uncertainties for the alternatives, with respect to a single measure or goal.

In Figure 37, each row represents an alternative and each column represents one aspect of the utility uncertainty for the alternative, with respect to the active goal or measure. These results are based on a Monte Carlo analysis that the software perform.

All of the columns are self-explanatory, except for the 5%P and 95%P columns, which represent a utility with only 5% of the simulation trials below, and a utility with only 5% of the simulation trials above. Here, all alternatives have a negative minimum utility due to the revenue generation measure. The normal and the pre-spill operations have almost the same mean utility value.



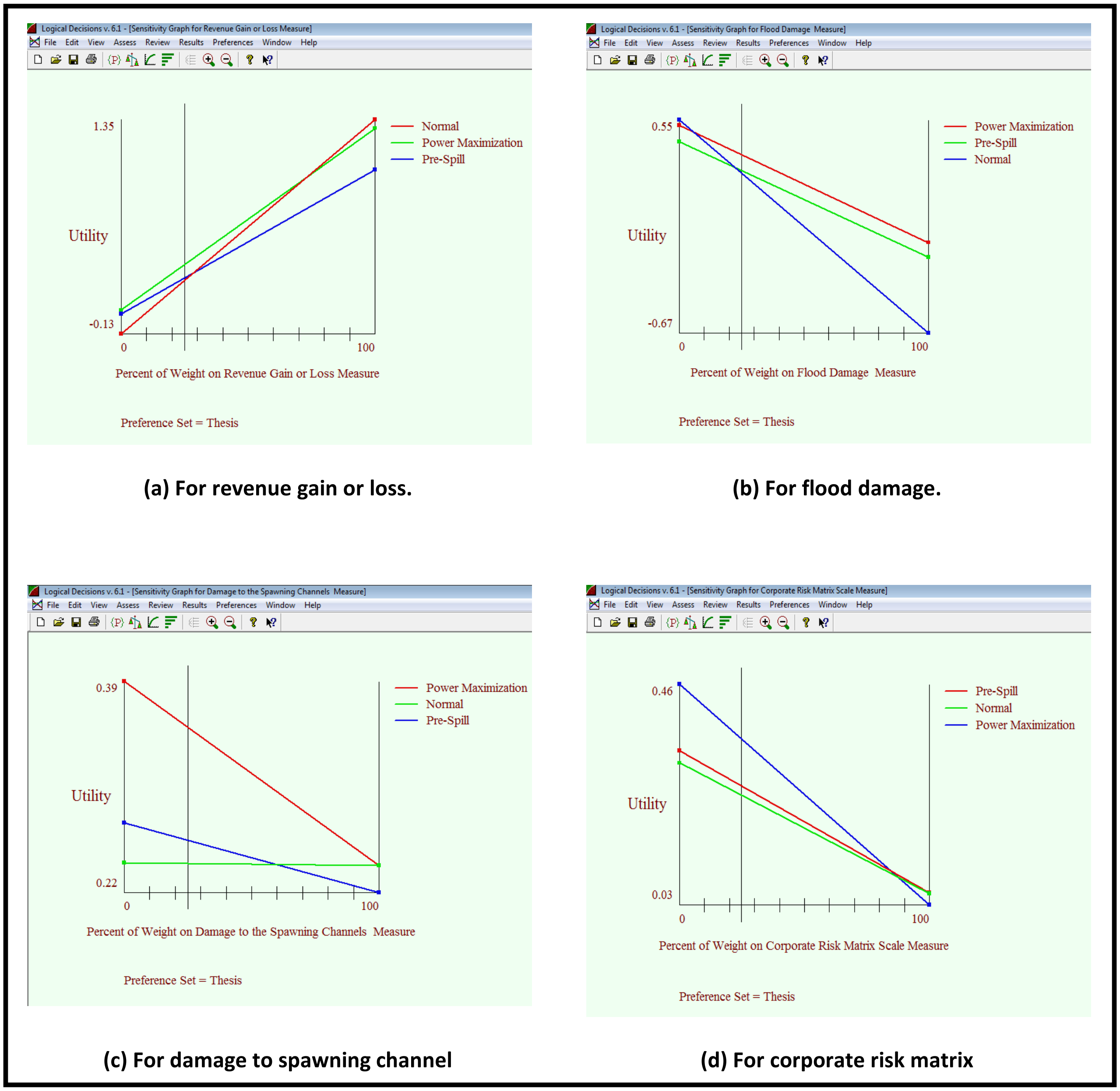
Alternative	Mean	Std. Dev.	Median	Min.	5%P	95%P	Max.
Normal	0.39	1.33	0.77	-7.58	-0.66	0.87	0.87
Power Maximization	0.49	1.01	0.75	-7.59	-0.13	0.80	0.85
Pre-Spill	0.39	1.10	0.62	-7.56	-0.20	0.78	1.01

Figure 37: Uncertainty summary for the best flood routing operation goal.

<u>Sensitivity Graph</u>

Sensitivity graphs display the effects of varying a measure or a goal's weight from 0 to 100%. The graph has relative utilities on its vertical axis and the % total weight for the member on its horizontal axis. The left side of the graph represents no weight at all on the active member and the right side represents 100% of the weight on the member. The lines represent overall utilities for the alternatives at different weights. A vertical line shows the weight for the member in the active preference set. For this research, all measures are set at the same weight in the preference set (i.e., 25% out of 100%).

Figure 38 shows that, except for the revenue gain and loss measure, all measures have decreasing utility with the more weight. The preference set weight for the measures was 25. The highest line represents the most preferred alternative (overall) for a given weight on the active member. So, from inspection of the sensitivity graphs, for all measures, it can be seen that when evaluated using the 25% weights for the measures the power max alternative scores best utility for this preference set.



(a) For revenue gain or loss. **(b) For flood damage.**

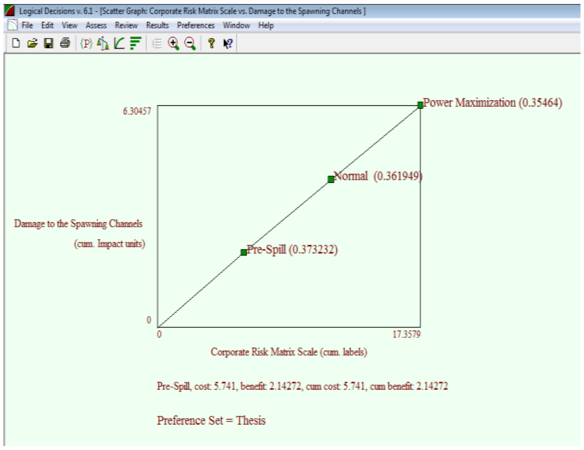
(c) For damage to spawning channel **(d) For corporate risk matrix**

Figure 38: Sensitivity graphs for the best flood routing operation goal.

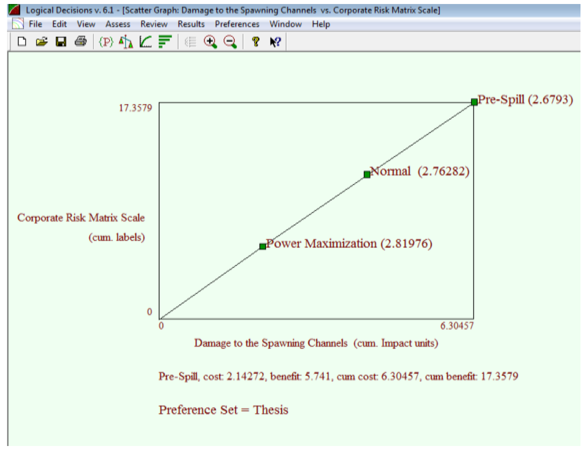
Efficient Frontier

The Efficient Frontier option identifies and orders the alternatives, according to the highest benefit to cost ratio. The alternatives are ordered on a cumulative "efficient frontier" where the alternative with the highest ratio is drawn first, the one with the second comparison is drawn second, and so on. The cost member is shown on the horizontal axis in nominal units (i.e., $). The benefit member is shown on the vertical axis in units of utility.

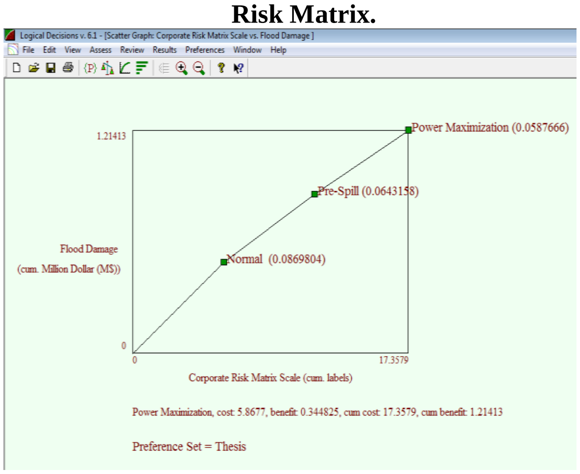
Figure 39 shows the efficient frontier between each two measures consecutively. Considering Damage to Spawning Channel and the Corporate Risk Matrix (39.a), the pre-spill alternative has the best efficient frontier (0.37323), though the Corporate Risk Matrix and Damage to Spawning Channel 39.b) indicates that power max has the best efficient frontier (2.83). Considering Flood Damage and Corporate Risk Matrix (39.c), the normal alternative has the best efficient frontier (0.0869), but for the Damage to Spawning Channel and Flood Damage (39.e), the normal alternative has the best efficient frontier (0.24). Considering the Flood Damage and Corporate Risk Matrix (39.d), the power maximize has the best efficient frontier (17.01), but for the Damage to Spawning Channels and Flood Damage (39.f), power max has the best efficient frontier of 6.035.



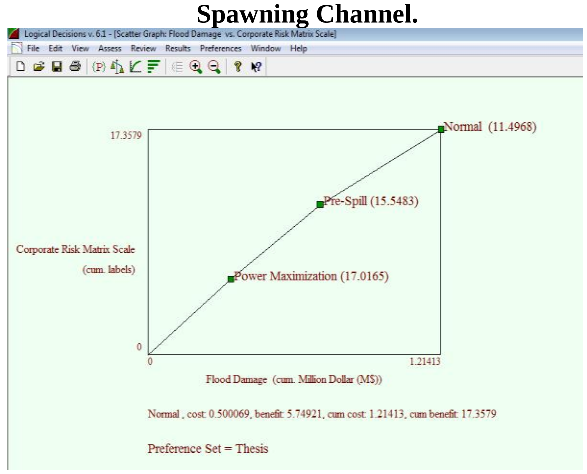
(a) For Damage to Spawning Channel and Corporate Risk Matrix.



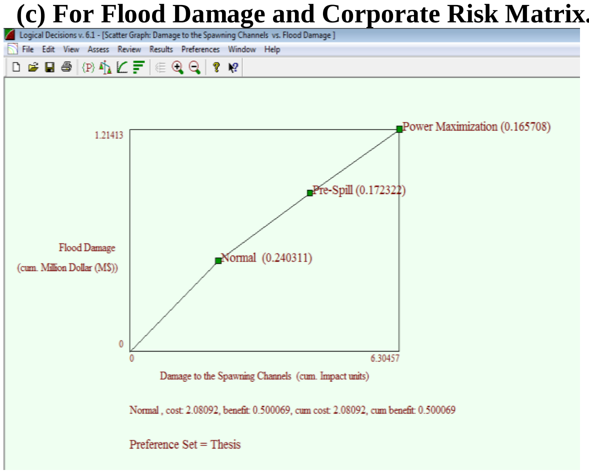
(b) For Corporate Risk Matrix and Damage to Spawning Channel.



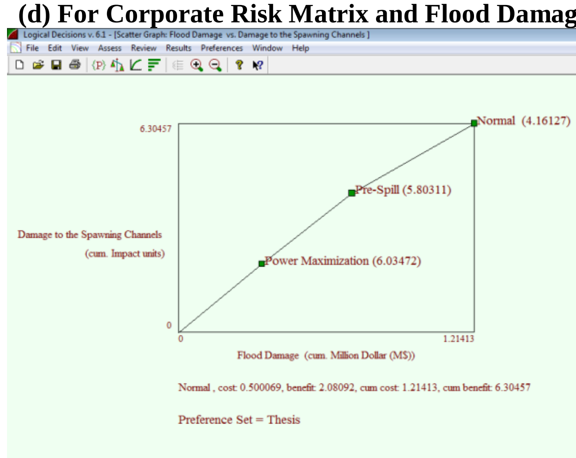
(c) For Flood Damage and Corporate Risk Matrix.



(d) For Corporate Risk Matrix and Flood Damage.



(e) Flood Damage and Damage to Spawning Channel.



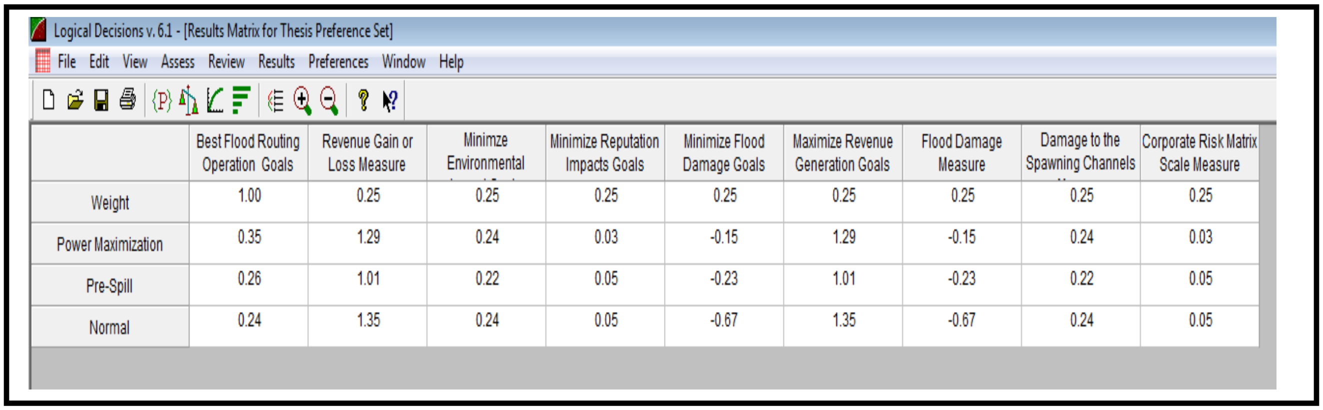
(f) For Damage to Spawning Channel and Flood Damage.

Figure 39: Efficient frontier between the measures.

Ranking Results Matrix

The Ranking Results Matrix option shows a matrix of the utility results for all alternatives, based on the measures and goals.

Figure 40 shows that for the Generation Revenue measure, the normal operation has the best utility (1.35), for the Flood Damage measure, power max has the best utility (-0.15), and for Environmental Impact and Public Image measures, all of the alternatives are almost the same.



	Best Flood Routing Operation Goals	Revenue Gain or Loss Measure	Minimze Environmental	Minimize Reputation Impacts Goals	Minimize Flood Damage Goals	Maximize Revenue Generation Goals	Flood Damage Measure	Damage to the Spawning Channels	Corporate Risk Matrix Scale Measure
Weight	1.00	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Power Maximization	0.35	1.29	0.24	0.03	-0.15	1.29	-0.15	0.24	0.03
Pre-Spill	0.26	1.01	0.22	0.05	-0.23	1.01	-0.23	0.22	0.05
Normal	0.24	1.35	0.24	0.05	-0.67	1.35	-0.67	0.24	0.05

Figure 40: Ranking of the utility results for the best operation goal

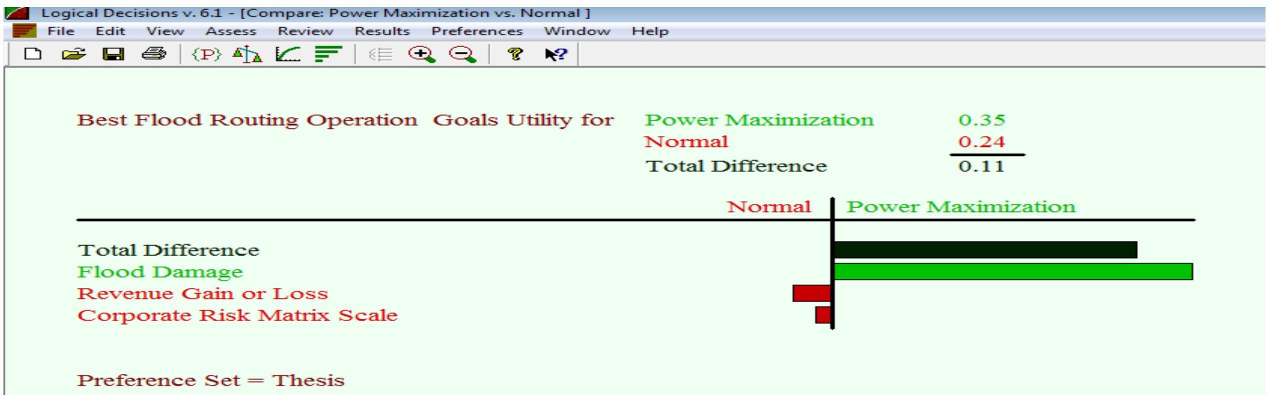
Compare Alternatives

The Compare Alternatives option shows detailed comparisons of the differences between two alternatives. In the graph, the bars represent measures that favor one alternative over the other. Longer bars indicate more influence on the overall ranking. The first bar always indicates the difference in overall ranking between the two alternatives. Figure 41 shows the comparison among the alternatives.

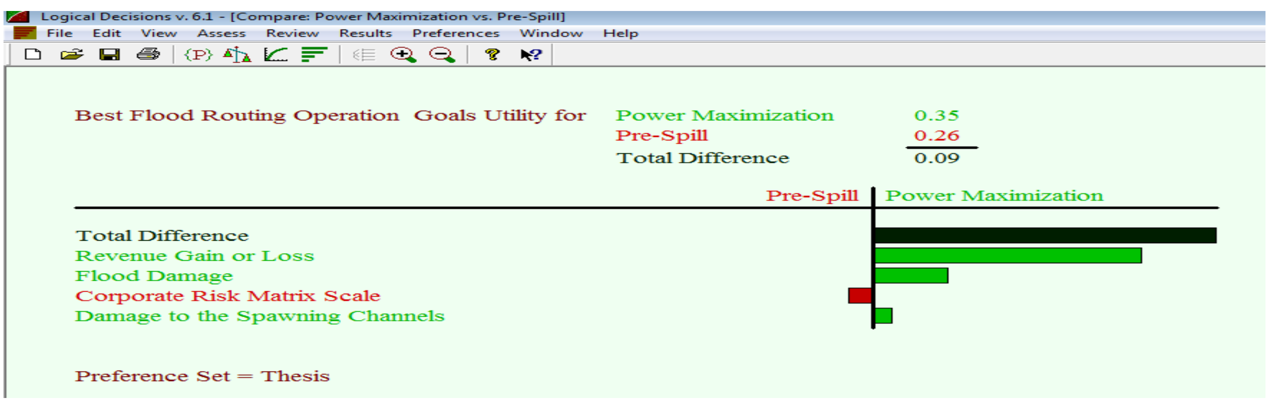
Figure 41.a shows the difference between the power max and the normal operation, where most of the utility impact is from the flood damage measure. Power max has a utility advantage but normal operation has the advantage for its impact on public image and for generation revenue measures, which are very small. The alternatives have no relative utility advantage from the environmental impact measure.

Figure 41.b shows the difference between power max and pre-spill operations, where most of the utility impact is dominated by the power max alternative over all measures except the Corporate Risk Matrix. The pre-spill operation only has some advantage from the public image impact measure.

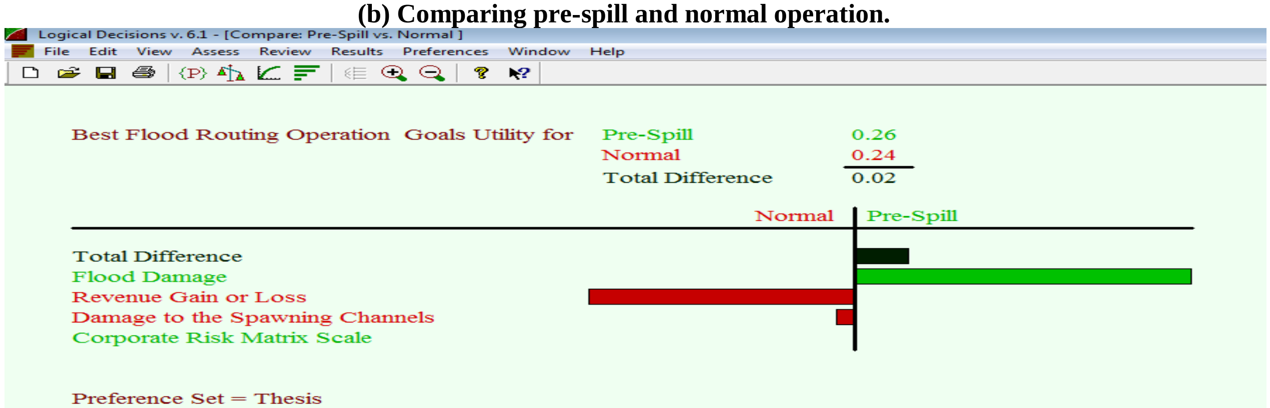
Figure 41.c shows the difference between the pre-spill and normal operation, where most of the utility impact is again from the flood damage measure. Pre-spill, however, has the utility advantage from the public image measure but normal operation has the advantage from the generation revenue and the environmental impact measures. Among these, the utility from the generation revenue measure is very high for the normal operation.



(a) Comparing power maximization and normal operation.



(b) Comparing pre-spill and normal operation.



(c) Comparing power maximization and pre-spill operation.

Figure 41: Comparison of alternatives for the best operation goal.

Chapter 5: Summary and Conclusions

This chapter summarizes the findings of this research on the applicability of the operational decision analysis framework to high inflow and flood events. Then, a discussion of how the results of the research can be adapted and applied to other river systems in BC and elsewhere. Finally, the assumptions used in this research and how they could impact the results of the analysis can provide a more complete understanding of the decision-making, are outlined.

5.1 Summary

The purpose of this research was to develop a Decision Analysis Framework and a prototype tool kit software to support the Operation Planning Engineers (OPEs) during operation planning function during high inflow events. Several steps have been taken to make the DAF tool applicable and practical. First, the clarification of different objectives, values, and risk preferences which can be assessed analyzed and prepared before hand for use in high inflow situations. Second, it was shown that the simulation and/or optimization models can be used to derive the magnitude of the measures for different objectives and that the steps that need to be executed are doable in real time. Third, the development of different damage or impact curves can be analyzed and developed before-hand using the current state of the system and state-of-the art techniques, for each hydro system. Finally, good commercially available decision analysis software can be selected and practically used for this type of applications (reservoir flood routing events).

The Cheakamus River flood event of October, 2003 was chosen as a case study for this research, as it was a recent event that most current planning engineers are familiar with. In addition, up-to-date data on this event is available for analysis. The Cheakamus river flood plain is vulnerable to several types of damages particularly as the storage capacity of the Daisy reservoir is small. Some of the flood zones along the river have been defined by BC Hydro and other governmental entities to be include public properties and First Nation’s heritage sites. In addition, a number of fish spawning channels also exist along the river and are considered important to the spawning of many species of Salmon. According to the Department of Fisheries, these channels have experienced diminished wild stock property. During periods of high inflow events the majority of properties in these flood zones are often flooded causing significant losses.

One of the main functions of a company like BC Hydro is to increase the value of resources by producing more energy from existing resources, while meeting the environmental and social constraints. Under current practices the OPEs run simulation optimization models for operating the dams during different periods. Inflow forecasts and the energy market prices are highly uncertain and this uncertainty is not directly included in the simulation models; decisions based on these models do not adequately include the risk of flood damage and various other power and non-power impacts. To deal with such risks and uncertainties, it is recommended a Decision Analysis Framework be developed and implemented for high inflow events to aid the OPEs in ensuring that the TBL operating rules, guidelines and procedures are followed.

The result of this research shows that the most suitable operation for the flooding event of October 14-18, 2003 would have been (and it was) to follow the "power maximization" alternative as it provides more benefits than that of normal operation, and is more advantageous than the pre-spill operation, when comparing all the utilities and the impact objectives together. Nevertheless, the decision-maker must also analyze the particular impact objectives measures such as flood mitigation, minimizing environmental impact, minimizing public image impact or maximizing the generation revenue etc. individually, for their contribution to the result. When these considerations are taken into account, and based on the results of the analysis, if the decision-maker prefers to maximize the power generation revenue during the event, normal operation would be the best alternative as it scores 1.35 on the utility measure, while power maximization and pre-spill operation scores on utilities are 1.29 and 1.01, respectively. It can be seen that these back and forth checks will help the decision-maker to choose the most appropriate alternative for the event while factoring the departmental and organizational preferences into the decision taken.

5.2 Conclusions

This research has shown that the application of decision analysis techniques leads to a ranking of the alternatives and can also provide a probability distribution for the rankings, which can be used by the decision-makers or that can be provided to the stakeholders in their deliberations and discussions. While the rankings are an important result of this decision analysis framework, other benefits are also possible (Reichert et al., 2005), including:

Improved insight into social and scientific aspects of the decision problem and more confidence that all of the relevant aspects of the decisions have been taken into account, after extensive discussion and valuation of objectives, and careful consideration of cause-effect relationships in the simulation or optimization models;

Stimulation of the development of new and compromise alternatives with a lower conflict potential among the conflicting parties or objectives, by means of analyzing the possible conflicts of alternatives;

A sensitivity analysis of the rankings can be used to analyze important sources of uncertainty, such as those in input parameters and model structure uncertainty, or uncertainty in value elicitation of the utility or trade-off functions and could also used to demonstrate robustness of the decisions taken;

Increased transparency of the decision-making process, through documentation of predicted effects and decision outcomes, and the elicitation of values and resulting rankings;

The advantage of this framework when adopted in ingoing practice of BC Hydro OPEs is that it provides a more objective and transparent decision-making process, which will be more aligned with the risk tolerances and Triple Bottom-line guidelines of the corporation. The framework can allow planners to quickly respond to flood emergencies and openly communicate operational decisions to stakeholders and other senior management of the company.

5.3 Future Work

The analysis can be extended in many ways and can be tailored to meet specific needs. The research approach and the results of this analysis suggest a number of potential research projects that would be worth exploring to further improve the framework. An approach and a framework have been laid out in this project, which could be extended to involve a more robust investigation of different damage curves, utility functions, and generation of inflow scenarios. Specifically, further research is needed on the following suggested areas:

1. ***Damage Curves*.** Several types of damage curves were used in this research and they were based mainly on expert opinion. The procedure may have lacked consensus from all experts. To best develop the damage curves in the future, extensive modeling needs to be used which combines special hydraulics, hydrology, bathymetric, and weather conditions of the river

basin. Most importantly, at each step, an uncertainty analysis needs to be performed of the results as discussed in the USACE Manual No. 1110-2-1619.

2. ***Utility Curves.*** Utility functions for the different objectives were chosen on the basis of expert opinions from the OPEs team at BC Hydro. These utility functions could be further developed and enhanced in many ways. Keeney (1976), for example, describes the mathematical formulation of the utility functions, while the current, state-of-the-art development and elicitation of utility functions uses the "value-based utility functions," as described by Keeney and McDaniels (1992) in their work on BC Hydro's value tradeoffs.
3. ***Inflow Forecasts.*** As described in Chapter 1, BC Hydro's current forecasting system has a very limited capability to provide a probabilistic inflows forecast for high inflow events. The forecasting system needs to be enhanced and expanded to provide this type of forecasting capabilities. Fortunately, the H&TS Department in GRM is currently upgrading the RFS to provide an ensemble inflow forecast using the Ensemble Stream Flow Prediction (ESP) method (Smith & Weber, 2003), which is believed by many to be the most sophisticated inflow forecasting methodology currently available. A further desirable extension would be to further enhance the ensemble forecast to provide a conditional probabilistic forecast on the current forecast.

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