THE ECONOMIC WORTH OF HYDROMETRIC DATA USED IN THE REAL TIME OPERATION OF WATER RESOURCE PROJECTS

by

TIMOTHY ALLAN LOCK ㉞

A Thesis

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in Partial Fulfillment of the Requirements

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ABSTRACT

Hydrometric data are required for the planning, design, and operation of water resource projects. The worth of additional data, or of data that will no longer be collected can be identified by determining the economic impact of that data on plans, designs or operations of water resource projects. Little research has been performed on identifying the economic impact of network changes when the data is used in the real-time operation of a water resource project. A general framework was developed for addressing this problem which was then applied to a case study. The framework focused attention on uses of the data, the required attributes of the data, and the economic impact of changes of those attributes due to changes in the data collection network. The framework was applied to Southern Indian Lake, through which water is diverted for the purpose of hydro-power production. The sensitivity of the regulation of Southern Indian Lake to the uncertainty of the lake level data was investigated using a computer simulation. Attributes of the data which contribute to uncertainty were investigated using a statistical analysis. The information yielded made it possible to determine the marginal benefit cost ratios of discontinuing gauges, repairing a gauge, or adding a gauge to the existing network.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 Introduction

1.1 Background

Hydrometric data are required for the planning, design, and operation of water resource projects. Typically, historical records and current readings of streamflows and lake levels at various sites are used to estimate current and future conditions on lakes, reservoirs and rivers. Collecting additional hydrometric data benefits the planning, design, and operation of water resource projects, but at some point the cost of collecting additional data outweighs the benefits.

The costs of collecting additional data are immediate and usually quite evident as is the cost-savings of collecting less data. The benefits of having data may not be realized immediately and are difficult to assess because of the many uses and users. When needs or legal requirements dictate or legislate data collection activities, the knowledge of the benefits of the data is irrelevant. However, when data collection activities are discretionary, knowledge of the benefits of the data could be used to justify and optimize the data collection activities.

Currently, hydrometric data collection is funded through cost sharing agreements between the federal government, the provincial government, and some end users of the data. In recent years, governments have been cutting back funding for data collection. As funding for particular data collection sites is discontinued, end users must decide what the economic impact is of losing the data, and whether or not it is economically beneficial to perpetuate data collection at their own expense. The government agencies which perform the data collection would also be interested in the economic worth of the data they collect, as it would aid in optimizing their network and justifying their budget.

1.2 Scope

The scope of this study was to investigate the current understanding and practice for determining the worth of data, develop a general framework or methodology for addressing data worth problems, apply the methodology to a case study, and then use the case study to derive additional generally applicable principles for determining the worth of data.

Determining the economic worth of data involves a number of complex questions, some of which are: how can economic worth be associated with individual data collection gauges, how can the sensitivity of operational decisions to the accuracy or reliability of the data be found, how does spatial data transfer affect worth, and, what economic analysis is valid or beneficial for making data collection decisions? A literature review and a mail survey served to reveal how well a number of methods for determining data worth address the issues. The methodology developed addresses each issue in a general way and the case study attempts to address the applicable issues in a rigorous way.

2.0 Current State of Knowledge and Practice

2.1 Literature Review

The literature on determining the economic worth of hydrometric data covers a variety of methods to determine worth for a variety of data types and end uses. Since data has no worth without being used or having potential use, each method of determining worth focuses on certain uses which, in turn, dictate the types and attributes of the data which are of value. Two methods of optimizing the effectiveness of a network, subject to its cost, are reviewed. Next, methods for determining the economic worth of hydrometric networks and individual data records are reviewed. Finally, methods for determining the worth of data are reviewed for operations, as opposed to the majority of the examples in the literature in which data were used for planning and design.

2.1.1 Network Cost Effectiveness

2.1.1.1 Network Error Minimization Approach

Scott and Moss (1986) described a method which was used to evaluate the cost effectiveness of the USGS network, state by state. The field operation, which consists of trips to gauging stations for the purpose of maintenance, making discharge measurements, and other required activities, was optimized to give the minimum data error for a given budget. In the first step of the study, uses of the data from each gauge were identified and compared with USGS purposes to check if the continued operation of the gauge could be justified. In the second step, gauge stations were checked to see if the data from them could be estimated from other gauge stations using a unit response flow routing method and/or regression analysis. In the third step, the error of the whole network was minimized subject to the constraint of the current budget, using Kalman Filtering for Cost-Effective Resource Allocation (K-CERA). The error minimized was the sum of the variances of the percentage errors of the instantaneous discharges at all continuously gauged sites.

About half of the USGS network (3493 gauge stations), was analyzed with this method. About 3% of the stations were identified as not having sufficient use to justify continued data collection, either currently or immediately following the completion of their respective short term studies. Between 1% and 10% of the gauge stations could be discontinued (depending on the level of accuracy required) by estimating data for them from other gauge stations. Using the K-CERA technique the average weighted standard error of the network was reduced from 19.9% to 17.8% while maintaining the current budget. Alternatively, the current standard error could be maintained and the budget could be reduced by 4.5%.

The USGS method is valuable for rationalizing a network describing regional hydrology. It does not address the possibility of adding or moving gauges, since it uses the accuracy of existing data as the main criteria for determining worth. It is most appropriate for a network which describes regional hydrology, rather than a network which has many site-specific uses with site specific accuracy needs, since the method attempts to minimize the overall network error without consideration of the accuracy requirements of specific sites.

For more detail on K-CERA see Moss and Gilroy (1980), Gilroy and Moss (1981), and Fontaine et al. (1984).

2.1.1.2 Rating Approach

The hydrometric network of New Brunswick was evaluated using rating factors to assign relative value to individual stations (Davar and Brimley, 1990). Existing and proposed stations were rated and a set of scenarios ranging from a minimum network to an optimal network were created and compared.

Davar and Brimley defined the optimum network as one for which the supply of hydrometric data equals the demand for the data. The supply of hydrometric data was the gauging station records and the regional data transfer capability. The demand for hydrometric data was the specific operational needs and the general regional requirements. Using demand for data as the measure of worth avoids the issue of economic worth, for which three reasons are given:

1. Each data record may have a number of uses with varying economic benefits.
2. Because of unanticipated needs, the demand is never fully defined and neither are the consequent benefits.
3. Error analysis, which is often used to compare the effect of having or not having a particular gauging station, usually focuses on a single purpose or project and a single station, which is far different from the actual situation of multiple users and a mature network.

Based on the work by Wahl and Crippen (1984), Davar and Brimley developed a set of criteria for rating the value of a gauging station. Wahl and Crippen argued that many of the analytical techniques to optimize a network deal primarily with the design of networks that define the regional hydrology and do not recognize multiple uses with individual requirements for data and accuracy. The criteria Wahl and Crippen developed were based on the need for information at that site, accuracy of data from the gauge, economic aspects of operation, and usefulness of data from the gauge for transfer to ungauged sites. The total points assigned to a gauging station defined its relative ranking and theoretically its relative worth. This method is subjective and relative but it recognizes the possibility of data transfer and is useful for prioritizing stations according to the uses made of the data.

A simplified optimization procedure for Davar and Brimley's study is as follows. First, each existing and proposed station is rated. Secondly, the stations are sorted in descending order of total rating points. Thirdly, the optimal network is chosen by including as many stations as the budgetary constraint will allow, beginning with the station with the most points.

The problem with this procedure is that in some cases a particular station can not be rated independently of knowing which other stations will be operated. This is partially addressed in the next stage where particular scenarios are proposed and it is known what changes will be made to the existing network. Also, because of formal or legal commitments there may be no choice regarding the operation of some stations.

A set of network scenarios was constructed and plotted according to their cost and total station points. The scenarios ranged from a minimum network to an all inclusive network in which all needs were addressed and all regions were sufficiently represented.

Davar and Brimley concluded with some specific recommendations to create a more cost-effective network for New Brunswick. They also concluded that the audit approach, though subjective, was valuable in bringing together all of the relevant considerations for network evaluation.

The audit approach seems very strong in that it does consider all the users and uses of station data as well as the quality and length of the record, and data transfer capability. The relative measure of worth incorporates uses that are difficult to quantify in dollars, but an economic measure of worth would be helpful in establishing a base value to work from in determining worth. The optimization procedure has the weakness that each station is rated individually rather than as part of a particular network. So, the most beneficial aspect of this approach is the rating scheme which incorporates all the uses of each gauging site and which can be applied to proposed stations as well as to existing stations.

2.1.2 The Economic Worth of Networks

Network cost-effectiveness methods have great value as starting points in determining economic worth, which is why they have been reviewed here. Each of the two methods discussed could be developed to incorporate a determination of economic worth. Each provides a framework to address the worth of networks. Each framework attempts to address the issues of data transfer, the difference in need for data at different locations, and the cost of obtaining data. This section takes the next step, moving from relative worth to economic worth. These studies are similar to the previous ones in that they consider a network of gauges which collect data for multiple uses.

Ingledow (1970) calculated benefit-cost ratios for network expansions in the maritimes. Various rates of expansion over a 20 year period were used to find the corresponding reduction in error of estimation of mean flow, flow dependability, and flood frequency used in the design of water resource projects. Benefit-cost ratios varied from 2.8 to 21.2 depending on existing network density. Wilson (1972a) improved upon the benefit calculations of this study by incorporating projections of estimated future expenditures for the design projects considered.

Wilson (1972b) considered the improvement in accuracy of regional flood frequency analysis gained by increasing the density of a hydrometric network in the New Brunswick-Gaspe area of eastern Canada. The error in flood flow estimates was related to construction costs of small flood control structures and to the cost of probable future damage.

Watt and Wilson (1973) defined an adequate hydrometric network to be one for which the marginal cost of obtaining data equals the marginal benefit of the data. The marginal cost is the relationship between additional cost and the increase in design parameter accuracy. The marginal benefit, which is the focus of this paper, is the relationship between increase in design parameter accuracy and savings in total cost. Total cost is the sum of capital cost and cost of future losses, for which relationships were developed. The benefits considered were from small structures designed using flood flows and reservoirs designed using dependable flows.

Solomon (1976) used a method similar to Ingledow (1970) to obtain benefit-cost ratios for expanding the Canadian network.

Acres (1977) applied benefit-cost analysis to water resources data for the whole Canadian network. Uses of data were identified and a fixed percentage of the construction or mitigation cost of each of these applications was assumed to be the benefit of the hydrometric data. For example, the assumed benefits of data for hydro-electric projects was assumed to be

5% of the capital cost of the associated hydraulic structures. Using this approach, the overall benefit-cost ratio for the Canadian Network was found to be 9.3. The obvious weakness of this method is the lack of justification of the benefits assumed.

Attanasi and Karlinger (1977) proposed a method of determining the optimum number of basins to gauge and the corresponding number of years of data to collect. A production function was created which embodied the technical and input resource constraints, and a utility function, combined with risk aversion parameters, was created which embodied the economic worth of the data. The point of tangency of the two functions determined the optimal solution.

The marginal benefit of increasing, and marginal disbenefit of decreasing, Canada's hydrometric network by 20% was calculated by McMahon and Cronin (1980), by considering the value of the data in optimizing the design of dams, reservoirs, culverts, bridges, spillways, and hydro-power plants.

The first of two steps correlated gauge station density with the error of hydrologic parameters estimated from the data. This approach makes no judgement on or evaluation of the rationality of the existing network. The total error in the estimate of hydrologic parameters was broken down into measurement error, inhomogeneity error, sampling error, and transposition error. Measurement error is due to error in measuring stage and discharge and to hydraulic regime variations (i.e. ice effects). Inhomogeneity error is due to systematic changes in stage or flow over time caused by man's activities. Sampling error, related to flood frequency analysis, is poor representation of flows due to short records, and is inversely proportional to the length of the data record. Transposition error is due to data transfer to ungauged sites and is a function of station density and location. The study assumes that inhomogeneity error can be eliminated. The remaining sources of error were used to determine expected hydrologic error in parameters used to design the above projects.

The second step related the error of hydrologic parameters to the change in project construction cost for each of the four uses. Previous studies, (Acres, 1977, Shawinigan, 1970, and Ingledow 1970), were used to establish the relationship between parameter error and construction cost. For the fourth use, hydro-power, no design benefits were attributed to the network, since the authors understanding was that the benefit-cost function is flat near optimum plant capacity and so small errors have little effect on the scale of development selected.

Two scenarios were created where the Canadian network was increased and decreased by 20% in the year 1977. The construction costs were assumed to be constant over time. The marginal benefit ratio was defined as the incremental construction savings divided by the cost of the additional gauging stations. The marginal disbenefit ratio was defined as the incremental construction costs divided by the savings from reducing the network size. The marginal benefit ratio increased with time and was greater than 1 by 1990. The marginal disbenefit ratio also increased over time and was greater than 1 by 1985. The marginal disbenefit ratio was broken down by province to show the sensitivity to the network reduction. Newfoundland was the most sensitive because of its small existing network. Quebec and Ontario were the next most sensitive because of the magnitude of the water related engineering projects in those provinces.

McMahon and Cronin recognize that this study considers a limited set of quantifiable benefits. There are additional non-quantifiable benefits from flood forecasting, water quality, waste disposal, navigation, water resources management, apportionment, recreation, investigation, and research.

The Australian Water Resources Council (1988) commissioned a comprehensive report and literature review on the importance of surface water resources data to Australia. (See also Simpson and Cordery (1987) for a literature review.) For Australia, data users and the attributes of the data needed were identified. The problems of data worth analyses are discussed and a comprehensive review is made of data worth studies.

The report stated that costs of data collection were relatively easy to obtain in Australia but because there are a number of state water authorities and other organizations with varying administrative overheads collecting data, adjustments had to be made to compare costs from site to site within Australia. A comparison was also made of Australia with Canada, showing that Australia's annual expenditure on data collection was half that of Canada despite a higher variability of runoff and therefore a greater "need" for data. The comparison of the two countries was made because of the similarity in total land area, total population, distribution of the population, and standard of living. Significant differences between the two countries are that the total runoff in Canada is about five times higher, but the variance of the distribution of runoff is higher in Australia. Expenditures on data collection in Australia decreased by 29% between 1977-78 and 1986-87, causing concern that the worth of data lost was not being considered by those cutting the expenditures.

Three approaches for obtaining costs and benefits of hydrometric data were presented:

1. Proportion of capital cost of structures, as previously reviewed in Acres, 1977;
2. Savings achieved with more accurate and reliable data, which is the basis of most data worth studies; and
3. Cost of restoration after failure because of inadequate data.

The first two have been used in benefit-cost analyses but few examples exist of the third. Since the time of the writing of the report, Cloke et al (1989) combined the second and third approaches to obtain the costs and benefits of over-designing or under-designing small bridges and culverts (appears later in this review).

The Australian Water Resources Council report stated that assessing benefits is difficult in contrast to assessing costs because of the difficulty of defining benefits, the lack of standard procedures for assessing benefits, the different times at which costs and benefits are incurred, requiring discounting, and the multiple uses, many of which are in the future and are impossible to predict. It also stated that because of the difficulties in calculating benefits, most benefit-cost studies have been research projects rather than analyses carried out by the data collection agency to justify or modify their network.

Doran (1989) performed a marginal benefit cost analysis for Australia's network which parallels McMahon and Cronin's study of the Canadian network (1980). Doran's analysis is conservative (the author estimates that probably only 50% of the benefits are accounted for) resulting in a minimum benefit cost ratio, just as in McMahon and Cronin's study. The benefits considered are the economic implications of data accuracy on the design of hydraulic structures. Benefits unaccounted for are the improvements in the design of flood plain structures, in flood proofing and mapping, in flood warning systems, in environmental and water quality monitoring, in soil conservation, in urban drainage, and in water regulation other than dams. The marginal benefit-cost ratios of reducing the network by 20% changes from -1.12 in five years to -4.03 in fifty years. The marginal benefit-cost ratios of expanding the network by 20% changes from 0.32 in five years to 2.25 in fifty years. Clearly, reducing the network would not be economically beneficial and expanding it would be.

Doran's findings conflicted with his observations of the gradually declining network in Australia. He believed that some reduction may have been due to rationalization but that most was probably due to the stringent economic policies. "The cost side of the economics has been allowed to dominate and budget cuts have led to immediate decreases in the network" (Doran, 1989). He pointed out that decision-makers are not persuaded by benefit-cost ratios. Rather, the persuasion is in the marginal benefit-cost ratio which indicates the value of additional dollars invested in network expansion or the value of dollars saved in the case of network reduction.

Cloke et al.(1989) performed a benefit cost study of the stream gauging network of New South Wales. The use of the data considered is for the design of small bridges and culverts. The authors recognized that there are other uses, but that this approach would determine the minimum worth of the streamflow data.

The premise of the paper by Cloke et al. was that hydrometric data have benefited New South Wales by supporting design methods which are more accurate resulting in fewer structures being over-designed or under-designed. Compared to an optimally designed structure, an over-designed structure is overtopped less frequently, but the increase in capital expenditure is greater than the additional savings. Compared to an optimally designed structure, an under-designed structure has a lower capital expenditure but is overtopped more often, costing more than the initial savings in capital. Five design methods had been used, in New South Wales, over the years, based on the amount of hydrometric data available at the time. The latest method used the greatest amount of data and was considered the "true" estimate to which the results of the other methods were compared. The 20 and 50 year peak flows were estimated for 50 sites representing New South Wales using each of the 5 methods.

The major parts of the cost of overtopping a structure was determined to be the repair to the structure and the disruption of traffic. The cost of repair of a structure which had been overtopped was estimated to be 7.5% of the capital expenditure. The expense to the public was determined to be due to the disruption of traffic and was calculated from average vehicle occupancy, value of occupant's time, average distance of detour, and average speed travelling the detour.

A survey of local government authorities yielded a rough relationship between design flow and capital cost of small structures. Cost of operating a full time gauging station was estimated to be $4500 (1988) per year.

The minimum benefit-cost ratio for a network in New South Wales designed solely for the purpose of designing small structures was estimated to be 33. The minimum benefit-cost ratio decreased to 8 when the costs of the whole Department of Water Resources streamflow data collection program was considered.

Cordery and Cloke (1990 and 1991) used this method of assessing the impact of improved design procedures in New South Wales for considering the design of a reservoir for a water supply project and for the design of small structures, respectively. Cloke and Cordery (1993) found for the design of reservoirs in New South Wales that the benefit cost ratio was 3.5 for the collecting and using of 40 years of data compared to 20 years of data.

This method is an ingenious way of observing the impact that additional data have made on design methods of hydraulic structures in New South Wales. However, this approach is only applicable under similar circumstances, where the design methods over the years are known and where it is reasonable to assume that improvements in the design methods are mainly due to the increased amount of data available.

2.1.3 The Economic Worth of Individual Data Records

By narrowing the scope of a problem it is often possible to do a more rigorous analysis. In this section, the economic worth of a single data record is determined when it is used for a single purpose.

Moss (1970) developed a scheme to find the optimum length and accuracy of record for a streamflow gauge to be installed for the sole purpose of designing a water supply reservoir. Accuracy of design parameters for the reservoir was deemed to be controlled by the number of discharge measurements made per year to update the rating curve, and the length of the streamflow record.

The optimum operating procedure is that which results in the greatest net benefits which is the difference between the worth of the data and the cost of the data, both reduced to the present value. The cost of the data is the sum of the initial capital cost and the annual operating cost which is dependent on the number of discharge calibration measurements per year. The worth of the data is equal to the benefits forgone if the data were not available for designing the water supply reservoir. The worth varies with the length and accuracy of the record. The worth can not be determined until sufficient stage and discharge measurements are available to perform an error analysis.

Constraints on the project would not change the cost and worth evaluations but would change the way that the analysis proceeds. Two constraints are considered: one, the existence or non-existence of a previous streamflow record, and two, the flexibility of the point in time when the reservoir construction will be started. Four cases of the different combinations of these constraints were analyzed.

The proposed approach was applied to the design of a reservoir on the Arroyo Seco near Soledad California. The approach was not able to identify an optimum number of discharge measurements because of the low sensitivity of the worth of the data to the low computational error. The error introduced by the natural variance of the streamflow was higher than the error introduced by discharge calibration. The low sensitivity to the number of discharge measurements indicated that a minimal number of discharge measurements were required, so four discharge measurements per year were chosen. The sensitivity of optimum record length to cost of data was negligible, and the sensitivity of optimum recorded length to discount ratio was small. The optimal number of years of record was around 10 years which is often greater than the length of time that politicians or the public want to wait. Instead of waiting for a long site specific record, a regional long - term network and a regression model could be used to synthesize an optimal length record for the site.

Dawdy et al.(1970) assessed the worth of data by measuring the net benefits forgone as a result of the lack of data. A 500 year record for a single gauge station was simulated, from which the optimal design of a multi-purpose reservoir was found. To obtain the benefits forgone, the optimal design was compared to designs using smaller subsets of the record. Each reservoir design was based on a streamflow record and benefit and cost curves developed for the reservoir. A cost function for construction and maintenance of the reservoir was approximated from existing information. Benefits derived from flood control were neglected. The benefit considered was the yield and the minimization of loss due to shortage. The economic impact of the number and amounts of shortages depend on the uses made of the resource. This paper used a hypothetical function of shortage versus benefits.

Tschannerl (1971) and Shawinigan (1970) also related the length of data records to the benefit of reducing uncertainties in reservoir design.

Davis et al.(1972) described the application of Bayesian decision analysis to a flood protection project in Tucson, Arizona and found that the Bayesian risk decreased as additional data was made available. In Bayesian decision theory a prior expectation of a state or an event is revised by additional information to get a posterior expectation. The impact of the additional information is measured by the improvement in the outcome of a decision based on the posterior expectation compared to the decision based on the prior expectation. Parameters describing hydrometric data are treated as random variables and are used to formulate the expectation matrix. The method is statistically elegant but mathematically complex as reflected in the Australian Water Resources Council statement, "while the Bayesian approach appears valuable in making future decisions in network design (Jackson, 1976; Moss, 1976b) it is believed that as long as more accurate objective or utility functions are not developed and additional work is not carried out on the probability distribution of the design parameters, the large amount of computations necessary to solve the complicated relationships militates against the general application of the approach" (Australian Water Resources Council, 1988).

Moss and Dawdy (1972) combined two previously used methods to determine the worth of flood data in the design of highway crossings. The first method, used by Dawdy et al.(1970) as well as Tschannerl (1971), used various length synthetic records to determine the value of flood data for design. Moss and Dawdy pointed out that the restriction of this method is that the statistical moments of the hydrometric data must be known prior to the analysis. The second method, used by Davis (1971) and Davis et al. (1972) as well as others since 1972, applied Bayesian decision theory. The two methods were combined by using various lengths of synthetic record under the assumption of known statistical moments of the data and incorporating the expected distribution of the statistical moments in the Bayesian formulation.

Jacobi (1975) determined the economic optimum record length of sediment load data using a Bayesian decision approach for the design of the sediment storage portion of the Cochiti Reservoir on the Rio Grande. The economic optimum record length was achieved when the marginal costs of acquiring the data and delaying the project was equal to the marginal economic benefits of having a longer length record to base the project design on.

Cordery and Simpson (1986) showed that the incremental benefits exceeded the incremental costs of data collection for a single station used to design a flood mitigation scheme for the town of Forbes, New South Wales.

2.1.4 The Economic Worth of Data Used for Operations

Very little analysis of the economic worth of data has been performed for cases where the data is used for operating decisions, such as reservoir operation, diversions, extractions, and apportionment. The greatest difference in data requirements is that, typically, planning and design requires long historical records while operations requires accurate, reliable, real-time data.

Curtis and Dotson (1993) proposed a framework for optimizing the size of a rain gauge network used for flash flood warning systems. The number of gauges was related to the coefficient of variation of data from the gauges, which is a measure of the variability of the data. The coefficient of variation was used in an expression which relates it to the annual potential damage reduction from a flood warning and preparedness program. A hypothetical 500 square mile watershed with $1,000,000 in average annual flood damages was analyzed for network sizes from 2 to 30 gauges. It was found that the incremental cost of adding gauges exceeded the incremental benefit beyond 18 gauges. The authors note that an incremental economic analysis is more suitable than comparing total average annual benefits and costs.

The following papers dealt with the worth of data used for forecasting. Moore and Armstrong (1976) used linear programming and Bayesian statistics to assess the incremental benefits resulting from increased accuracy in forecasting water supplies for irrigated agriculture. A benefit cost ratio of 6.6 was calculated by Heatherwick and Quinell (1976) for the Brisbane flood warning system and supporting data network. Made (1982) looked at the value of increased accuracy of water levels for navigation on the Rhine River. Zhidikov (1982) examined Russian data networks used for hydrologic forecasts for the operation of hydro electric power plants and concluded that the benefit-cost ratios were very high.

2.2 Questionnaire

Questionnaires with introductory letters were mailed to people who routinely use real-time hydrometric data. The purpose of the questionnaire was to obtain any information on current practice and knowledge in determining the worth of hydrometric data which was not available in literature. Mr. Marc Drouin of Manitoba Hydro provided the GOES Data Collection System Users Mailing List which listed five users of hydrometric data from Canada and seventy from the United States. On June 21, 1993, a letter explaining the purpose of this research and a brief questionnaire was sent to each contact. A sample letter, sample questionnaire, and a summary of responses can be found in Appendix A. Three letters of the seventy-five were returned by the post office and eight letters of the seventy-five were returned by respondents.

With the limited number of responses and the limited sources of those responses it was difficult to make any broad generalizations about current practice. No new methods were brought to light. Organizations which have a mandate to collect hydrometric data may lack impetus to justify data collection costs on an economic basis. The impetus is more likely to be to create a cost-effective network using a definition of worth different from economic worth, as seen in the papers about network cost-effectiveness.

3.0 Methodology

3.1 A Basic Framework

The basic requirement to determine the economic worth of data is to make the connection between an increment in the data collection system and the resulting economic costs and benefits. Data collection costs are relatively simple to determine. There is a capital cost for equipment and installation, an annual operating cost, a replacement cost, and intermittent servicing costs. Benefits associated with uses of the data are as difficult to determine as data collection costs are simple to determine, thus, the need exists for a method, framework, or process, to approach the problem of determining worth.

The basic framework presented here assumes that a location or project has been chosen for which the worth of the hydrometric data is needed, and that it has been decided with respect to whom the worth of the data will be determined, i.e., society in general, or a specific corporation, organization, or user. The three phases of the framework are:

1. determining how the data are used;
2. determining attributes of the data which are significant to the uses; and then,
3. determining the economic impact of changing the data collection system.

3.1.1 Uses of Hydrometric Data

The first step of the first phase is to determine what the hydrometric data are used for. This immediately identifies hydrometric data which either may have no worth because they are not being used or may have worth beyond measure because they are required to meet a legal obligation. The nature of the use made of the data will determine much of how the assessment of worth is performed.

The second step of the first phase is to determine which data uses are associated with measurable economic benefit. Benefits which are difficult to measure economically may have great worth, but it is judicious to begin with the most easily measured benefits. With the current trend towards decreasing funding for data collection, it is important to be able to convert as many of the benefits as possible into economic terms to compare to the costs of data acquisition. Benefits realized from hydrometric data were summarized by Scott and Moss (1986) and are as follows.

1. Hydrometric data can be used to define regional hydrology, which is useful for developing transferable information about the relationship between basin characteristics and runoff, and can be the source of useful information for water supply and fisheries issues.
2. Hydrometric data can be used to define the current state of hydrologic systems for operational purposes.
3. Hydrometric data which describes current sources, sinks, and fluxes of water through hydrologic systems, including regulated systems, is useful for water resources management, water apportionment and regulation, and urban drainage design.
4. Hydrometric data may serve to fulfil legal obligations of environmental licenses, treaties, and agreements.

5. Hydrometric data can be used for the planning and design of specific projects such as dams and reservoirs, culverts and bridges, spillways and hydro-power plants, and buildings in flood plains.
6. Hydrometric data can be used to produce hydrologic forecasts and to warn of imminent floods.
7. Hydrometric data can be used to monitor sediment load and other water quality parameters.
8. Hydrometric data can be used for other purposes such as monitoring for navigation and recreation.

It is recognized that benefits may not be easy to quantify and may require some innovation to quantify in economic terms.

3.1.2 Data Attributes

The first step of the second phase is to determine the types of data required, the length of record, the frequency and time of year of measurements, and the accuracy needed. The type of data required will vary according to the use or application of it. Annual maximum daily flow rates may be required for flood design of a project, or daily levels and discharges may be required to monitor and regulate a water resource project.

The second step of the second phase is to identify alternate sources of data which may have economic advantages. The same type of data may be transferred from other locations using models or correlations. Other types of data may be used to estimate the required type of data, for example, meteorologic data may be used to estimate streamflow.

3.1.3 Economic Impact

The economic impact of the hydrometric data is dependent on the uses of the data and on the attributes of the data itself, but actually singling out the impact of the hydrometric data is difficult because it is a multi-dimensional problem. Determining the economic impact of hydrometric data is a multi-dimensional problem in that there are many different hydrological, mechanical, and political aspects besides the hydrometric data, which impact decision making, and it is a multi-dimensional problem in that there are many different kinds, qualities, and amounts of hydrometric data which can be collected and used in decision making. Because many things affect a decision in a design or in operations other than hydrometric data, the sensitivity of the decision to the uncertainty of the hydrometric data must be tested. Legislation or other agreements may make the decision insensitive or less sensitive to the uncertainty, or may limit the range of situations for which the decision is sensitive to the data uncertainty.

The distinction between the decision of how to optimize data collection and how to optimize a design, or an operation should be kept clear. The optimal design, or operation is a function of the data available, among other things. The decision of how much data to collect is a function of the sensitivity of the optimal design or operation to changes in that data. Both optimizations may use the same decision technique. For example, a benefit-cost analysis could be used to determine an optimal design of a reservoir, and another benefit-cost analysis could be used to optimize the amount of data collected.

The basis of all methods of determining the economic worth of hydrometric data is to relate changes in data collection activities to economic benefits through uses of the data. In some studies, the least cost of obtaining a certain level of data quality of the network was used to optimize a network. The USGS method, K-CERA, attempts to achieve a trade-off between the lowest overall data error and the least cost. This method is most valid for a network defining regional hydrology. However, network development is often driven by specific data needs at specific locations and not by regional hydrology. If this method was combined with an analysis of marginal economic benefits from uses of a regional network, it would be very powerful for determining the economic worth of a regional network.

Another network cost effectiveness approach is to change the criteria for optimizing a network to the uses, or demand for data, where the various uses and demands are subjectively assigned a level of value. This approach recognizes the location specific nature of the worth of data by recognizing the variations in demand for the data. This subjective determination of worth also provides for assigning value to uses which are difficult to quantify in dollars. However, this strength is also a weakness, in that if assigning value is not coupled with a determination of economic worth, data may be valued at more or less than it is economically worth. This may occur in the situation where data collection is decreased to save money, possibly resulting in costs which outweigh the savings because of the reduced hydrometric information for planning, design, and operations.

Overall, the network cost effectiveness methods are of little value in and of themselves in determining the economic worth of data. The rating approach is site specific but it stops short of using economic measures for worth. It is more suited to rationalizing a network than to economically justifying a network or a station. The K-CERA approach uses no measure of benefits derived from individual sites. It is more suited to rationalizing a network used to define regional hydrology.

Determining the economic worth of hydrometric data by assessing the cost of restoration of a structure after failure or by assessing the benefits and costs of over-designing or under-designing a structure are similar and are applications of marginal benefit-cost analysis.

The method of simply assuming that the worth of hydrometric data is a percentage of the capital cost of any project planned or designed with the data (Acres, 1977) is unacceptable for justifying expenditures for data. This bypasses the need to demonstrate the economic benefits of the hydrometric data.

Hirshleifer and Riley (1992) apply Bayesian Decision Theory in a field of economics known as Information Economics. This method assumes that the decisions are at a single point in time, the probabilities of each outcome are known, all possible outcomes are known, the economic impact of all outcomes are known, and the impact of additional information on all of the probabilities can be found. Bayesian decision theory is statistically effective, but it does not solve the problem of initially determining all the required statistical information.

Risk analysis seems like it would be a valid approach. The information needed would be the relationship between incremental changes in data collection and the expected economic penalties or losses. The objective would be to achieve some balance of least risk with least cost or maximum benefits that the decision maker is comfortable with.

Marginal benefit-cost analysis is a particularly appropriate method for determining the economic worth of hydrometric data because it measures the benefits and costs for an increment in the data collection network. Simply determining that a whole network is invaluable says nothing about whether to expand or rationalize it, or to continue or discontinue a particular gauge site. Determining the marginal benefits and marginal costs of a change in a network gives insight into whether to expand or rationalize a network, or to continue or discontinue a particular gauge.

The most appropriate method of determining the economic impact of data will depend largely on the uses of the data and on the attributes of the data. All methods will require assumptions, but a more rigorous analysis with less significant assumptions will have a more solid footing to stand on. The most appropriate method of reporting the worth of hydrometric data will depend on the nature of the decisions which are based on the data. In general, the most appropriate method of reporting the worth of hydrometric data is the marginal benefit cost ratio, because it reveals the economic sensitivity to incremental changes of the data collection network, but, for example, if risk was an important part of the decision structure, it would be most appropriate to report worth in terms of risk as well.

3.2 Methodology for Operations

3.2.1 Uses of Hydrometric Data for Operations

From the literature review and the questionnaire it is clear that investigations into the worth of data have focused on the use of data for planning and designing structures, while little attention has been given to the use of data for real-time operational needs. Real-time operations are on-going activities requiring current data for decision making. Examples of real-time operations in the literature were flood warning systems, forecasting for water supplies, for irrigation, and hydro-power production, and for navigation. Another example of a real-time operation is reservoir management.

Economic impacts can be associated with most or all of these uses by imagining what would happen if there were either no data available or poor data available. The economic benefits of some of the uses are from loss prevention or risk reduction, like flood warning systems. The economic benefits of data used for navigation, or reservoir management for irrigation or hydro-power production will likely realize economic benefits on a more routine basis because the commodities they involve, crops, hydro-power, and shipping, have routine economic benefits.

3.2.2 Data Attributes for Operations

Marginal benefit-cost analysis is applicable for operations as demonstrated by Curtis and Dotson (1993). The marginal cost is that of adding a gauge or upgrading a gauge or otherwise changing the data collection network. The marginal benefit is derived from improved operational decisions, due to less uncertainty in the decision parameters. The marginal benefit-cost analysis is the technique adopted for reporting economic worth for this study.

For real-time operational decisions, the accuracy and reliability of the raw data are the most important. It is the raw, uncorrected data which are available in real-time, so it is the raw data which should be analyzed for accuracy and reliability. Accuracy in this study refers to how close the measurements usually are to the "true" value, and reliability refers to the likelihood that the gauges are functional and are reporting data within the expected accuracy.

A difference in data attributes between operations and design of structures is that design of structures requires a long historical record, and operations requires current or real-time data. Operations may require weekly, daily, or hourly reports to assess decisions or make changes. Another difference related to this is that a change of the data collection network will take time to affect the historical record and the design of structures, whereas a change in data collection will affect operational decisions almost immediately, although some length of record is required for verifying the accuracy of a gauge before it can be trusted and used. Much more foresight is required in collecting historical records. Real-time data networks are much more flexible, though installation or relocation costs can still be significant.

3.2.3 Economic Impact for Operations

The methods for assessing the economic impact of data used for design as opposed to operations are different. The difference in methods is because of the difference in the decisions that the data affects. Planning and design decisions are completed once the structure is built. Operation decisions are at regular increments of time.

Obviously, the method of assessing the cost of over-design or under-design is not appropriate for determining the worth of data used for operations. However, the concept of making decisions which are overly conservative or not conservative enough is applicable to operations. There are economic impacts of operating water resource projects too conservatively and foregoing benefits, and of not operating conservatively enough and incurring needless risk or penalties.

The appropriate method of determining the economic impact of data will rigorously investigate and document the relationship between changes in available data and benefits measured in dollars. This relationship will then be used to find the marginal benefit-cost ratios for increments in the data collection network. The marginal benefit-cost ratio will identify the worth of a set of data within the context of a specific data collection network.

4.0 Case Study - Southern Indian Lake

4.1 Choice of a Case Study

The strategy of choosing a case study was to seek a study area which was well-monitored for the use of operational decisions which have economic impacts. The case study needed to be well-monitored to provide hard data for the analysis of the contribution of each gauge. The case study needed to have operational uses with economic impacts so that the sensitivity of the economic benefits to changes in the data collection network could be tested.

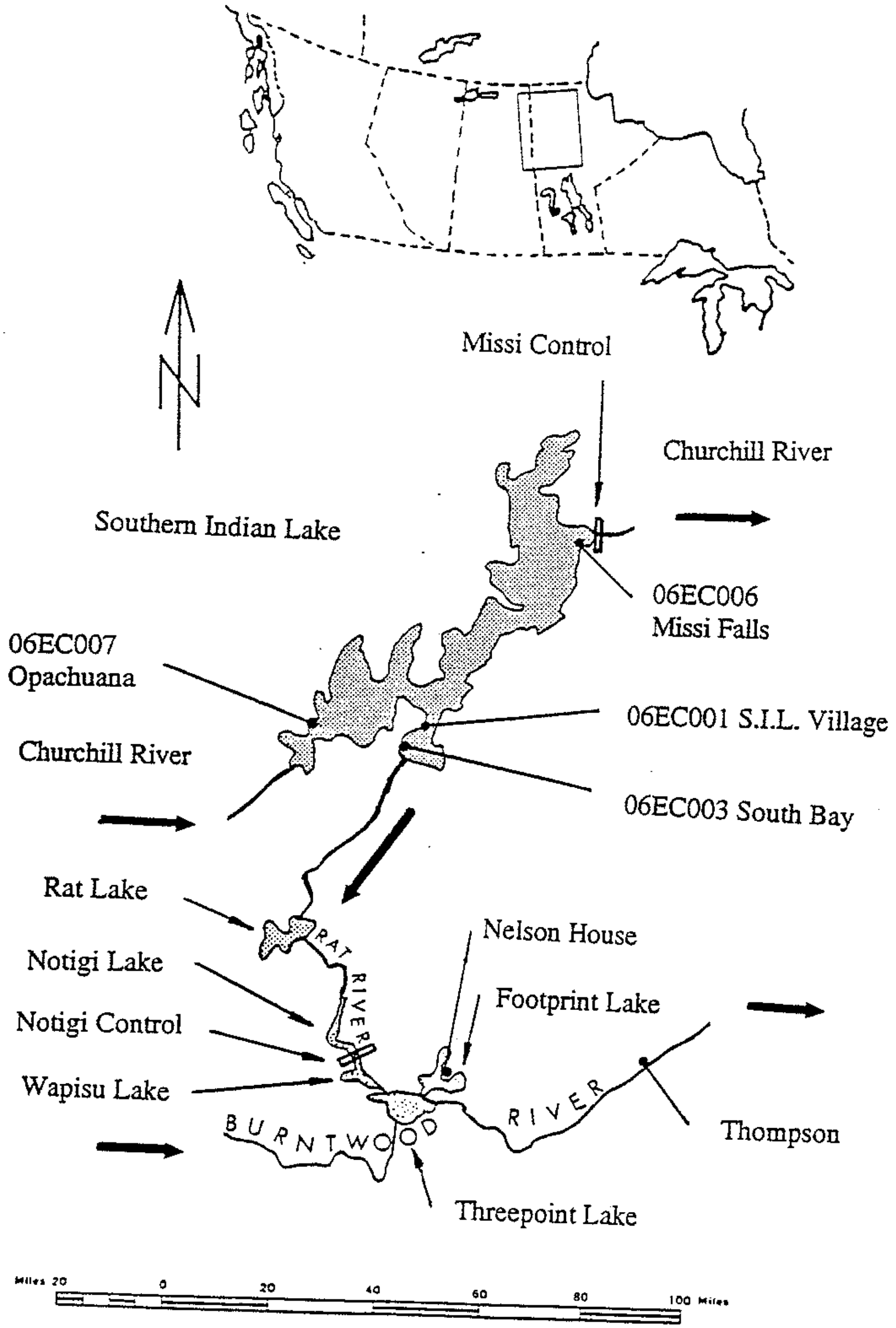
Southern Indian Lake, in northern Manitoba, met these conditions. There are lake level gauges at four remote locations around the lake (see Figure 1, Location Map). Each site is equipped with sensing and telemetry equipment to measure and transmit real-time data. The level of the lake is regulated for the purpose of diverting water for hydro-power production, subject to legal constraints on the maximum and minimum lake levels.

4.2 Description of the Churchill River Diversion

The Churchill River drainage basin is approximately 283,350 square kilometres with its headwaters in Alberta and its outlet in Manitoba. The flow of the Churchill River enters Southern Indian Lake in northern Manitoba and either continues down the Churchill River through the Missi Falls control structure or is diverted down the Rat River into the Nelson River through the Notigi control structure.

Figure 1

Location Map



The Churchill River Diversion came about because of a $600 million cost advantage of being able to capture the hydro-electric potential of the Churchill River without having to build generating stations on it (Manitoba Hydro, 1992). The diverted flow of the Churchill River currently produces approximately $100,000 worth of hydro-electric power per 1000 cfs-months during the winter and $40,000 worth of hydro-electric power per 1000 cfs-months during the summer (Drouin, 1994) and has an average monthly flow of 28,000cfs. The seasonal difference in benefits drives the basic operational policy of filling Southern Indian Lake in the summer and draining it in the winter. The three generating stations on the Lower Nelson River (Kettle, Long Spruce, and Limestone) produced 74.4% of Manitoba Hydro's system supply in 1991-92 (41st Annual Report, 1992). The winter generating capability of Kettle is 1272 megawatts (MW), of Long Spruce is 980 MW, and of Limestone is 1064 MW as of March 31,1992 (41st Annual Report,1992). Potentially, the diverted flow can be used at additional sites on the Lower Nelson River and at sites along the Burntwood River.

The Churchill River Diversion was put into operation in 1977. A control structure was built at Missi Falls, the natural outlet of Southern Indian Lake. Missi Falls is required to discharge a minimum flow of 14 m^3/s (500 cfs) during the open water season and a minimum flow of 43 m^3/s (1500 cfs) during the ice cover season, in compliance with the Interim License granted by the province of Manitoba in 1975, to maintain the viability of the Churchill River and the water supply of the Town of Churchill. The water level of Southern Indian Lake was raised three meters above pre-diversion levels in order to divert water out of Southern Indian Lake through an excavated channel from South Bay of Southern Indian Lake to the Rat River system. The Rat River flows through Rat Lake, Notigi Lake, the Notigi control structure, and

Wapisu Lake, joining with the Burntwood River at Threepoint Lake. The Burntwood River flows through the City of Thompson and joins the Nelson River at Split Lake. See Figure 1 for locations.

4.3 Application of the Basic Framework to Southern Indian Lake

4.3.1 Uses of Hydrometric Data

The lake level data collected at Southern Indian Lake have many uses. Lake level data are useful for forecasting future levels and flows which is beneficial for communities downstream such as Churchill, Nelson House, and Thompson. Lake level data are the simplest measure for relating changes in the water regime, due to the Churchill River Diversion, to the impacts on the lives of people and on the environment. The independently measured lake levels,are useful for settling disputes between affected parties. Settlements are currently being negotiated with the Nelson House Band which may include constraints on the levels and rate of change of levels of Footprint Lake which is downstream of Notigi. Lake level data would be useful for the operation of a hydro-power plant at Notigi. Currently, the feasibility of a hydro-power plant at Notigi is being investigated. Operation of the plant may require daily fluctuations in discharge which would increase the value of accurately knowing in real-time the level of Southern Indian Lake.

The current and most consistent benefit of the lake level data is the operation of the Churchill River Diversion for the purpose of hydro-power production on the Nelson River. The Southern Indian Lake level data are required for planning releases from the Missi Falls and Notigi control structures so that hydro-power production is optimized subject to maintaining acceptable levels and flows at various points along the diversion. The economic benefits come from avoiding litigation from violating one of the legal constraints, and from the power produced by the water diverted from the Churchill River into the Nelson River. There is a great deal of information on the dollar value of the water diverted, and there is some information on the expenses that litigation causes. The economic benefits are expected to be sensitive to the lake level data since Southern Indian Lake is the main storage component of the Diversion.

4.3.2 Data Attributes

The type of data required for the operation of Southern Indian Lake, for the purpose of optimizing hydro power production while maintaining acceptable lake levels, is real-time lake level data. Levels and flows for other parts of the Diversion are also required, but this study is limited in scope to the lake level data of Southern Indian Lake. The level of Southern Indian Lake must be measured accurately and reliably so that trustworthy lake level data are available for operational decisions.

Alternate sources for lake level data were considered, but no appropriate alternate source was found. In practice, all inflows to, and outflows from, Southern Indian Lake are either gauged or estimated using rating curves. Because of ice conditions and other influences, the rating curves are subject to error. One flow which cannot be measured directly is local inflow. In practice, the local inflows are estimated by calculating the change in storage of the lake from successive lake level measurements then adding all known inflows and subtracting all known outflows. If local inflow could be found from nearby basins which already have gauges, a correlation might be found to estimate the local inflow to Southern Indian Lake. The local inflow combined with the other estimates and measurements of flows could then be used to estimate the lake level. However, streamflow gauges are sparse in the northern region, and no basins which would be expected to have similar local inflow are gauged. If a hydrological model was developed, meteorological data might be used to estimate local inflow. There are a few weather stations in the area, but the data from them indicates a high variability of weather with location, so that a much denser meteorological network would be required to obtain meaningful results. If local inflow combined with the other estimates and measurements of flows were used to estimate the lake level, the lake level values would be subject to the combined error of all the estimates and measurements used. Due to the error involved in data transfer from other locations or other types of data, and the sparseness of other data, it would be most appropriate to limit the possibility for data collection to lake level gauges on Southern Indian Lake.

"Freeze-proof" gauges were installed in tandem with the existing lake level gauges at S.I.L. Village and at Missi Falls in 1991 to increase the reliability of the network. However, by 1993, at the beginning of this research, the freeze-proof gauges had performed less reliably than the existing gauges had. This was unexpected and the causes were unknown. A limited amount of data had been collected by the freeze-proof gauges since their installation. For these reasons the effect of the freeze-proof gauges was not included in this research.

Detailed analysis of the hydrometric data is discussed in section 4.4.

4.3.3 Economic Impact

The first phase of the methodology, identifying the uses of the lake level data, identified the operation of Southern Indian Lake for the production of hydro-power while avoiding the violation of legal constraints as the most significant use of the data with quantifiable economic impact. The second phase of the methodology, identifying the data attributes required, identified that real-time accurate and reliable lake level data are required, and that transfer of information from other locations or sources is not feasible.

The third phase of the methodology is to identify the economic impact of changes in the data collection network. No information was available on the impact of lake level uncertainty on regulation decisions of Southern Indian Lake. The regulation optimization model used by Manitoba Hydro is insensitive to the uncertainty of hydrometric data, so uncertainty is incorporated by the planner at Manitoba Hydro by running various scenarios to take into account the uncertainties that exist. The computer models of Manitoba Hydro which include Southern Indian Lake were not readily available or easily applied, so two computer models which simulated the hydraulics and the regulation decisions of Southern Indian Lake were developed to test the sensitivity of the regulation to the accuracy of the lake level data. Discussion of the model development and results can be found in section 4.5. Discussion of the economic impact of making changes in the data collection network can be found in section 4.6.

4.4 Analysis of the Uncertainty of the Data from Southern Indian Lake

Datum shifts, the standard deviation (or noise) of the gauges, and the probability of gauge failure were the three characteristics of the uncertainty of the data from the four lake level gauges which were incorporated into the analysis. Each of these characteristics had to be estimated for each gauge individually as well as for every possible combination of two and three gauges, and for all four gauges. As well, the cost of obtaining data is incorporated into the analysis. The lake level data analyzed were supplied by Manitoba Hydro and are the data on which operational decisions were based.

4.4.1 Datum Shifts

Because the "true" lake level is never known, gauge data must be compared to the best estimate of the true lake level, in order to estimate the accuracy of the gauges. It was assumed that the true average lake level follows a smooth trend, and that the trend does not change significantly from day to day. Wind and localized events will cause rapid local changes in level, but, the average lake level follows a smoother trend because of the lake's volume. It is reasonable, then, that a moving average of the daily levels would better represent the true lake level.

The daily data from each gauge was compared to two moving averages: the seven day moving average from the gauge, and the seven day moving average of the average reading from all four gauges. The daily gauge readings were subtracted from each of the two moving averages to obtain a record of the differences, or residuals, for each estimate of the "true" lake level, for each gauge. These residuals are the noise of the data of the gauge, and, typically, each gauge has its own noise "signature" (Drouin, 1994, and, Lake Winnipeg Datum ad hoc Committee, 1982).

The difference between the individual gauge reading and the moving average of itself represents localized rapid changes of the water level as well as random error of the gauge. The mean of the residuals was close to zero, as is expected. The standard deviation of the residuals is a measure of the uncertainty of the gauge data assuming that the average lake level follows a smooth trend. The correlation of the residuals for each pair of gauges was found so that the relationships between gauges could be investigated and so that the standard deviation of any combination of gauges could be calculated.

The difference between the individual gauge reading and the moving average of the average of all four gauges represents localized rapid changes, random gauge error, as well as longer term trends in deviation of that gauge from the average lake level. The mean of the residuals was different from zero, since the lake normally has a gradient on it, and the gauges are spaced out around the lake, resulting in different mean levels around the lake. The standard deviations and correlations of the residuals were calculated for the same reasons as before. Table 1 summarizes the standard deviations of each individual gauge for both estimates of the true lake level, and Table 2 summarizes the correlations of the gauges to each other for both estimates of the true lake level. The standard deviation of the residuals appeared to be consistent through the period of record and did not appear to be a function of the season of the year.

Table 1

Standard Deviation of the Residuals of the Gauges (feet)

Gauge	Compared to 7 day Moving Average of the Gauge	Compared to 7 day Moving Average of All 4 Gauges
S.I.L. Village	0.023	0.047
South Bay	0.028	0.046
Missi Falls	0.048	0.068
Opachuana	0.047	0.061

Table 2

Correlations of the Residuals of the Gauges (R not R^2)

Gauge	Compared to 7 day Moving Average of the Gauge	Compared to 7 day Moving Average of All 4 Gauges
S.I.L. Village to South Bay	0.76	0.45
S.I.L. Village to Missi Falls	-0.13	-0.17
S.I.L. Village to Opachuana	0.60	0.27
South Bay to Missi Falls	-0.21	-0.35
South Bay to Opachuana	0.67	0.27
Missi Falls to Opachuana	-0.57	-0.45

The second set of standard deviations were higher than the first set, and the magnitude of the correlations of the second set were generally lower than those of the first set, as expected. The first set of standard deviations minimizes and underestimates the uncertainty of the data since it is a comparison with itself. In this case, the "true" lake level is influenced in the same direction as the short term fluctuations in the lake level. In practice, Manitoba Hydro uses the seven day moving average of all four gauges as the representative lake level. For these reasons and because of datum shifts, which are discussed next, the seven day moving average of all four gauges was adopted as the "true" lake level for the calculation of standard deviations and correlations.

Datum shifts occur when the calibration of a gauge drifts either slowly or suddenly and begins to read consistently high or low. In retrospect, readings can be (and are) adjusted for this kind of gauge error since trends before, during, and after the occurrence can be examined. In real time operations, a small datum shift may be undetectable, since it may be interpreted to be a change in the trend of the lake level itself. See Appendix B for a summary of typical datum shifts, which were recorded by Manitoba Hydro, for eight lake level gauges on Lake Winnipeg, in Manitoba. A summary of datum shifts was not available for all of the gauges on Southern Indian Lake. The magnitude of the shift, the rapidity of the shift, and the existence of other real-time gauges are factors in minimizing the impact of this kind of uncertainty. A large sudden change in the recorded lake level would be easily detected, while a small change or a slow drift would be much more difficult to detect in real-time. The existence of other gauges, for comparison, would be of the greatest benefit for detection of datum shifts.

It is believed that the error introduced by datum shifts is incorporated in the calculation of the standard deviation of the residuals when each gauge is compared to the seven day moving average of all four gauges. Comparing the gauge to the seven day moving average of itself would minimize the datum shift and have little effect on the standard deviation calculated. Comparing the gauge to the seven day moving average of all four gauges will expose datum shifts better since the average of all four gauges is less affected by the datum shift of the one gauge. The error introduced by the datum shift is therefore partially reflected in the standard deviation calculated for the residuals from the seven day moving average of all four gauges.

4.4.2 Variance of Gauges

The standard deviation of the residuals of each gauge compared with the seven day moving average of all four gauges and the correlations of each pair of residuals was calculated in order to calculate the standard deviation of any combination of gauges. The residuals of the gauges are assumed to be random variables. In order to find the variance or standard deviation of the mean of random variables, the joint behavior must be known. If the random variables are independent, the covariance and correlation are zero and the variance of the mean of the random variables is simply the sum of the variances of the random variables divided by the square of the number of variables. Because it is divided by the square of the number of variables, the variance tends to decrease with additional independent gauges. See Equation 1, the variance of the mean of n random variables. If the random variables are not independent, the variance of the mean of the random variables is changed by twice the sum of the covariances divided by the square of the number of variables. A positive correlation between gauges will increase the second term of the equation which increases the variance of the mean. A negative correlation between gauges will decrease the second term of the equation which will decrease the variance of the mean.

$$Var(\overline{Y}) = 1/n^2 \sum_{i=1}^{n} Var(Y_i) + 2/n^2 \sum_{i\neq}^{n} \sum_{j}^{n} Cov(Y_i, Y_j) \qquad (1)$$

$$where: Cov(Y_i, Y_j) = r_{ij}\sqrt{Var(Y_i) \bullet Var(Y_j)}$$

Y is a random variable.

n is the number of random variables.

Var is the variance and is equal to the square of the standard deviation.

Cov is the covariance.

r is the correlation coefficient.

i and *j* are the numbers of the gauge stations

The gauges at Southern Indian Lake Village and at South Bay have the least variance, while the gauge at Missi Falls has the highest variance (see Table 1). Judging by this alone it would seem that the gauges at Southern Indian Lake Village and South Bay contribute the most valuable information about the lake level, and that the gauge at Missi Falls contributes the least valuable information about the lake level. However, since the gauge readings are not independent, their joint behavior must be taken into account.

The three gauges at the southern end of the lake are all positively correlated with each other and negatively correlated with the gauge at Missi Falls at the north end of the lake (Refer to Figure 1, Location Map, and Table 2, Correlations of the Residuals of the Gauges). The Southern Indian Lake Village and South Bay gauges are the closest together and have the largest positive correlation. The Opachuana and Missi Falls gauges are the farthest apart and have the largest negative correlation. The interpretation of this is that gauges close together experience many of the same localized rapid changes as well as the same general lake level for that portion of the lake. The lake level from one end of the lake to the other may be different due to hydraulic gradient and wind effects. Negative correlations of the three southern gauges with the Missi Falls gauge in the north indicates that sloshing of water back and forth in the lake is occurring. A constant hydraulic gradient would cause a constant difference in lake level readings between gauges but would not produce a negative correlation. The sloshing would not seem to be caused by rapid changes in flows of the control structures, since changes are not generally made rapidly or often. The sloshing would seem to be from changes in the prevailing wind direction and magnitude. Wind pile up has also been observed on Lake Winnipeg.

Missi Falls is the most valuable gauge for increasing accuracy of the estimated lake level, even though it individually has the highest uncertainty. This can be seen from Table 3, the table of standard deviations of all the combinations of the gauges. The three combinations of two gauges with the lowest standard deviations all include Missi Falls. The same is true for combinations of three gauges. The mathematical reason for this is the negative correlation it has with the other gauges. The physical reason is that when the lake sloshes from end to end, Missi Falls is the only gauge on its end to balance out the measurement.

Table 3

Standard Deviation of All Combinations (Networks) of Gauges (feet)

Gauges (Network)	Standard Deviation
S.I.L. Village	0.047
South Bay	0.046
Missi Falls	0.068
Opachuana	0.061
S.I.L. Village and South Bay	0.040
S.I.L. Village and Missi Falls	0.038
S.I.L. Village and Opachuana	0.043
South Bay and Missi Falls	0.034
South Bay and Opachuana	0.043
Missi Falls and Opachuana	0.034
S.I.L. Village, South Bay, and Missi Falls	0.029
South Bay, Missi Falls, and Opachuana	0.026
S.I.L. Village, South Bay, and Opachuana	0.038
S.I.L. Village, Missi Falls, and Opachuana	0.028
S.I.L. Village, South Bay, Missi Falls, and Opachuana	0.026

4.4.3 Probability of Gauge Failure

Gauges intermittently fail to function due to severe environment, vandalism, or age and condition of equipment. Sensors that use mercury in the equipment freeze up when the air temperature drops below minus forty degrees Celsius. Equipment goes through a life cycle, with a higher failure rate just after installation and at the end of its serviceable life (Drouin, 1994).

Manitoba Hydro supplied a record of the gaps in the hourly data record from each of the four gauges on Southern Indian Lake between 1992 and 1994 (see Appendix C). Gauges often failed for three hours but then returned to full operation without any servicing. Less frequently the gauges fail for a longer duration. The gauge at Missi Falls has had the longest periods of missing data due to gauge failure.

When a gauge fails, the uncertainty of the remaining network on Southern Indian Lake will increase due to the reduction in information, until some time after the gauge becomes operational again. When a gauge fails, it is unknown how long it will be down, or if servicing will be required or not. Readings from a recently failed gauge will be suspect and will need to be confirmed by the other lake level gauges.

The impact of a gauge failure depends on the duration of the failure and on what time of the year the failure occurs. If a gauge fails for less than a day, it likely will not affect the regulation decision, which is usually done every two to four weeks. Any gauge failure longer than a day may result in operational decisions being made without the benefit of that gauge. The greatest impact of a gauge failure is when the lake level is approaching the upper or lower acceptable limits because it is needed for making regulation decisions.

Since sufficient information was not available to incorporate the timing and duration of gauge failures, the record of the gaps in the hourly data record of each gauge was simply reduced to a probability of failure for each gauge, as shown in Table 4. The percentages are the number of hours that a gauge failed to record data divided by the total number of hours for which the gauge was supposed to record data. The percentages calculated for gaps greater than twenty-four hours were used in the analysis as an estimate of the probability that the gauge will fail, resulting in operational decisions being made without the benefit of that gauge.

Table 4

The Percentage of Time that Data Were Not Recorded

Between 1992 and 1994

Gauge	All Gaps (%)	Gaps Greater Than 24 Hours (%)
S.I.L. Village	3.4	2.2
South Bay	3.6	2.4
Missi Falls	16.5	15.6
Opachuana	3.3	2.1

4.4.4 Cost of Collecting Data

The cost to Manitoba Hydro for the operation of the water level gauges on Southern Indian Lake, as of June, 1993, is outlined in Table 5. The four gauges are operated and administered by the Water Resources Branch and the Inland Waters Directorate. Currently, the agreement between Manitoba Hydro and the Water Resources Branch is that Manitoba Hydro will bear the full cost of the operation of the gauges at Missi Falls and Opachuana Lake, Manitoba Hydro will share the cost of the operation of the gauge at S.I.L. Village with the Water Resources Branch, and the Water Resources Branch will bear the full operating cost of the gauge at South Bay. Cost sharing agreements are common between the federal and provincial levels of government and Manitoba Hydro, however, both the federal and provincial data collection agencies are experiencing reduced budgets and are in the process of reducing the number of gauges they operate. It is plausible that funding for the gauges at S.I.L. Village and South Bay could be cut and Manitoba Hydro would have to decide whether the benefits of the data outweigh the additional costs of operating the station.

Table 5

Cost to Manitoba Hydro For Gauge Operation as of June 1993

Name of Gauge Station:	Cost per Year:
S.I.L. near S.I.L. Village	$2950
S.I.L. at South Bay	$0
S.I.L. at Missi Falls	$5900
S.I.L. near Opachuana Lake	$5900

4.5 Economic Impact of Data from Southern Indian Lake

To test the economic impact of the data from Southern Indian Lake, two computer simulation models were developed; one for the summer, and one for the winter. The models include the hydraulics of a portion of the Churchill River Diversion and regulation rules which attempt to capture the governing principles of regulation decisions made by Manitoba Hydro. The basic principle of the regulation of Southern Indian Lake is to fill it during the summer when demand for hydro-power is low and draw it down in winter when demand for hydropower is high. The maximum and minimum allowable lake levels for Southern Indian Lake usually govern the regulation planning, that is, there is usually sufficient inflow in the summer to fill the lake to the maximum allowable level, and there is usually sufficient ability to discharge during the winter to draw the lake down to its minimum acceptable level. Since the goals of regulation are opposite for the summer and the winter, two separate simulation programs were written. Each program required more than fifteen hundred lines of Fortran code. The hydraulics for the summer and winter models are essentially the same except for the effect of ice conditions on the flow through the South Bay channel, however, the regulation rules are different, to reflect the different goals.

4.5.1 Hydraulic Modelling

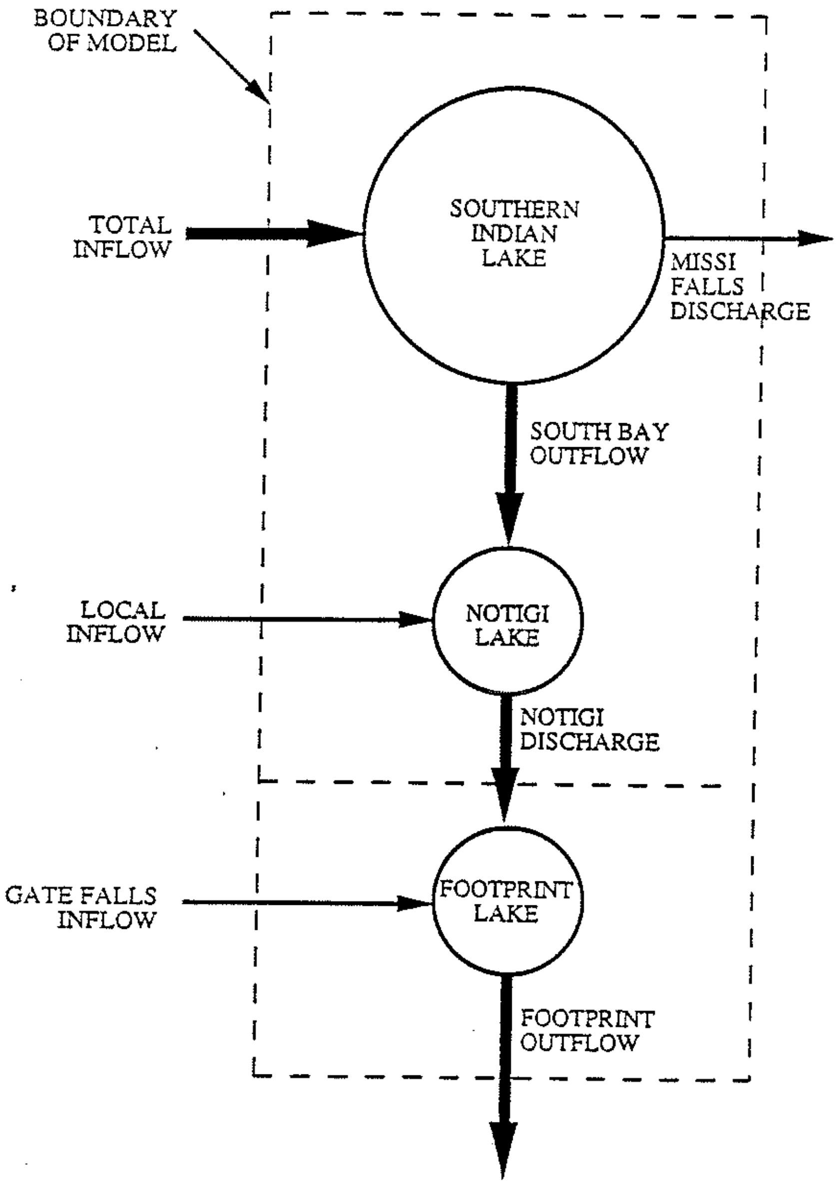
The portion of the Churchill River Diversion modelled is from Southern Indian Lake to Threepoint Lake. The system is modelled as three lakes or reservoirs: Southern Indian Lake, Rat-Notigi Lake, and Wapisu-Threepoint-Footprint Lake. See Figure 2, Model of Flows Through Southern Indian Lake, Notigi Lake, and Footprint Lake.

Inflow to Southern Indian Lake is from the Churchill River and from natural local inflow. In the model these are combined together as total inflow to Southern Indian Lake. Outflow from Southern Indian Lake occurs at Missi Falls and South Bay. An historically typical release schedule was adopted for the minimum base flow required from Missi Falls (See Table 6). The winter release of 2000 cfs is higher than the licensed minimum release of 1500

Figure 2

Model of Flows Through Southern Indian Lake,

Notigi Lake, and Footprint Lake



cfs (Appendix D), but it is likely the minimum required for other practical purposes. The discharge from Missi Falls can be increased above the typical release (later referred to as "spilling") in order to regulate the level of the lake. The magnitude of the flow from South Bay through the excavated channel is a function of the gradient and ice conditions. Generally, a higher gradient is required under ice conditions to obtain the same flow.

Table 6

Typical Releases from the Missi Control Structure

Month	Flow (cfs)	Month	Flow (cfs)
January	2000	July	500
February	1500	August	500
March	1000	September	500
April	1000	October	500
May	500	November	2000
June	500	December	2000

Notigi Lake is the collective storage of the Rat River, Rat Lake and Notigi Lake. Inflow is from South Bay of Southern Indian Lake and from local inflow. Outflow is through the Notigi control structure.

Footprint Lake is the collective storage of Wapisu Lake, Threepoint Lake and Footprint Lake. Inflows are from Notigi Lake and from the Burntwood River. Local inflows are small compared to the other inflows, and are not significant in the calculations used by Manitoba Hydro. Outflow is from Threepoint Lake and is unregulated.

Routing of flow through the system was performed by conserving mass on a daily basis for each of the three lakes, i.e. inflow minus outflow equals the change in storage. From the change in storage the new lake elevations can be found. The model required stage-storage relationships for the three lakes, and stage-discharge relationships for the flow from South Bay of Southern Indian Lake and from Three Point Lake. Each of these relationships was obtained from Manitoba Hydro, and are currently in use by Manitoba Hydro. Manitoba Hydro uses a stage discharge rating curve to calculate the outflow from South Bay during the summer. Rating curves were available for each month of the year. In the winter Manitoba Hydro uses an alternate method for estimating the flow from South Bay. In the winter, the local inflow to Notigi Lake is estimated to be 98.3% of the flow in the nearby Burntwood River at Gate Falls. The discharge from Notigi is known from the gate positions of the control structure and the change in storage from one day to the next can be calculated from the known elevations. The inflow from South Bay to Notigi Lake is the change in storage of Notigi Lake plus the discharge from Notigi Lake minus the estimated local inflow. The simulation could not use this alternate method, so the winter rating curves were implemented. The difference in estimated flow was small compared with the relative accuracy of either method.

4.5.2 Regulation Modelling

Two models, one for the summer and one for the winter, were developed because these are the two times when the lake level is approaching a limit and because the regulation goals for these two times of the year are opposite.

4.5.2.1 Summer Modelling

Southern Indian Lake usually reaches its peak level near the beginning of August. The discharge from Notigi is increased to maximum or near maximum discharge near the beginning of July to keep the lake level below the maximum limit. The goal of the summer regulation is to put into storage as much water as possible for release during the winter when the demand for hydro-power is higher.

The governing constraints for the summer regulation are the maximum level of Southern Indian Lake, the maximum rate of discharge from Notigi, and the maximum rate of change of the elevation of Footprint Lake which is downstream of Notigi (see Appendix D for a summary of the constraints). At least two weeks notice must be given to local communities of any change in the discharge of Notigi, and the time between the increase in discharge at Notigi and the level of Southern Indian Lake reaching its peak is one to two weeks. This lag time is because of the constriction to flow due to the channel and because of the distance that separates Notigi and Southern Indian Lake.

The variables in the summer regulation decision are: when to make the change in discharge at Notigi, how much to change it by, and the daily rate at which to change it. The rate of change is governed by the maximum rate of change, which is 5000 cfs per week, and by the rate of change of elevation allowed on Footprint Lake. The time and magnitude of the change are governed by the acceptable maximum level of Southern Indian Lake and the goal to keep as much water in storage as possible. In the event that the level of Southern Indian Lake cannot be kept within the maximum level by discharging from Notigi alone, flow must be spilled from Missi Falls. Rates of discharge from Missi Falls which are greater than the typical release (see Table 6) are benefits foregone for hydro-power production, and, abnormally high discharges to the Lower Churchill River are disbenefits because of the cost of damage to docks, vegetation, and wildlife such as geese during their nesting season.

The summer simulation period begins between April 1 and 15 and ends in August. Throughout the simulation period it is assumed that Missi Falls is discharging its typical flow unless spilling is required. The discharge at Notigi is maintained at the rate that it actually was discharging on the first day of the simulation, until an increase in the discharge is required to keep Southern Indian Lake below the maximum limit. The first day of the simulation period was chosen so that the discharge value would be representative of the typical discharge through the summer.

4.5.2.2 Winter Modelling

Southern Indian Lake usually reaches its lowest level just prior to the spring freshet in April. Typically, the discharge from Notigi is at its maximum through the fall and winter and is decreased around March so that Southern Indian Lake is not drawn down below its lower limit. The goal of the winter regulation is to discharge as much water as possible in order to maximize hydro-power production at downstream locations.

The governing constraints for the winter regulation are the minimum lake level of Southern Indian Lake, the minimum level at Notigi, the maximum rate of discharge from Notigi, the maximum level of Footprint Lake, and the maximum rate of change of the level of Footprint Lake (see Appendix D). At least two weeks notice is required for any change in the scheduled discharge of Notigi, and approximately four weeks is required for the effect of a change in discharge to reverse the downward trend of the lake level.

The variables in the winter regulation decision are: when to make the change in discharge at Notigi, how much to change it by, and, the rate at which to change it. The rate of change is governed by the maximum rate of change allowed and by the rate of change allowed for the level of Footprint Lake. The time and magnitude of the change are governed by the minimum levels of Southern Indian Lake and Notigi, and the maximum level of Footprint Lake. The minimum level at Notigi governs only occasionally, since an additional four feet of draw down at Notigi was granted under the yearly approvals. The maximum level of Footprint Lake only governs occasionally when total inflow to Footprint Lake is higher than normal. So the minimum level of Southern Indian Lake governs the majority of the time.

The winter simulation period begins between Nov. 1 and 15 and ends in May just before the spring freshet begins. Through the winter simulation period it is assumed that Missi Falls is discharging its typical flow (see Table 6). The discharge at Notigi is maintained at the rate that it actually was discharging on the first day of the simulation until a decrease in the discharge is required to keep Southern Indian Lake above the minimum limit. The first day of the simulation period was chosen so that the discharge value would be representative of the average discharge through the fall.

It appears that the level of Southern Indian Lake is the primary governing constraint of the Churchill River Diversion. The maximum levels imposed by the Interim License at the City of Thompson, which is downstream of Footprint Lake do not seem to govern decisions for winter or summer (from observation of the discharge and lake level records of Southern Indian Lake, Notigi, Missi Falls, and the Burntwood River at Thompson). The total amount of inflow to Southern Indian Lake during the simulation period governs the regulation occasionally. During a very dry summer the lake level may never reach the maximum limit. During a very wet winter or when the spring freshet is early, the lake level may never reach the minimum limit. Since Southern Indian Lake and the Churchill River Diversion is part of the larger hydro-power production system of Manitoba Hydro, it is reasonable to expect the larger system requirements to sometimes govern or at least influence the operation of Southern Indian Lake, but the larger system requirements do not appear (from observation of the discharge and lake level records of Southern Indian Lake, Notigi, and Missi Falls) to influence the operation significantly.

The Interim License, the Northern Flood Agreement, and, soon, a settlement with the Nelson House Band will constrain the operation of the Churchill River Diversion. Lake level and flow constraints are summarized in Appendix D. Over the years, Manitoba Hydro has made requests to deviate from the licensed constraints by specific amounts for specific periods of time. The 1993/94 approval for augmented flows is relatively typical of approved deviations over the years. The Northern Flood Agreement (1977) places a constraint on the level of Footprint Lake at Nelson House downstream of the Notigi control structure and provides for arbitration and claim processes for any adverse effects of the altered levels and flows due to the

Churchill River Diversion. A more specific settlement with the Nelson House Band is expected, and a likely set of these constraints is also contained in Appendix D. The difference with these constraints is that specific amounts of compensation are attached to them.

4.5.3 Benefits and Penalties Modelling

The benefits of operating the Churchill River Diversion and regulating Southern Indian Lake come from the hydro-power which is produced from the diverted flow which was estimated to be worth approximately $100,000 per 1000 cfs months in the winter and $40,000 per 1,000 cfs months in the summer (Drouin, 1994). The rate of $40,000 per 1000 cfs months was applied to all discharge from Notigi during the summer simulation period. The rate of $100,000 per 1000 cfs months was applied to the volume of water put into storage in Southern Indian Lake during the summer simulation period since this volume could be released later during the winter.

No schedule for compensation is specified for violation of the constraints named in the Interim License or in the yearly renewed approvals to deviate from the License. Violations are normally considered unacceptable by the office of the Minister of the Environment and generally by those affected in the local area. Violation of constraints is embarrassing to officials of Manitoba Hydro and it could prompt litigation from native Bands or jeopardize approvals for deviations from the licensed operating constraints in the future. These are very real concerns since there have been 3,565 claims by individuals and 161 claims by Bands between 1979 and 1993, and over 116.6 million dollars in compensation and remedial measures have been provided by Manitoba Hydro (41st Annual Report, 1992). The average value of the annual approvals for extended ranges of operation is estimated to be $3 million (Gunter, 1990). The economic penalties for violating any of these constraints was set very high in the model to reflect the risk involved. The results of the modelling are not sensitive to the amount used for the penalty. The penalty was set high enough to make the regulation model avoid it, so that the penalty is not incurred. The difference with the proposed constraints on Footprint Lake is that compensation is specified if they are violated. The compensation is simply $5000 per foot per day that the water level exceeds the limit, or that the rate of change of water level exceeds the limit. These proposed constraints and compensations were adopted for the regulation model since it is the best estimate of economic impacts available.

Compensation must be made for damage to geese nesting sites if the discharge from Missi Falls exceeds 5,000 cfs during the last week of May and the month of June. Geese nest in the reeds and bulrushes near the water's edge, and once the eggs are laid they cannot be moved to higher ground to escape rising water levels. In a study that M. Drouin was aware of, geese were compensated at a rate of $50 each. M. Drouin estimated that a maximum of 20,000 geese would be affected. He also estimated that nesting sites began to be threatened at a discharge rate of 5,000 cfs and that all nesting sites would be affected at 20,000 cfs with a linear relationship between these two points.

These benefits and penalties were used to evaluate the net benefit of the regulation of Southern Indian Lake.

4.5.4 Running of the Model

The summer and winter computer simulation models were developed using equations and data which Manitoba Hydro uses in its operations of the Churchill River Diversion. The models used estimates of the inflows and outflows to determine the storage and elevations of each composite lake. The regulation simulation ran up to fifty different regulation scenarios, calculating the net benefit of each, in order to find the best discharge schedules for Notigi and Missi Falls. A set of rules written into the regulation program incorporated all the constraints discussed as well as logic which adjusted the various decision parameters in order to seek out the best solution by trial and error. See Appendix E for a flowchart of the hydraulic and regulation simulation program.

To run the simulation, the starting elevations of each lake must be given, and the inflows and discharges from Missi Falls and Notigi must be known for each day. In a forecasting mode, the same information must be given, except that the inflows will be an estimate of the flows expected, and the discharges from Notigi and Missi Falls are the proposed discharges. Making allowances for uncertainty in the forecast inflows and in the current lake level reading, the discharge schedules of Missi Falls and Notigi can be adjusted to achieve the most beneficial results. Regulation decisions regarding the discharge schedules of Missi Falls and Notigi are generally reviewed every two to four weeks. The simulation of the regulation of Southern Indian Lake stops every two weeks and re-evaluates the discharge schedules. Changes to the discharge schedules take effect in two weeks, since two weeks notice of any changes must be given. This simulation provides for on-going changes to allow for adjustments and corrections to regulation decisions.

The basic assumption of the modeling of the regulation of Southern Indian Lake is that uncertainty in data causes the decision maker to be conservative to account for that uncertainty. Uncertainty is accounted for by making decisions based on the range that the data is expected to be within. The measurement of the lake level is the data which is of primary interest, but the uncertainty of the forecast inflows was also investigated as it was thought that gross uncertainty in a forecast may obliterate the effect of the uncertainty of the lake levels.

The uncertainty of the forecast inflows was investigated by first examining the range of inflows to Southern Indian Lake that have been experienced historically. Table 7 contains the statistics on the inflows to Southern Indian Lake during the summer and winter simulation periods. From the years of record available, dry, average, and wet years were chosen for summer and winter simulation (see Table 8). This was done to investigate and account for the difference that the amount of inflow makes to the regulation and thereby to the worth of the lake level data. Table 7 shows that the relative range of inflows experienced, shown by the ratio of the maximum to mean and the minimum to mean, is slightly higher for the winter than for the summer.

Table 7

Statistics of the Average Rate of Inflow

to Southern Indian Lake for the years 1977 to 1992

	Summer (May 1 to July 31)	Winter (Aug. 1 to April 30)
Mean	37,400 cfs	29,700 cfs
Maximum	47,100 cfs	43,300 cfs
Minimum	29,800 cfs	20,700 cfs
Maximum/Mean	1.3	1.5
Minimum/Mean	0.8	0.7

Table 8

Average Rate of Inflow to Southern Indian Lake

for the Years Chosen for Simulation

	Summer (May 1 to July 31)	Winter (Aug. 1 to April 31)
Dry - 1991	29,800 cfs	
Average - 1988	34,100 cfs	
Wet - 1986	46,400 cfs	
Dry - 1990/91		20,700 cfs
Average - 1987/88		26,600 cfs
Wet - 1986/87		31,300 cfs

The uncertainty of the forecast inflows was next investigated by basing regulation decisions on imperfect forecasts to find the safety margins, or hedges, required so that the constraints of the levels of Southern Indian Lake, Notigi, and Footprint Lake would not be violated. For each of the years chosen for simulation, the inflows were multiplied by 0.7 or by 1.4 to get an imperfect forecast which would make the regulation the most difficult, i.e. in summer, a low forecast would result in the level of Southern Indian Lake rising faster towards the maximum level, than expected. By making regulation decisions based on a lower maximum level of Southern Indian Lake, Notigi, and Footprint Lake, a safety margin is introduced. The appropriate safety margin to guard against the worst expected forecast was found by trial and error.

The uncertainty of the lake levels was investigated first by finding the safety margin associated with imperfect lake level data in a similar manner as was done with imperfect forecasts. The appropriate safety margin, for the maximum level of Southern Indian Lake, used for regulation decisions, was found by trial and error for expected ranges of uncertainty of lake level data of plus or minus 0.1, 0.2, 0.3, and 0.4 feet.

The uncertainty of the lake levels was then investigated with the effect of uncertain forecasts. The safety margins for imperfect forecasts was held constant for a particular simulation year, while the accuracy of the forecast was varied between 0.7 and 1.4 times the historical actual inflow, for successive runs. The effect of the economic impact of the uncertainty of the lake level data is the effect of the safety margin required because of the uncertainty, hence, the simulation was run with the safety margins found for lake level gauge uncertainty. For each combination of inflow forecast and lake level gauge safety margins, the simulation was run and the net benefit of the diverted flows was calculated.

4.5.5 Results of the Model

The net benefits of the flow diverted for combinations of inflow forecasts and lake level gauge uncertainty safety margins, are presented in Tables 9 through 13 and Figures 3 through 12 for each of the simulation periods. In the tables, each row is for a different inflow forecast and each column is for a different lake level uncertainty. For example, a ratio of forecast to actual inflow of 0.7 means that the forecast used in the simulation predicted only seventy per cent of the inflow that actually occurred. A lake level uncertainty of 0.4 means that a safety margin to account for a lake level data accuracy of plus or minus four tenths of a foot was used in the simulations. Missing from the tables is the wet year of the winter of 1986/87, since the regulation was found to be insensitive to the uncertainty of the lake level gauges. The inflow during the winter of 1986/87 was so high that Southern Indian Lake could not be drawn down to its minimum level.

The plot of the rows from the table of results is the relationship of net benefits to lake level uncertainty which is what this study is seeking. The problem of finding this relationship is in determining the effect of other factors on it, such as the magnitude of the lake level uncertainty, the distribution of inflow throughout the simulation period, the total inflow during the period, and the forecast of the inflow. This is why the analysis includes more than one year for simulation, a range of lake level uncertainty, different amounts of total inflow, i.e. wet, average, and dry years, and different inflow forecast accuracies. The effects of the total inflow and the distribution of the inflow during the simulation period may be taken into account by averaging the results from the three summer years and averaging the results from the two winter years.

Table 9

Net Benefit of the Regulation of Southern Indian Lake ($\$ x 10^6$)

Ratio of Forecast to Actual Inflow	Summer 1986 - Wet Lake Level Uncertainty (feet)					Average Benefit to Uncertainty Rate ($Million/0.1ft)
	0.0	0.1	0.2	0.3	0.4	
0.7	10.916	11.016	10.829	10.652	10.806	0.028
0.8	11.391	11.211	10.806	10.856	10.863	0.132
0.9	10.879	10.806	10.709	10.560	10.411	0.117
1.0	9.906	9.942	9.814	9.711	9.584	0.081
1.2	8.123	8.019	7.942	7.826	7.701	0.106
1.4	6.601	6.523	6.443	6.364	6.284	0.079
					Average:	0.090

Table 10

Net Benefit of the Regulation of Southern Indian Lake ($\$x10^6$)

Ratio of Forecast to Actual Inflow	Summer 1988 - Average Lake Level Uncertainty (feet)					Average Benefit to Uncertainty Rate ($Million/0.1ft)
	0.0	0.1	0.2	0.3	0.4	
0.7	11.834	10.090	9.263	9.942	9.850	0.496
0.8	10.150	9.995	9.772	9.772	9.570	0.145
0.9	9.982	9.894	9.864	9.793	9.730	0.063
1.0	9.720	9.690	9.629	9.536	9.458	0.066
1.2	8.526	8.428	8.325	8.269	8.073	0.113
1.4	6.806	6.757	6.703	6.664	6.566	0.060
					Average:	0.157

Table 11

Net Benefit of the Regulation of Southern Indian Lake ($\$x10^6$)

Ratio of Forecast to Actual Inflow	Summer 1991 - Dry Lake Level Uncertainty (feet)					Average Benefit to Uncertainty Rate ($Million/0.1ft)
	0.0	0.1	0.2	0.3	0.4	
0.7	9.315	9.291	9.247	8.931	9.500	-0.046
0.8	9.430	9.538	9.722	9.544	9.399	0.008
0.9	9.888	9.821	9.779	9.704	9.639	0.063
1.0	9.775	9.697	9.661	9.531	9.429	0.087
1.2	8.328	8.237	8.185	8.026	7.922	0.102
1.4	6.985	6.890	6.796	6.645	6.586	0.100
					Average:	0.052

Table 12

Net Benefit of the Regulation of Southern Indian Lake ($\$x10^6$)

Ratio of Forecast to Actual Inflow	Winter 1987/88 - Average Lake Level Uncertainty (feet)					Average Benefit to Uncertainty Rate ($Million/0.1ft)
	0.0	0.1	0.2	0.3	0.4	
0.7	16.854	16.854	16.854	16.854	16.854	0.000
0.9	18.036	18.036	18.036	17.992	17.992	0.011
1.0	18.383	18.340	18.294	18.298	18.252	0.033
1.2	18.215	18.000	17.427	18.142	17.843	0.093
1.4	18.363	18.277	18.349	18.283	18.273	0.023
					Average:	0.032

Table 13

Net Benefit of the Regulation of Southern Indian Lake ($\$x10^6$)

Ratio of Forecast to Actual Inflow	Winter 1990/91 - Dry Lake Level Uncertainty (feet)					Average Benefit to Uncertainty Rate ($Million/0.1ft)
	0.0	0.1	0.2	0.3	0.4	
0.7	13.082	12.886	12.841	12.706	12.519	0.141
0.9	14.091	13.875	13.764	13.678	13.585	0.127
1.0	14.320	14.155	14.031	14.017	13.841	0.120
1.2	13.930	13.824	13.841	13.754	13.588	0.086
1.4	14.273	14.149	14.062	13.904	14.383	-0.028
					Average:	0.089

Figure 3

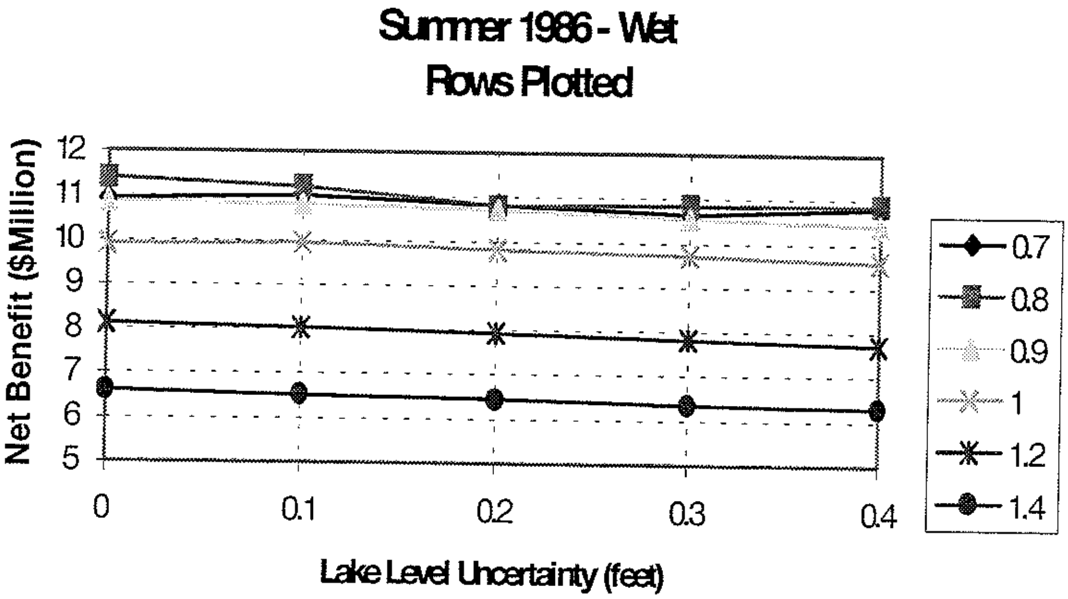


Figure 4

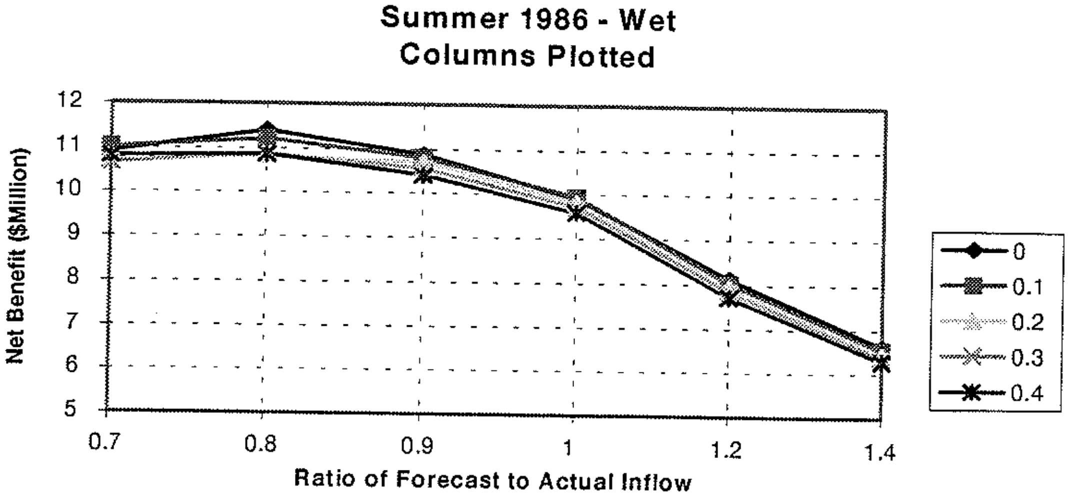


Figure 5

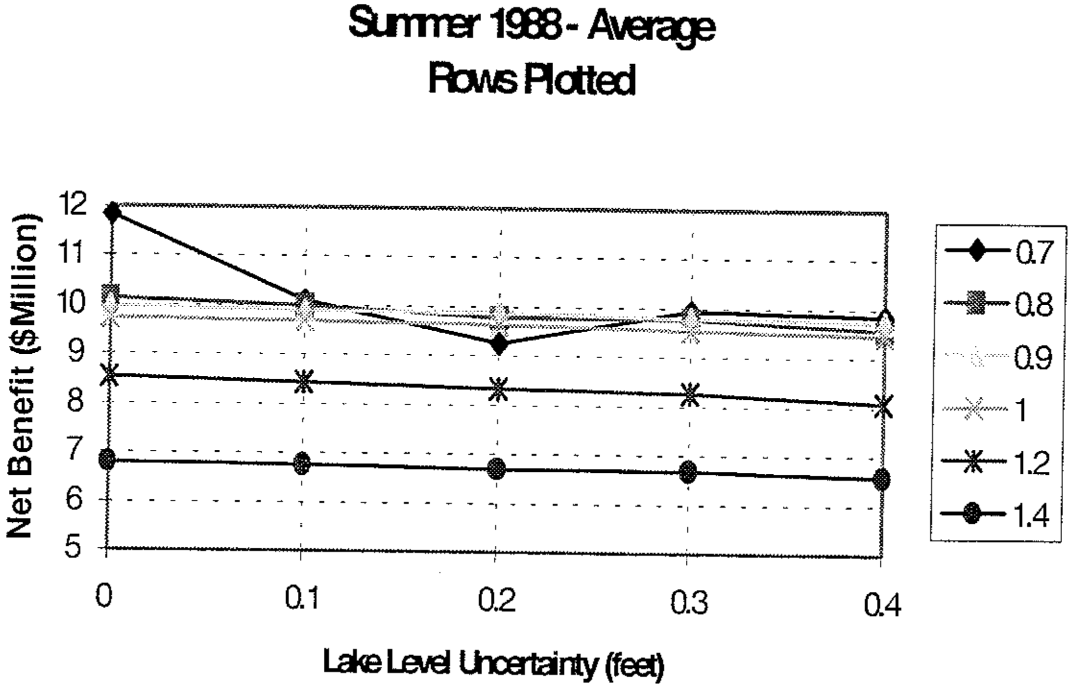


Figure 6

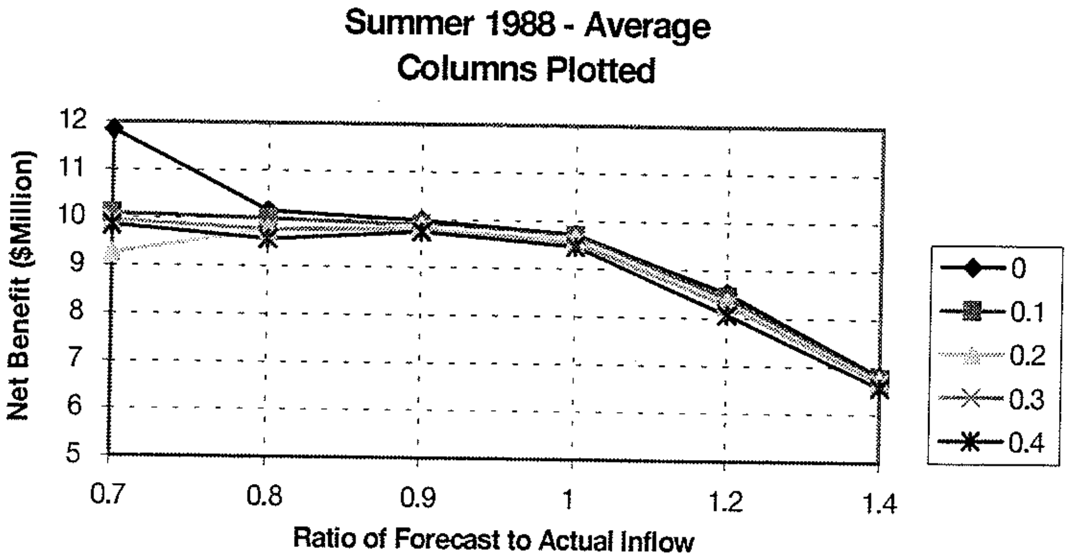


Figure 7

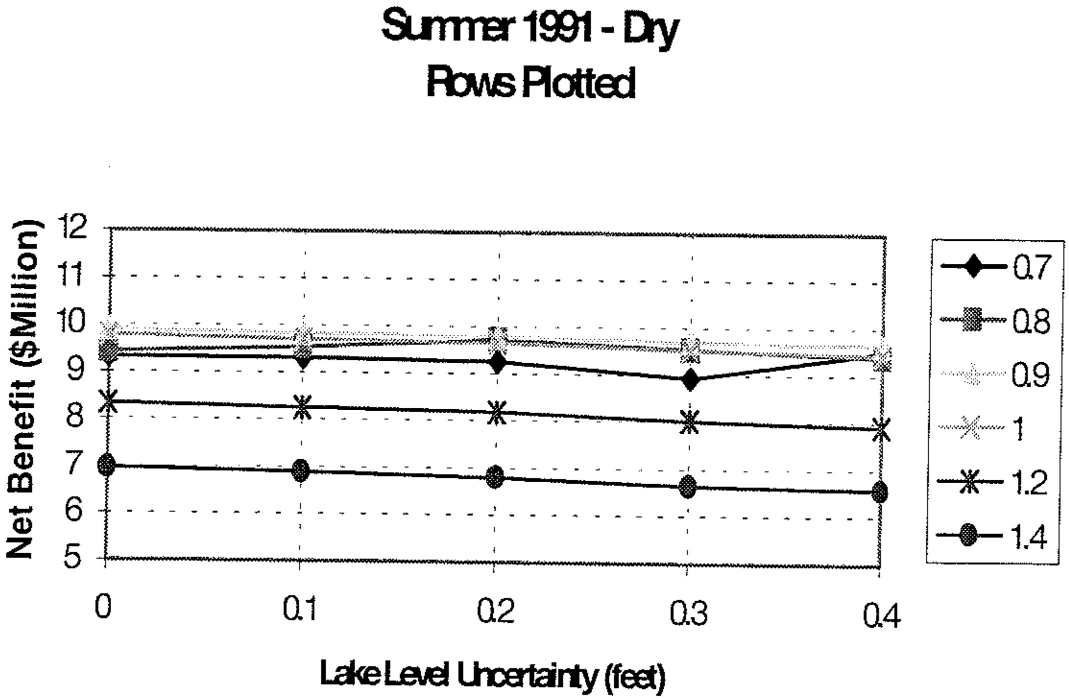


Figure 8

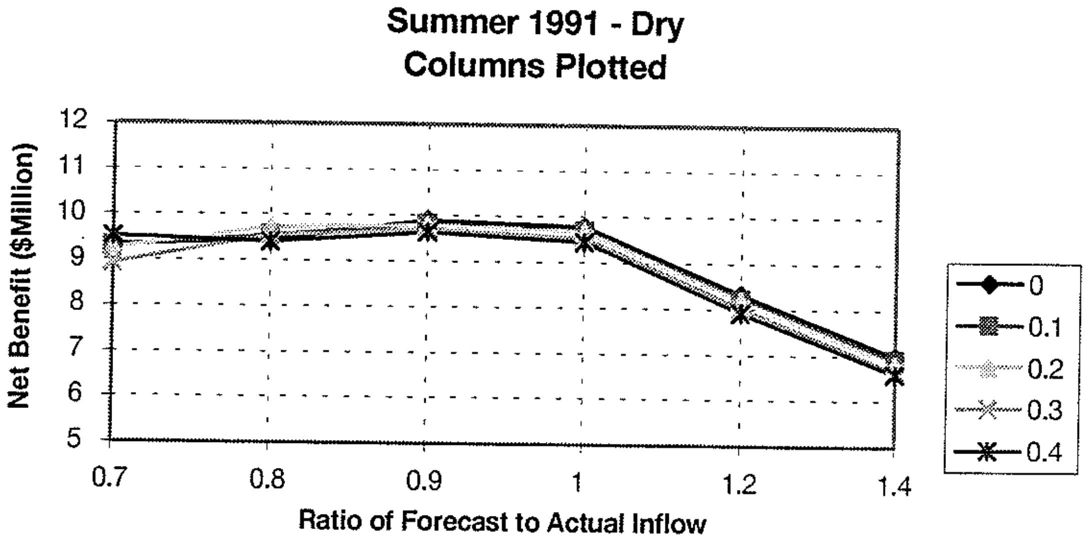


Figure 9

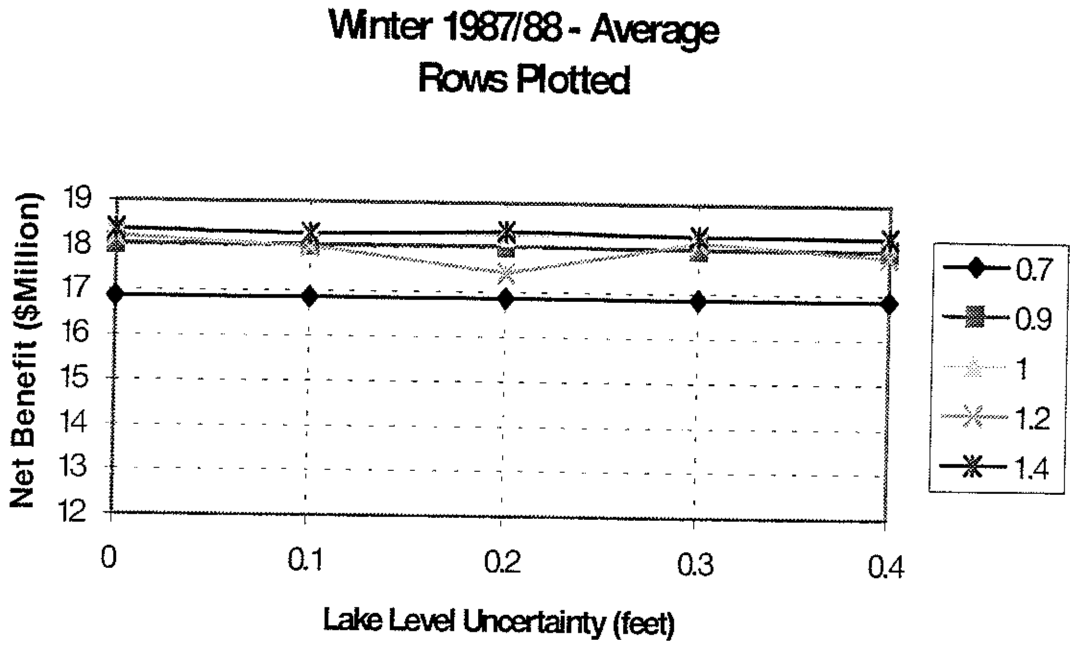


Figure 10

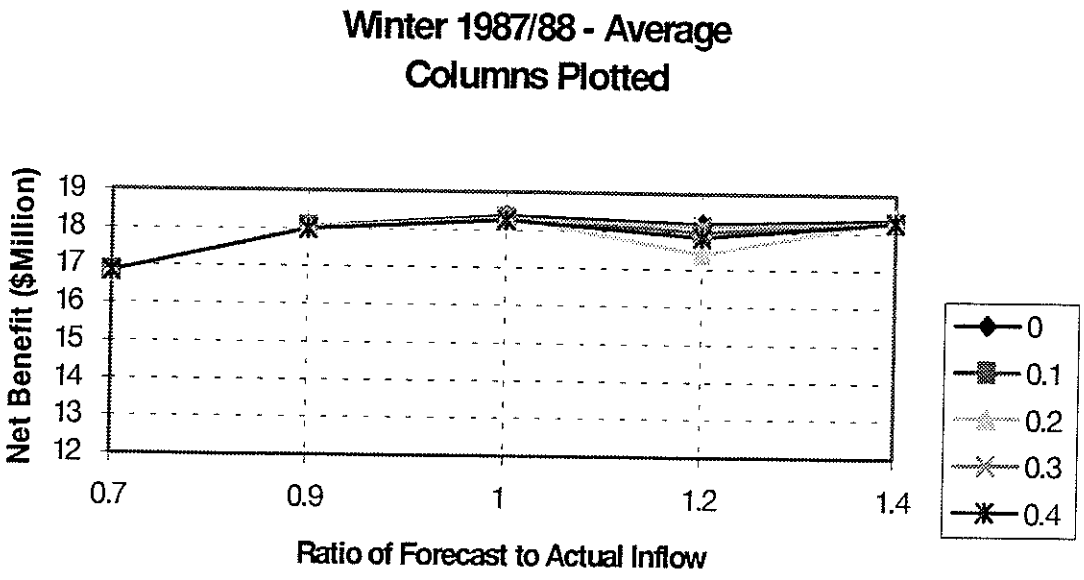


Figure 11

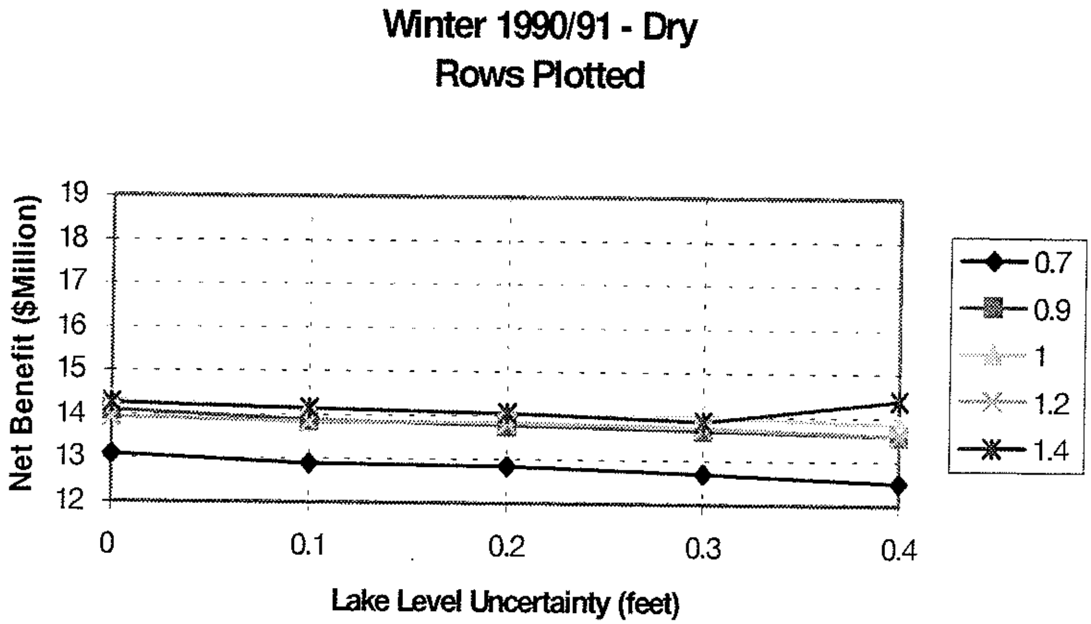
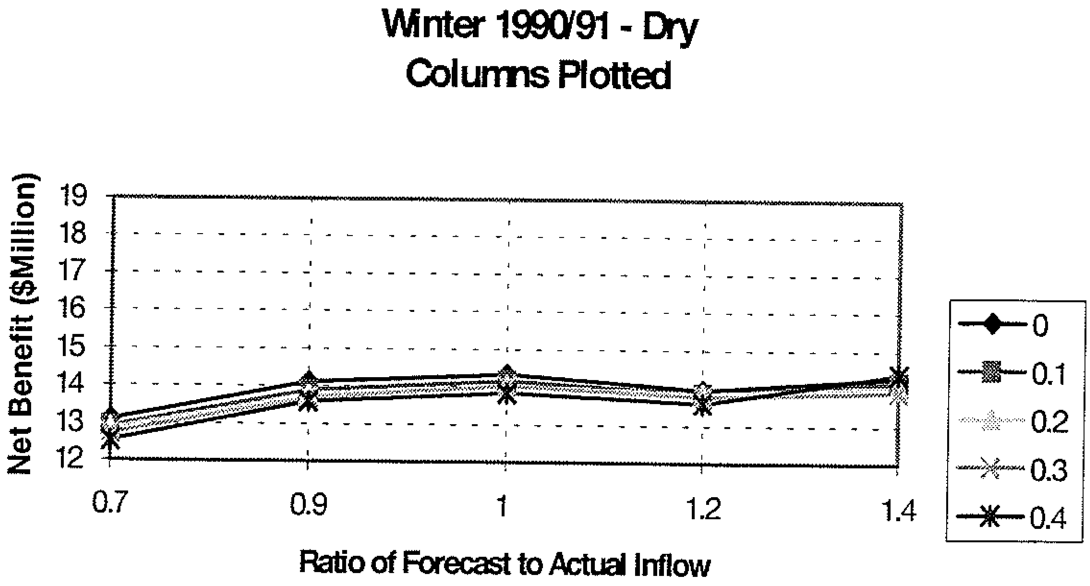


Figure 12



From examination of tables 9 through 13 and the plots of simulation results, Figures 3 through 12, a number of observations and simplifications can be made.

From all the simulation periods it can be observed that the net benefit tends to decrease as the lake level uncertainty increases. Most exceptions to this occur for the summer simulations where the forecast inflow is 0.7 of the actual inflow. Since the expected inflow is less than the actual inflow the lake level rises more than expected during each two week regulation period. The unexpected rise can be controlled by releases from Notigi and spills from Missi Falls. When spilling from Missi Falls is required, the net benefit of regulation will be significantly different from a similar simulation where spilling was not required, likely resulting in the anomalies observed in the net benefits for an inflow forecast of 0.7.

In the summer simulations the net benefit generally increases as the ratio of forecast to actual inflow decreases, which results in the lake level rising closer to its maximum acceptable level. The exceptions occur for low inflow forecasts as discussed above.

In the winter simulations a high ratio of forecast to actual inflow results in the lake level falling more than expected during each two week regulation period. This results in the lake approaching closer to its minimum acceptable limit but may result in a more drastic reduction of the discharge from Notigi to control the lake level. The results of the winter simulations show a tendency of increasing net benefits with increasing rates of forecast to actual inflow, but the trend is not a clear one.

A helpful simplification is that the relationship of net benefit to lake level uncertainty is independent of the forecast accuracy. This follows from observing that the plots of net benefit versus lake level uncertainty have similar slope regardless of the forecast accuracy. Another helpful simplification is that the relationship of net benefit to lake level uncertainty is independent of the magnitude of the lake level uncertainty. This follows from observing that the plots of net benefit versus lake level uncertainty are generally linear. Anomalies may be due to the problems discussed above or may be associated with simulating regulation decisions using two week time steps, using fixed steps of discharge, strict if-then logic, or may be due to undetected errors in the regulation logic.

Since the rate of change of net benefits with respect to lake level uncertainty is apparently independent of forecast inflows and magnitude of uncertainty of lake levels, it should be possible to estimate a single rate of benefit to uncertainty which reflects the average rates found for the simulation periods and which reflects the representativeness of the simulation periods. The right hand column in the tables, the average benefit to uncertainty rate, is the average slope of the line when net benefits are plotted against lake level uncertainty. These values may be used to aid in determining an overall average rate.

The simulation periods for the summer reflect an average rate of $100,000 per tenth of a foot of lake level accuracy. The simulation years chosen are fairly representative. Historically, the level of Southern Indian Lake was significantly lower than the maximum level in 1987 and in 1990, indicating that something other than the lake level governed the regulation in those years.

The simulation periods for the winter reflect an average rate of $40,000 per tenth of a foot of lake level accuracy when the rate of zero for the winter of 1986/87 is included. Historically, the level of Southern Indian Lake was significantly higher than the minimum level in 1984, perhaps due to high inflows. During many winters, high levels of Footprint Lake coincided with a reduction in discharge from Southern Indian Lake, but Southern Indian Lake was still drawn down close to its minimum level.

Each year, the uncertainty of lake levels impacts both the summer and winter regulation of Southern Indian Lake, so it would seem that the rate of change of net benefits with respect to lake level uncertainty for a year is the sum of the rates for the summer and winter. This may not be completely true because the benefits of summer regulation are largely from storing water which will be released during the winter. There may be some dependence of realizing summer benefits on the performance of the winter regulation. The sum of the average summer and winter rates, from the simulations, is $140,000 per tenth of a foot. Reducing the yearly rate by about thirty percent to $100,000 per tenth of a foot would seem reasonable to account for possible interdependence of realizing winter and summer benefits and to account for occasional years when the level of Southern Indian Lake does not govern regulation decisions.

4.6 Economic Impact of an Increment in the Data Collection Network of S.I.L.

From simulations of the regulation of Southern Indian Lake, economic benefits were related to the uncertainty of the data. Uncertainty of the data was related to the set or subset of gauges used through statistical analysis. The simulations identified a value of $100,000 per tenth of a foot, per year, for the uncertainty of the lake level data. The analysis of the existing gauge data identified a standard deviation for each combination of gauges and the probability of failure for each gauge. These results are to be applied to scenarios to show how the economic impact of making a change to the data collection network can be calculated.

When a change is made in a data collection network, there will be a change in the accuracy of the lake level, measured by the standard deviation. Assuming that the distribution of lake level measurements is normally distributed, 99% of all measurements will fall within 2.576 standard deviations of the "true" lake level. 99% confidence limits were chosen because it was understood that violating lake level constraints was unacceptable to Manitoba Hydro and that therefore Manitoba Hydro would have to use high confidence limits for the expected range that the actual lake level could be within.

When a gauge is discontinued, fails, or is added to a network, the accuracy of the network changes accordingly. The economic impact of the change in accuracy, over a period of a year, can be found by multiplying the change in accuracy of the network by $100,000 per tenth of a foot, per year, which was found from the simulation.

Example: Discontinuing the gauge at Missi Falls from the existing network.

Standard deviation of existing network: 0.02579

Accuracy range of existing network (2.576 x standard deviation): 0.066ft

Standard deviation of network without Missi Falls gauge: 0.03805

Accuracy range of network without Missi Falls gauge (2.576 x standard deviation): 0.098ft

Change in accuracy: 0.032ft

Economic impact of change in range of accuracy ($100,000 per tenth of a foot x change in accuracy): $31,582/year

When a change is made in a data collection network, there will also be a change in the reliability of the network due to the probability of failure of each of the gauges. Essentially, the impact of a gauge failing is the same as discontinuing the gauge, resulting in a change of accuracy of the network. The probability of a gauge failing multiplied by the economic impact of discontinuing the gauge, calculated as outlined above, gives the economic impact of the reliability of that gauge. This is referred to later as the reliability cost.

Example:

The probability of the gauge at Missi Falls failing: 15.6%

Economic impact of discontinuing the Missi Falls gauge: $31,582/year

Economic impact of the reliability of the gauge at Missi Falls: (probability x economic impact) $4,916/year

In a network, it is possible to have more than one gauge fail at a time. On Southern Indian Lake up to three gauges have failed at one time. To find the economic impact of the reliability, or, the 'reliability cost', the probability of each gauge and combination of gauges failing is multiplied by the economic impact due to the loss in accuracy of the remaining network; see Table 14.

Table 14

Example of Calculating the Reliability Cost of a Network

Reference No.	Gauge Name	Probability of Failure
1	S.I.L. Village	0.021520
2	South Bay	0.023653
3	Missi Falls	0.155648
4	Opachuana	0.021168

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Cost of Unreliable Gauges $/year
Base Case:						
1,2,3,4		0.02579	0.066			
Possible Cases:						
1,2,3	0.02117	0.02909	0.075	-0.009	-$8,501	-$180
2,3,4	0.02152	0.02590	0.067	-0.0003	-$283	-$6
1,2,4	0.15565	0.03805	0.098	-0.032	-$31,582	-$4,916
1,3,4	0.02365	0.02842	0.073	-0.007	-$6,775	-$160
1,2	0.00329	0.03959	0.102	-0.036	-$35,549	-$117
1,3	0.00050	0.03790	0.098	-0.031	-$31,195	-$16
1,4	0.00368	0.04321	0.111	-0.045	-$44,874	-$165
2,3	0.00046	0.03373	0.087	-0.020	-$20,453	-$9
2,4	0.00335	0.04282	0.110	-0.044	-$43,869	-$147
3,4	0.00051	0.03396	0.087	-0.021	-$21,046	-$11
1	0.00008	0.04700	0.121	-0.055	-$54,637	-$4
2	0.00007	0.04600	0.118	-0.052	-$52,061	-$4
3	0.00001	0.06800	0.175	-0.109	-$108,733	-$1
4	0.00008	0.06100	0.157	-0.091	-$90,701	-$7
none	0.000002	NA	?!	?!	?!	?!
				Reliability Cost=		-$5,743

The probability of two or more gauges failing at the same time was calculated by assuming that the probabilities calculated for each gauge failing are independent and can therefore be combined without having to calculate conditional probabilities. It is recognized that gauge failures are likely related to some degree, since some causes of gauge failure would be experienced at the same time by all gauges, for instance, severe temperatures. Since the additional information to analyze the time dependence and interdependence of gauge failure was not readily available, the simpler approach of assuming independence allowed the calculation of the probability of two independent events occurring simultaneously to be calculated as the product of the probability of each occurring individually.

To calculate the economic impact of a change in the data collection network, the accuracy and the reliability cost of the existing network must be calculated so that they can be compared to those of the changed network. Next, the accuracy and the reliability cost of the changed network must be calculated. The economic impact of the change in accuracy and the change in reliability cost can be summed to find the total economic impact of changing the network. The economic impact can be compared to the change in costs of data collection using marginal benefit cost ratios. When networks are expanded, the benefit is the economic impact of the change in data and the cost is the additional cost of collecting data. When networks are reduced, the benefit is the savings in the cost of data collection and the cost is the economic impact of having less data. Examples of the benefit-cost ratio calculations follow in the analysis of four network change scenarios. In these scenarios the salvage value from discontinuing a gauge is zero because Manitoba Hydro does not own the gauges.

4.6.1 Scenario 1

The first scenario considered is discontinuing one or more of the four existing gauges on Southern Indian Lake. The economic impact of discontinuing a gauge is dependent on the gauge(s) discontinued, since each gauge contributes differently to the accuracy of the network. The economic impacts for discontinuing any possible combination of gauges can be found in Table 15. The calculations of the changes in accuracy and reliability cost can be found in Appendix F.

When a gauge is discontinued, the benefit is the savings of the operating cost of the gauge and the cost is the reduction in hydro-power production due to poorer lake level data. A marginal benefit-cost ratio greater than one indicates that the incremental economic benefits are greater than the incremental economic costs of the action. Discontinuing the gauge at S.I.L. Village has a marginal benefit cost ratio of greater than one, indicating that this gauge should be discontinued based on the economic impact it has on the regulation of Southern Indian Lake. It is recognized that there may be other benefits of this gauge, such as future development, public relations, and settling disputes with the citizens of S.I.L. Village which may require the continued operation of this gauge. The marginal benefit cost ratio of the other gauges are less than one, indicating that these gauges should not be discontinued. The marginal benefit cost ratio of zero for

Table 15

Marginal Benefit/Cost Ratio of Discontinuing

One or More Gauges on Southern Indian Lake

Gauges Discontinued:	Benefit (1) ($/year)	Benefit (2) ($/year)	Cost ($/year)	B/C Ratio (1)	B/C Ratio (2)
S.I.L. Village	$2,950	$5,900	$2,800	1.05	2.11
South Bay	$0	$5,900	$8,271	0.00	0.71
Missi Falls	$5,900	$5,900	$26,552	0.22	0.22
Opachuana	$5,900	$5,900	$8,128	0.73	0.73
S.I.L. Village and South Bay	$2,950	$11,800	$28,001	0.11	0.42
S.I.L. Village and Missi Falls	$8,850	$11,800	$39,407	0.22	0.30
S.I.L. Village and Opachuana	$8,850	$11,800	$21,718	0.41	0.54
South Bay and Missi Falls	$5,900	$11,800	$40,324	0.15	0.29
South Bay and Opachuana	$5,900	$11,800	$30,769	0.19	0.38
Missi Falls and Opachuana	$11,800	$11,800	$30,612	0.39	0.39
S.I.L. Village, South Bay, Missi Falls	$8,850	$17,700	$84,958	0.10	0.21
South Bay, Missi Falls, Opachuana	$11,800	$17,700	$48,894	0.24	0.36
S.I.L. Village, South Bay, Opachuana	$8,850	$17,700	$102,990	0.09	0.17
S.I.L. Village, Missi Falls, Opachuana	$14,750	$17,700	$46,318	0.32	0.38

Notes:

- Case (1) is under current operating cost sharing agreements.
- Case (2) is if the total operating cost was born by Manitoba Hydro.
- The benefit of discontinuing a gauge is the reduction in operating cost of that gauge.
- The cost of discontinuing a gauge is the reduction in hydro-power production it causes.

discontinuing the gauge at South Bay for case (1) reflects common sense, in that it is pointless to discontinue a gauge that has no operating cost.

Table 16
Sensitivity of Marginal Benefit-Cost Ratio, Case (2), to the Rate of Worth and the Number of Standard Deviations

Rate of Worth ($/.1ft) No. of Std. Deviations (Confidence Limits)	$100,000 2.576 99%	$50,000 2.576 99%	$100,000 2.326 98%	$100,000 3.291 99.90%
Gauges Discontinued				
S.I.L. Village	2.11	4.21	2.33	1.65
South Bay	0.71	1.43	0.79	0.56
Missi Falls	0.22	0.44	0.25	0.17
Opachuana	0.73	1.45	0.80	0.57
S.I.L. Village and South Bay	0.42	0.84	0.47	0.33
S.I.L. Village and Missi Falls	0.30	0.60	0.33	0.23
S.I.L. Village and Opachuana	0.54	1.09	0.60	0.43
South Bay and Missi Falls	0.29	0.59	0.32	0.23
South Bay and Opachuana	0.38	0.77	0.42	0.30
Missi Falls and Opachuana	0.39	0.77	0.43	0.30
S.I.L. Village, South Bay, Missi Falls	0.21	0.42	0.23	0.16
South Bay, Missi Falls, Opachuana	0.36	0.72	0.40	0.28
S.I.L. Village, South Bay, Opachuana	0.17	0.34	0.19	0.13
S.I.L. Village, Missi Falls, Opachuana	0.38	0.76	0.42	0.30

The marginal benefit-cost ratios are inversely proportional to the average benefit to uncertainty rate and to the number of standard deviations used to define the uncertainty range of the lake level data (See Table 16). The first column of benefit-cost ratios are for the rate of worth and confidence limits used throughout the analysis. The second column is for a reduced rate of worth and the third and fourth columns are for smaller and larger confidence limits. The change in confidence limits cause small changes because the number of standard deviations changes little. The change in rate of worth causes significant changes, causing the benefit-cost ratio for three network cases to exceed one when they had not before.

4.6.2 Scenario 2

The second scenario is of replacing the measuring equipment for the gauge at Missi Falls in order to improve its reliability. Part of the complexity of network optimization is that gauges can be upgraded as well as added or discontinued. The strength of this economic analysis is that it recognizes the attributes of individual gauges, permitting the estimation of the effect of repairing a gauge. Repairing the gauge at Missi Falls would improve the poor failure record of the gauge. It was estimated that the probability of failure after repair would be similar to the current probability of failure of the other gauges, so the average of the probability of failure of the other gauges was used for the repaired gauge (see Table 17). The standard deviation of the gauge is mostly a function of the location of the gauge and less so of the measuring equipment, so it was assumed that it would stay the same.

Table 17

Revised Probabilities of Failure

Gauge:	Probability of Failure (%)
S.I.L. Village	2.2
South Bay	2.4
Missi Falls	2.2
Opachuana	2.1

The analysis of finding the benefit-cost ratios for discontinuing one or more gauges was performed again, this time with the gauge at Missi Falls repaired. The improvement in the probability of failure of the gauge at Missi Falls is reflected in the analysis by a reduction in the reliability cost of any networks that Missi Falls is included in (see detailed calculations in Appendix G). The reliability cost of the four gauge network is reduced from $5,743 to $1141, a reduction of $4,602 per year. This reduction in reliability cost causes the cost of discontinuing the gauge at Missi Falls to increase from $26,552 (in Table 15) to $31,155 (in Table 18), a difference of $4,603 (or $4,602 with rounding errors). Repairing the gauge at Missi Falls results in a benefit of $4,603 per year, at a cost of $722 per year, approximated by annualizing the $9,000 equipment replacement and labor cost over a 20 year life at a discount rate of 5%. This results in a benefit-cost ratio of 6.4. After the gauge at Missi Falls is repaired, the marginal benefit-cost ratios of discontinuing gauges decrease or stay the same for all combinations except three; when the gauge at S.I.L. Village is discontinued, when the gauge at South Bay is discontinued, and when the gauges at S.I.L. Village and South Bay are both discontinued. The marginal benefit-cost ratios of discontinuing the gauge at S.I.L. Village increased from 1.05 to 2.58

Table 18

Marginal Benefit-Cost Ratio of Discontinuing Gauges on Southern Indian Lake

After the Repair of the Gauge at Missi Falls

Gauges Discontinued:	Benefit (1) ($/year)	Benefit (2) ($/year)	Cost ($/year)	B/C Ratio (1)	B/C Ratio (2)
S.I.L. Village	$2,950	$5,900	$1,145	2.58	5.15
South Bay	$0	$5,900	$7,405	0.00	0.80
Missi Falls	$5,900	$5,900	$31,155	0.19	0.19
Opachuana	$5,900	$5,900	$8,845	0.67	0.67
S.I.L. Village and South Bay	$2,950	$11,800	$23,294	0.13	0.51
S.I.L. Village and Missi Falls	$8,850	$11,800	$44,010	0.20	0.27
S.I.L. Village and Opachuana	$8,850	$11,800	$22,096	0.40	0.53
South Bay and Missi Falls	$5,900	$11,800	$44,926	0.13	0.26
South Bay and Opachuana	$5,900	$11,800	$32,239	0.18	0.37
Missi Falls and Opachuana	$11,800	$11,800	$35,215	0.34	0.34
S.I.L. Village, South Bay, Missi Falls	$8,850	$17,700	$89,560	0.10	0.20
South Bay, Missi Falls, Opachuana	$11,800	$17,700	$53,496	0.22	0.33
S.I.L. Village, South Bay, Opachuana	$8,850	$17,700	$107,592	0.08	0.16
S.I.L. Village, Missi Falls, Opachuana	$14,750	$17,700	$50,920	0.29	0.35

Notes:

- Case (1) is under current operating cost sharing agreements.
- Case (2) is if the total operating cost was born by Manitoba Hydro.
- The benefit of discontinuing a gauge is the reduction in operating cost of that gauge.
- The cost of discontinuing a gauge is the reduction in hydro-power production it causes.

for existing operating costs. Increasing the reliability of the gauge at Missi Falls decreases the worth of the gauge at S.I.L. Village because the need for an additional reliable gauge is decreased. In a more reliable network, the worth of the gauge at S.I.L. Village decreases because the need for reliability is less and because the gauge at S.I.L. Village contributes the least to accuracy since it is highly positively correlated with other gauges.

The third and fourth scenarios considered are of adding a fifth gauge to the network on Southern Indian Lake. The third scenario is of adding a fifth gauge to the existing network. The fourth scenario is of adding a fifth gauge to the network after the gauge at Missi Falls is repaired. Since there are already three gauges near the south end of Southern Indian Lake, the proposed location of the fifth gauge is near the north end of the lake, perhaps on the western shore, preferably in a bay sheltered from the wind (see Figure 13). Of course, accessibility would have to be taken into account as well as other potential uses for the data which may affect the choice of location.

The standard deviation of the data would probably be most similar to the gauge at Missi Falls due to its proximity, so the proposed north end gauge was assigned the same value.

The correlations of the proposed north end gauge to the other gauges were estimated by observing the relationship between the locations of existing gauges and their correlations (see Figure 14). The correlations of the proposed north end gauge to the three southern gauges would likely be similar to the correlations between the gauge at Missi Falls and the three southern gauges but perhaps not quite as strongly negatively correlated since the proposed location is slightly south of Missi Falls. The correlation

Figure 13

Location Map with Proposed North End Gauge

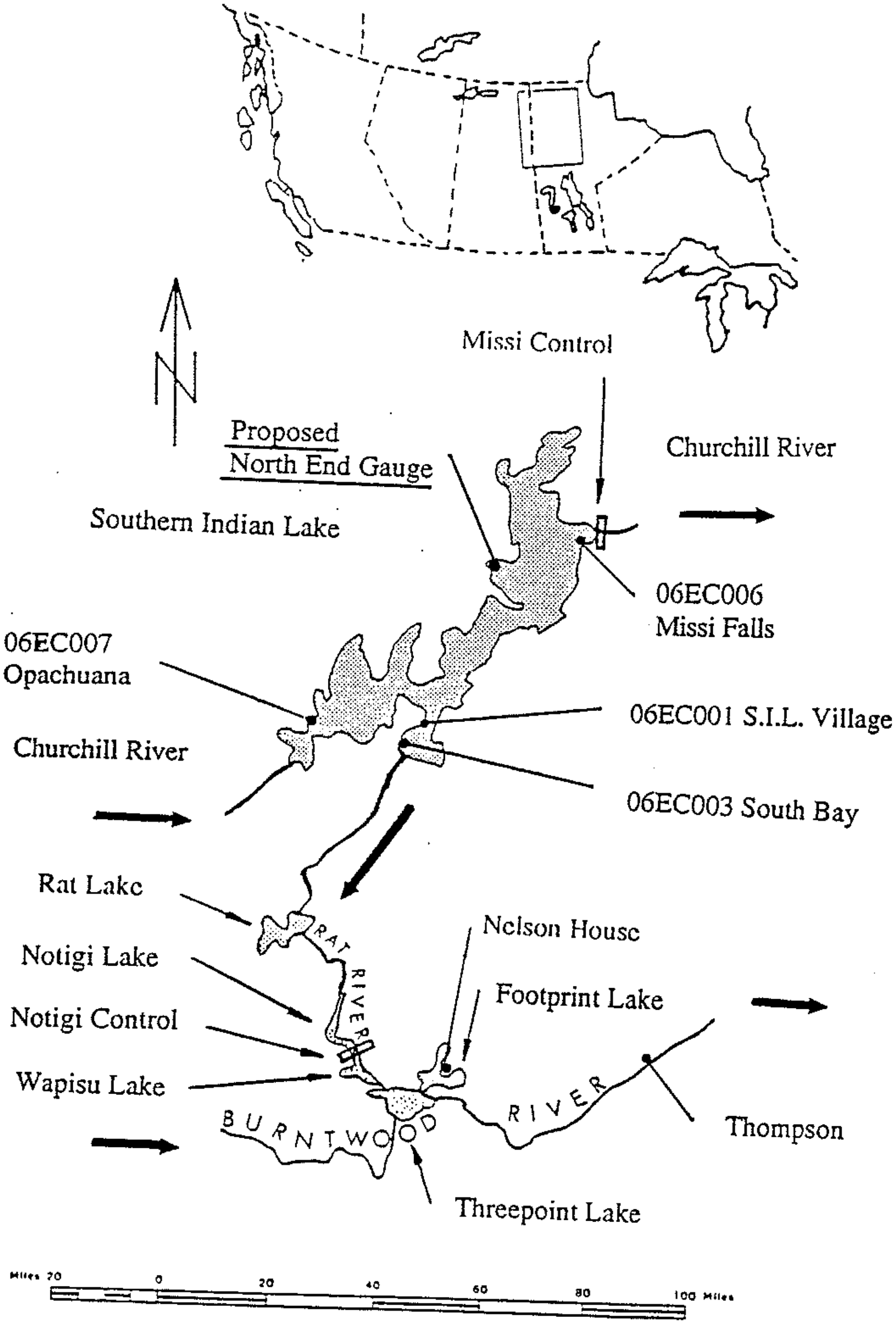
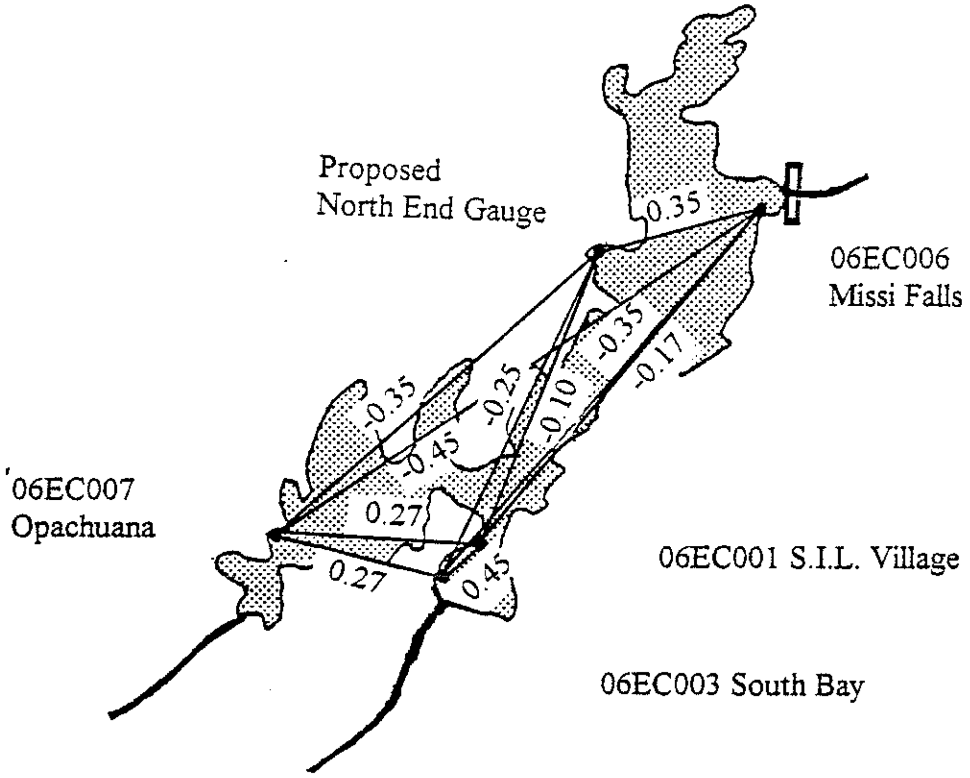


Figure 14

Location Map Showing Correlations (R not R^2)



between the proposed north end gauge and the Missi Falls gauge will likely be strongly positively correlated just as the gauges at S.I.L. Village and South Bay are.

The probability of failure of the proposed north end gauge would probably be similar to the probabilities of failure of the three gauges at the southern end of the lake. The average of the probability of failure of the three southern gauges, 0.022, was used for the north end gauge. This value is the same as that used for the repaired gauge at Missi Falls.

4.6.3 Scenario 3

When the north end gauge is added to the existing network, the accuracy of the network changes from plus or minus 0.0664 feet to 0.0596 feet (See Appendix H for detailed calculations) which results in a benefit of $6,826 per year ($100,000 per tenth of a foot). The reliability cost of the network changes from $5,743 to $3,104, which is $2639 per year in expected benefits from increased reliability. The benefit of adding the north end gauge is $9,465 per year. The cost of adding the north end gauge is an additional $5,900 per year for operating costs and $1,765 per year to cover the capital cost of installing the gauge, for a total cost of $7,665 per year. (The cost of installation is $22,000, which includes all equipment and labor as well as a helicopter pad for access. $1,765 is the equivalent annual cost assuming a twenty year life and a five per cent discount rate.) The marginal benefit-cost ratio is 1.23. Since it is greater than zero it is beneficial to add the north end gauge to the existing network.

The analysis for discontinuing one or more gauges from this modified network was performed again to check the effects that adding the north end gauge has on the network (See Table 19 and also Appendix H). The benefit of discontinuing the north end gauge is the benefit of not having to incur the operating cost or the installation cost of it. The marginal benefit-cost ratio of discontinuing the north end gauge is 0.81, which is the inverse of 1.23, and indicates that the north end gauge, by itself, should not be discontinued. The benefit-cost ratio of discontinuing the gauge at Missi Falls has increased while the ratio for all others has decreased, including the ratio for the gauge at S.I.L. Village. The addition of the north end gauge has decreased the worth of the gauge at Missi Falls, as expected. An additional result is that the worth of the southern gauges increases, due to their value in balancing out an additional north end measurement. For current operating cost sharing agreements, case (1), all benefit-cost ratios are less than one, so it is beneficial to retain all gauges. For case (2), where Manitoba Hydro bears the full operating cost of all stations, the highest benefit-cost ratio of 1.8 indicates that discontinuing the gauge at S.I.L. would yield the greatest benefit. The other benefit-cost ratio greater than one is 1.11 and indicates that it would be less beneficial but still worthwhile to discontinue the north end gauge and the gauge at S.I.L. Village. It is interesting to note for case (2) that if the gauge at S.I.L. Village can be discontinued, the north end gauge should not be added, but if the gauge at S.I.L. Village must be retained for other purposes, it is beneficial to add the north end gauge.

Table 19

Marginal Benefit-Cost Ratios of Discontinuing Gauges on Southern Indian Lake

After Adding a Fifth Gauge (Missi Falls Gauge not repaired)

Gauges Discontinued:	Benefit (1) ($/year)	Benefit (2) ($/year)	Cost ($/year)	B/C Ratio (1)	B/C Ratio (2)
North End	$7,665	$7,665	$9,465	0.81	0.81
S.I.L. Village	$2,950	$5,900	$3,277	0.90	1.80
South Bay	$0	$5,900	$9,584	0.00	0.62
Missi Falls	$5,900	$5,900	$10,456	0.56	0.56
Opachuana	$5,900	$5,900	$13,582	0.43	0.43
Opachuana and North End	$13,565	$13,565	$14,955	0.91	0.91
S.I.L. Village and North End	$10,615	$13,565	$12,265	0.87	1.11
Missi Falls and North End	$13,565	$13,565	$36,018	0.38	0.38
South Bay and North End	$7,665	$13,565	$17,736	0.43	0.76
Missi Falls and Opachuana	$11,800	$11,800	$18,460	0.64	0.64
South Bay and Opachuana	$5,900	$11,800	$36,969	0.16	0.32
South Bay and Missi Falls	$5,900	$11,800	$18,257	0.32	0.65
S.I.L. Village and Opachuana	$8,850	$11,800	$28,894	0.31	0.41
S.I.L. Village and Missi Falls	$8,850	$11,800	$13,363	0.66	0.88
S.I.L. Village and South Bay	$2,950	$11,800	$24,915	0.12	0.47
Missi Falls, Opachuana, North End	$19,465	$19,465	$40,078	0.49	0.49
South Bay, Opachuana, North End	$13,565	$19,465	$40,235	0.34	0.48
South Bay, Missi Falls, North End	$13,565	$19,465	$49,789	0.27	0.39
S.I.L. Village, Opachuana, North End	$16,515	$19,465	$24,357	0.68	0.80
S.I.L. Village, Missi Falls, North End	$16,515	$19,465	$42,046	0.39	0.46
S.I.L. Village, South Bay, North End	$10,615	$19,465	$30,639	0.35	0.64
South Bay, Missi Falls, Opachuana	$11,800	$17,700	$33,823	0.35	0.52
S.I.L. Village, Missi Falls, Opachuana	$14,750	$17,700	$25,615	0.58	0.69
S.I.L. Village, South Bay, Opachuana	$8,850	$17,700	$79,911	0.11	0.22
S.I.L. Village, South Bay, Missi Falls	$8,850	$17,700	$28,503	0.31	0.62
S.Bay, Missi Falls, Opach., N.End	$19,465	$25,365	$51,533	0.38	0.49
S.I.L. Village, Missi, Opach., N.End	$22,415	$25,365	$48,957	0.46	0.52
S.I.L. Village, S.Bay, Opach., N.End	$16,515	$25,365	$105,629	0.16	0.24
S.I.L. Village, S.Bay, Missi, N.End	$16,515	$25,365	$87,597	0.19	0.29
S.I.L. Village, S.Bay, Missi, Opach.	$14,750	$23,600	$105,629	0.14	0.22

4.6.4 Scenario 4

When the north end gauge is added to the network after repairing the gauge at Missi Falls, the accuracy of the network changes from plus or minus 0.0664 feet to 0.0596 feet (the same as for the previous scenario) which results in a benefit of $6,826 per year ($100,000 per tenth of a foot). The reliability cost of the network changes from $1,141 to $1,139, which is $2 per year in expected benefits from increased reliability (see Appendix I for detailed calculations). The reliability cost of the network has already been lowered by the repair of the gauge at Missi Falls so the addition of the north end gauge has little effect on reliability. The benefit of adding the north end gauge is $6,828 per year. The cost of adding the north end gauge is an additional $5,900 per year for operating costs and $1,765 per year to cover the capital cost of installing the gauge, for a total cost of $7,665 per year (as in the previous scenario). The marginal benefit-cost ratio is 0.89. Since it is less than one it is not beneficial to add the north end gauge to the network after the gauge at Missi Falls has been repaired.

The analysis for discontinuing one or more gauges from this modified network was performed again to check the effects that adding the north end gauge has on the network (See Table 20 and also Appendix I). The marginal benefit-cost ratio of discontinuing the north end gauge is 1.12, which is the inverse of 0.89, and indicates that the north end gauge should be discontinued. The benefit-cost ratio of discontinuing the gauge at Missi Falls has increased while the ratio for all others has decreased, including the ratio for the gauge at S.I.L. Village as in the previous scenario.

Table 20

Marginal Benefit-Cost Ratios of Discontinuing Gauges on Southern Indian Lake

After Repairing the Missi Falls Gauge and Adding a Fifth Gauge

Gauges Discontinued:	Benefit (1) ($/year)	Benefit (2) ($/year)	Cost ($/year)	B/C Ratio (1)	B/C Ratio (2)
North End	$7,665	$7,665	$6,828	1.12	1.12
S.I.L. Village	$2,950	$5,900	$3,323	0.89	1.78
South Bay	$0	$5,900	$9,903	0.00	0.60
Missi Falls	$5,900	$5,900	$12,421	0.47	0.47
Opachuana	$5,900	$5,900	$14,560	0.41	0.41
Opachuana and North End	$13,565	$13,565	$15,671	0.87	0.87
S.I.L. Village and North End	$10,615	$13,565	$7,973	1.33	1.70
Missi Falls and North End	$13,565	$13,565	$37,983	0.36	0.36
South Bay and North End	$7,665	$13,565	$14,233	0.54	0.95
Missi Falls and Opachuana	$11,800	$11,800	$20,425	0.58	0.58
South Bay and Opachuana	$5,900	$11,800	$38,165	0.15	0.31
South Bay and Missi Falls	$5,900	$11,800	$20,222	0.29	0.58
S.I.L. Village and Opachuana	$8,850	$11,800	$30,072	0.29	0.39
S.I.L. Village and Missi Falls	$8,850	$11,800	$15,328	0.58	0.77
S.I.L. Village and South Bay	$2,950	$11,800	$24,937	0.12	0.47
Missi Falls, Opachuana, North End	$19,465	$19,465	$42,043	0.46	0.46
South Bay, Opachuana, North End	$13,565	$19,465	$39,067	0.35	0.50
South Bay, Missi Falls, North End	$13,565	$19,465	$51,754	0.26	0.38
S.I.L. Village, Opachuana, North End	$16,515	$19,465	$22,098	0.75	0.88
S.I.L. Village, Missi Falls, North End	$16,515	$19,465	$44,011	0.38	0.44
S.I.L. Village, South Bay, North End	$10,615	$19,465	$23,295	0.46	0.84
South Bay, Missi Falls, Opachuana	$11,800	$17,700	$35,788	0.33	0.49
S.I.L. Village, Missi Falls, Opachuana	$14,750	$17,700	$27,580	0.53	0.64
S.I.L. Village, South Bay, Opachuana	$8,850	$17,700	$77,697	0.11	0.23
S.I.L. Village, South Bay, Missi Falls	$8,850	$17,700	$30,468	0.29	0.58
S.Bay, Missi Falls, Opach., N.End	$19,465	$25,365	$53,498	0.36	0.47
S.I.L. Village, Missi, Opach., N.End	$22,415	$25,365	$50,922	0.44	0.50
S.I.L. Village, S.Bay, Opach., N.End	$16,515	$25,365	$107,594	0.15	0.24
S.I.L. Village, S.Bay, Missi, N.End	$16,515	$25,365	$89,562	0.18	0.28
S.I.L. Village, S.Bay, Missi, Opach.	$14,750	$23,600	$107,594	0.14	0.22

For case (1) it is most beneficial to discontinue the north end gauge and the gauge at S.I.L. Village (the benefit-cost ratio equals 1.33). If the gauge at S.I.L. Village cannot be discontinued, at least the north end gauge should be discontinued (the benefit-cost ratio equals 1.12).

These four scenarios demonstrate the ability of this method to be used for assessing the economic impact of discontinuing gauges, adding gauges, and upgrading gauges. Many additional scenarios could be considered by calculating the impact that the change has on hydro-power production and calculating the costs or savings associated with making the change. The impact that the change has on hydro-power production is the change in accuracy multiplied by the worth of the accuracy ($100,000 per tenth of a foot) plus the change in the reliability cost. Accuracy and reliability cost are attributes of the particular network. This method can also be used to calculate the marginal benefit-cost ratio of a combination of actions, which is essential for evaluating alternative plans.

5.0 Conclusions

Investigation of the current understanding and practice for determining the economic worth of hydrometric data produced some valuable information, however, it was quite limited. Some ingenious methods have been used for determining the worth of data for planning and design of structures. Also, the literature provided enough information that a general methodology could be developed for determining the economic worth of hydrometric data used for operations. The number of responses to the questionnaire which was mailed out was disappointing. In general, very little information could be found on the current understanding and practice of determining the economic worth of hydrometric data used in the real-time operation of water resource projects.

The general methodology developed was valuable for approaching and working through the case study. The methodology succeeded in focusing attention on the issues which were critical for determining economic worth. The methodology is general so that it may be applied to other real-time operations of water resource projects. The case study demonstrated some specific methods which may be appropriate for other cases. The method of measuring the accuracy of the gauges was relatively straight forward and provided a way to estimate how changes in the network would affect the accuracy of the network. The method of using simulations to test the sensitivity of regulation decisions to the accuracy of data was valuable. Using a simulation to find the impact of data on an operating decision parallels the comparison of different designs of structures to find the impact of using different amounts of data. Using simulations would seem appropriate for finding the economic worth of hydrometric data used in the real-time operation of other water resource projects.

For the case study, the simulations identified a value of $100,000 per tenth of a foot of the expected range of lake level accuracy. Four scenarios of changes to the network were analyzed showing the capability of the method to assess expanding or reducing a network, or upgrading an individual gauge. The following are examples of what was found for the lake level gauge network on Southern Indian Lake:

- Discontinuing the gauge at S.I.L. Village from the existing network results in a benefit-cost ratio of 1.05 under current cost-sharing agreements but increases to 2.11 if the full operating cost is born by Manitoba Hydro.
- Adding a gauge to the existing network results in a benefit-cost ratio of 1.23.
- Repairing the gauge at Missi Falls and retaining the existing network results in a benefit-cost ratio of 6.4.
- After the gauge at Missi Falls is repaired, adding a gauge results in a benefit-cost ratio of 0.89.

As expected there are ample ways that the case study could be improved or that the methods developed could be refined, expanded, or tested on other case studies. The reasons behind gauge failures and datum shifts need to be investigated and understood better. The estimate of the true lake level could be improved by using a moving average of a spatially weighted average of the levels from each gauge. The costs of operating gauges could be improved by incorporating any maintenance, calibration, or administration costs that the user might incur. The area offering the greatest improvements is in better understanding of the decision structure that the data is used for, especially how uncertainty is accounted for. It would be interesting to see this case study expanded to determine the worth of data collected at other locations on the Churchill River Diversion. For instance, if an agreement is reached with the Nelson House Band that assigns penalties to unacceptable lake levels, it may be worthwhile to add a second gauge at that location to improve reliability and avoid the risk of having no data. This analysis could help determine whether another gauge really is worthwhile. Since the level of Footprint Lake is related to flows and levels measured at other points in the diversion, the concept of data transfer would have to be considered.

The contribution of this study has been to demonstrate how the economic worth of hydrometric data used in the real-time operation of water resource projects can be determined. This is significant because of the absence of previous work on this specific topic and because of the versatility of the methods demonstrated.

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Appendix A

Questionnaire and Summary of Responses

THE UNIVERSITY OF MANITOBA

FACULTY OF ENGINEERING
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June 21, 1993

Users Name
Address

How much is hydrometric data worth to you?

Dear Users Name,

Your assistance is requested in developing a framework for assessing the worth of hydrometric data. In the face of budgetary restraint a strong connection must be made between hydrometric data and the resulting economic benefits. A review of the available literature reveals that relative measures of worth have been developed for rationalizing networks, and that the economic worth of data has been assessed in a limited way only for specific data uses. Your information or referral is needed so that a more generally applicable framework can be developed.

This research is part of an M.Sc. thesis under the direction of Donald Burn, Professor of Civil and Geological Engineering, with the support of Manitoba Hydro. Liaison with Manitoba Hydro is provided by Mr. Marc Drouin of the Reservoir and Energy Resources Department, System Operating Division.

Included are some questions regarding how you as a data user make decisions about data collection. Any information, resources, or referrals would be greatly appreciated.

Sincerely,

Tim Lock
M.Sc. Candidate, Civil Engineering, University of Manitoba

The Worth of Hydrometric Data - Questionnaire

Please mark the types of hydrometric data that you (or your organization) currently use.

( ) streamflow (continuous stage reading with rating curve)

( ) lake or reservoir stage

( ) rainfall

( ) sediment load and other water quality measures

( ) other: ______________________________

Please mark the general approaches you (or your organization) use to assess the worth of data:

( ) benefit / cost studies, or marginal benefit / cost studies

( ) error analysis (relationship between error and decision making)

( ) risk analysis (relationship between risk and accuracy or confidence level)

( ) expert systems. Please describe: ______________________________

____

( ) fuzzy logic. Please describe: ______________________________

____

( ) artificial intelligence. Please describe: ______________________________

____

( ) other: ______________________________

____

Please elaborate if possible on your current methods of assessing the worth of hydrometric data. (Space is available on the back of the questionnaire.)

ie. -How do you quantify the benefits in economic terms from each of the many uses?

-If a gauge station is to be discontinued, how do you quantify the loss in benefits?

Do you wish to be informed of the results of this research (Yes/No)?

May I contact you again regarding the information you have supplied (Yes/No)?

your name: ______________________________

your organization: ______________________________

Summary of the Eight Responses to the Questionnaire

From U.S. Army Corps of Engineers:

1. In 1992 the USACE adopted a risk analysis framework for evaluation of hydrology/hydraulics and economics in flood damage reduction studies. The respondent believed that with the use of economic risk analysis for flood damage reduction the benefits of improved data collection could be determined. (User of stage, discharge, rainfall, and wind data.)

2. "We do not assess the worth of hydrometric data. Hydrometric data are required for the operation and maintenance of authorized multi-million dollar projects until the project is de-authorized." (User of stage, discharge, rainfall, and sediment load data.)

3. "We do not assess worth. It (rainfall data) is for basic research."

4. "No rigorous approaches are used. Only rough seat of the pants benefit cost analysis." (User of stage, discharge, rainfall, sediment, and snow equivalent data.)

5. "In the Southwestern Division we operate in excess of 100 lakes. Hydrometric data we obtain for the operation is a must. No economic analyses have been attempted or required to justify." (User of streamflow, lake level, rainfall, sediment, and NEXRAD data.)

From the Utah State University Climatologist

6. Assesses worth of hydrometric data according to the number of requests for data by users, and according to data quality, and network density. (User of stage and rainfall data.)

From the U.S. National Weather Service, Hydrologic Research Laboratory:

7. Hydrometeorlogical data is used to forecast water flow in rivers, lakes, and reservoirs for flood damage reduction and for water management. Flood damage reduction can be estimated in dollars. The reduction in damages accrues as a result of lengthened forecast lead times and more accurate forecasts. Similar benefits from water supply forecasts are anticipated. (User of stage, discharge, rainfall, and sediment data.)

From the Ministry of the Environment, Government of Quebec:

8. Uses error and risk analysis to assess benefits, but no elaboration was given.

Appendix B

Apparent Change in Local Datum (in meters)
for Eight Gauges on Lake Winnipeg for the Period Jan. 1, 1991 to June 30, 1994

(Zeros indicate small datum shifts.

Values are arranged from most negative to most positive.)

Berens	George	Matheson	Mission	Gimli	Pine	Victoria	Missi
0	-0.14	-0.2	-0.41	-0.76	-0.47	-0.23	0
0	-0.13	-0.11	-0.07	-0.75	-0.13	-0.07	0
0	-0.1	-0.06	-0.05	-0.75	-0.11	-0.05	0
0.01	-0.08	-0.03	-0.04	-0.72	-0.06	-0.04	0
0.06	-0.07	-0.03	-0.03	-0.46	-0.04	0	0
	-0.07	-0.03	-0.02	-0.02	-0.04	0	0.01
	-0.04	-0.02	0	-0.02	-0.04	0	0.02
	-0.04	-0.02	0	-0.02	-0.03	0	0.04
	-0.03	-0.02	0	0	-0.03	0	0.05
	-0.03	-0.02	0	0	-0.03	0	0.06
	-0.03	-0.01	0	0	-0.02	0	0.06
	-0.03	0	0	0	0	0.01	0.06
	-0.03	0	0	0	0	0.02	0.06
	0	0	0	0	0	0.04	0.06
	0	0	0	0.03	0	0.04	0.07
	0	0	0	0.03	0	0.04	0.07
	0	0	0	0.04	0	0.04	0.07
	0	0	0.01	0.04	0.01	0.04	0.07
	0	0	0.01	0.04	0.02	0.04	0.07
	0	0	0.01	0.04	0.03	0.04	0.09
	0	0	0.01	0.05	0.03	0.04	0.12
	0	0	0.02	0.12	0.04	0.04	0.15
	0.07	0	0.03	0.14	0.16	0.04	
	0.1	0	0.03	0.23		0.04	
		0	0.03	0.23		0.04	
		0	0.03	0.31		0.04	
		0	0.03			0.04	
		0	0.03			0.04	
		0.01	0.03			0.04	
		0.06	0.08			0.04	
		0.06	0.09			0.04	
		0.06	0.09			0.04	
		0.07	0.1			0.05	
		0.07	0.13			0.05	
		0.07	0.19			0.05	
						0.05	
						0.06	
						0.06	
						0.07	
						0.1	
						0.1	
						0.11	
						0.14	
						0.14	
						0.15	
						0.33	
						0.4	

Appendix C

Length of Periods of Missing Data Record in Hours

Between 1992 and 1994

S.I.L. Village	South Bay	Opachuana	Missi Falls
63	66	63	1647
51	63	51	600
48	51	48	570
48	48	48	345
48	48	48	63
36	48	36	51
33	36	36	48
30	33	30	48
27	30	27	48
24	27	24	36
24	24	24	36
24	24	24	30
24	24	24	27
23	24	23	24
23	23	23	24
23	23	23	24
18	23	18	23
18	18	18	23
18	18	18	23
18	18	18	18
12	15	12	18
12	12	12	18
6	12	6	12
6	6	6	12
6	6	6	6
6	6	6	6
6	6	6	6
6	6	3	6
3	6	3	3
3	3	3	3
3	3	3	3
3	3	3	3
3	3	3	3
3	3	3	3
3	3	3	3
3	3	3	3
3	3	3	3
3	3	3	3
3	3	3	3
3	3	3	3
3	3	3	3

S.I.L. Village	South Bay	Opachuana	Missi Falls
3	3	3	3
3	3	3	3
3	3	3	3
3	3	3	3
3	3	3	3
3	3	3	3
3	3	3	
3	3	3	
3	3	3	
3	3	3	
3	3	3	
3	3	3	
	3	3	
	3		
	3		
	3		
	3		

Appendix D

Operational Constraints

Which Affect the Regulation of Southern Indian Lake

Southern Indian Lake Level

max. level:	847.0 ft (Interim License)	847.5 ft (93/94 Approval)
min. level:	844.0 ft (Interim License)	843.0 ft (93/94 Approval)
max. 12 mo.drawdn:	2.0 ft (Interim License)	4.5 ft (93/94 Approval)

Notigi Forebay Level

min. level:	838.0 ft (Interim License)	834.0 ft (93/94 Approval)

Notigi Maximum Flows

30,000 cfs average weekly flow	(Interim License)
35,000 cfs average weekly flow	(May 16, 1993 - Oct. 31, 1993 Approval)
34,000 cfs average weekly flow	(Nov. 1, 1993 - May 15, 1994 Approval)

Missi Falls Minimum Flows

500 cfs minimum during open water period (Interim License)

1500 cfs minimum during ice cover period (Interim License)

Footprint Lake Level at Nelson House

max. level:

800.0 ft before construction of any dam (Northern Flood Agreement)

802.0 ft during and after construction of a dam (Northern Flood Agreement)

800.0 ft (1994 Proposal)

min. level:

791.5 ft (1994 Proposal)

max. rate of change of level:

Winter (Nov.1 to March 31):

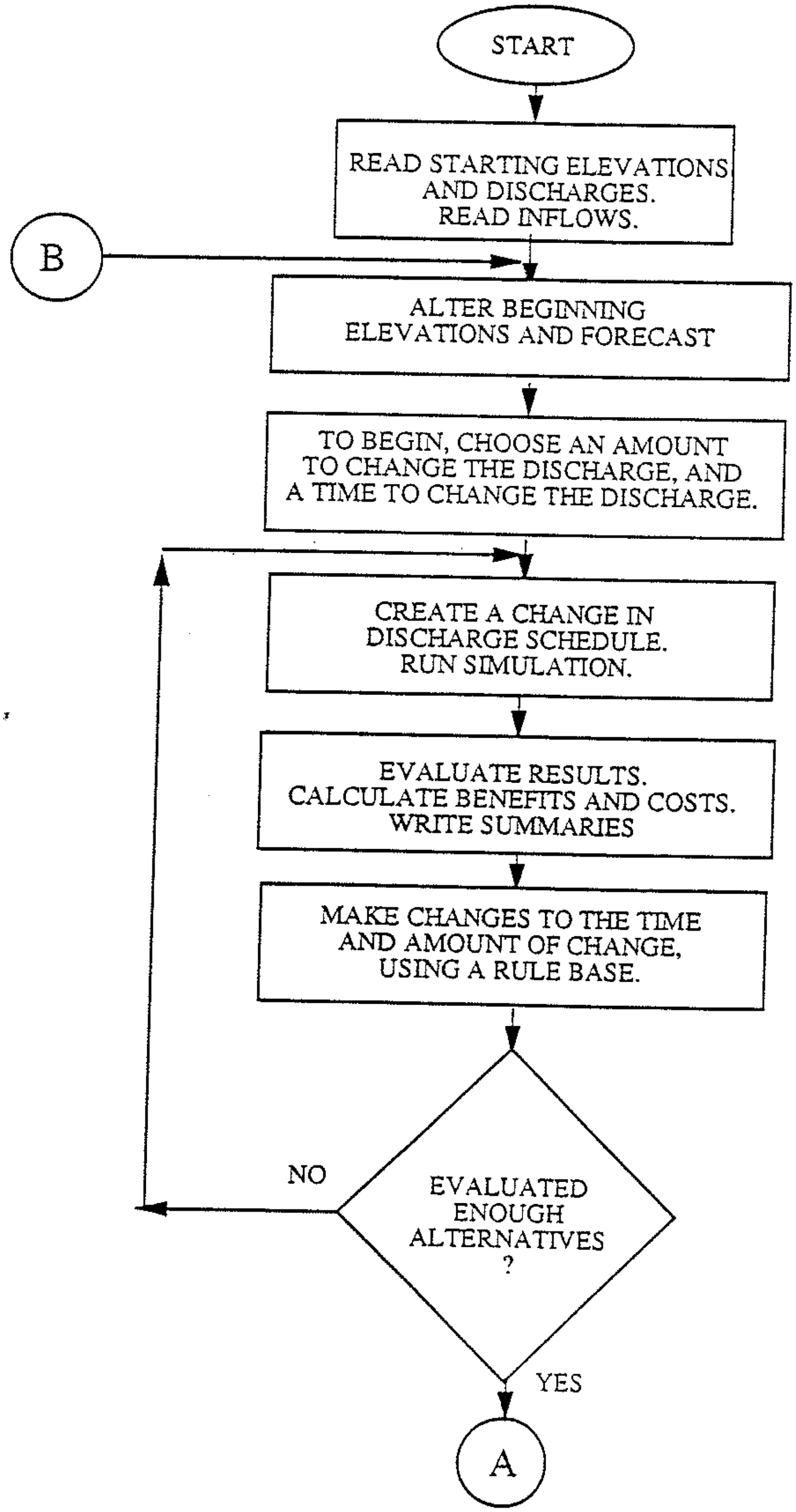
	Increase:	Decrease:
Weekly:	0.7 ft	1.0 ft
Monthly:	2.3 ft	3.0 ft

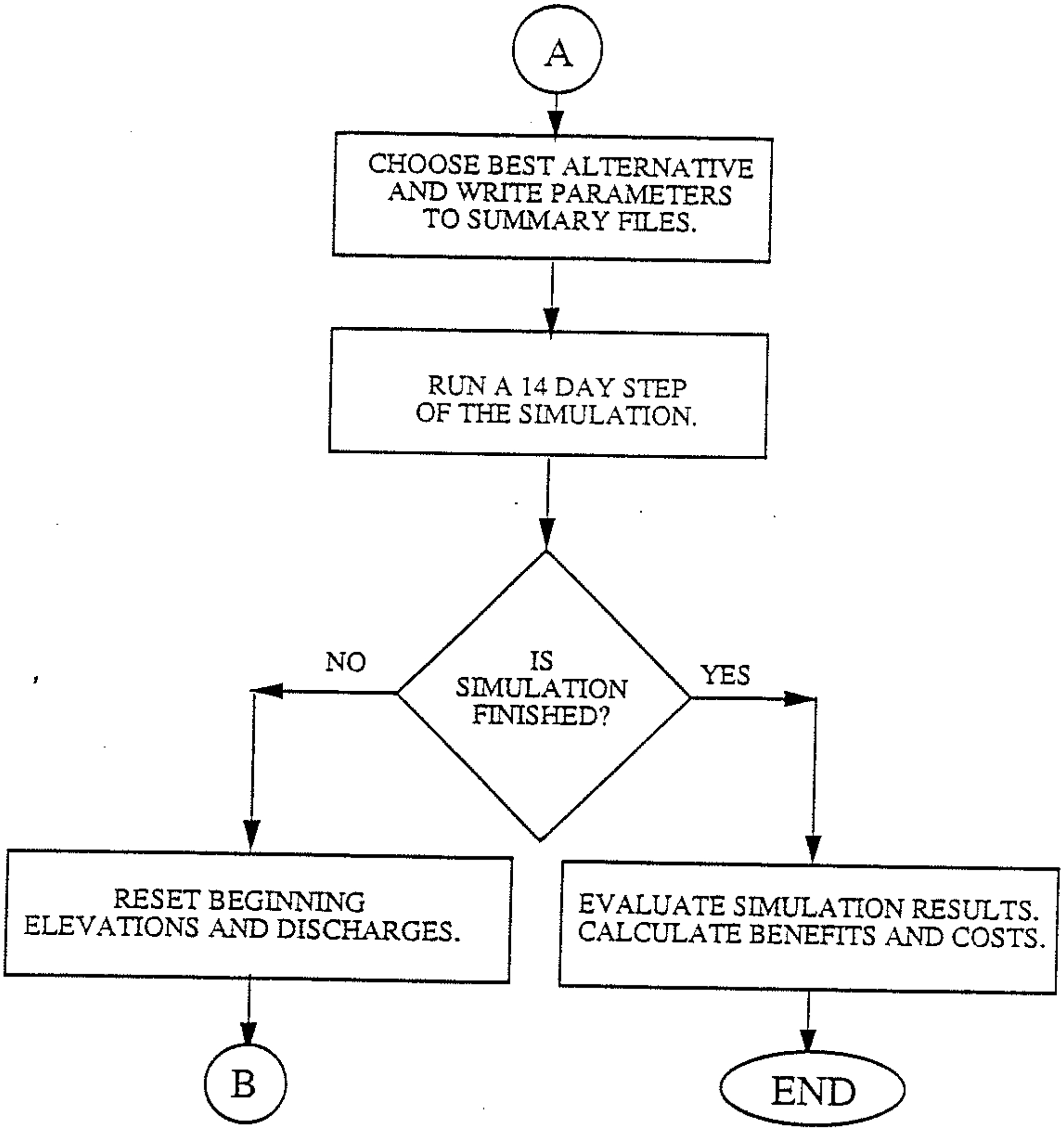
Summer (April 1 to October 31)

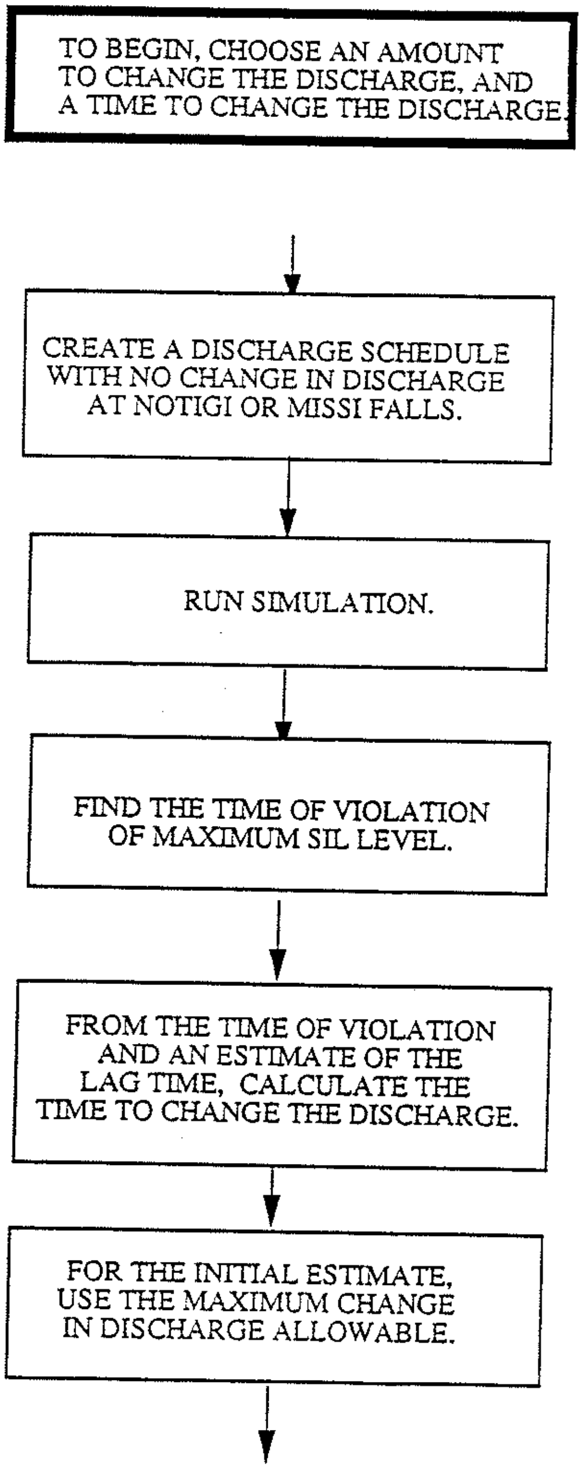
	Increase:	Decrease:
Weekly:	1.8 ft	1.4 ft
Monthly:	4.8 ft	4.6 ft

Appendix E

Flowchart of Hydraulic and Regulation Simulation Program


START
READ STARTING ELEVATIONS AND DISCHARGES. READ INFLOWS.
B
ALTER BEGINNING ELEVATIONS AND FORECAST
TO BEGIN, CHOOSE AN AMOUNT TO CHANGE THE DISCHARGE, AND A TIME TO CHANGE THE DISCHARGE.
CREATE A CHANGE IN DISCHARGE SCHEDULE. RUN SIMULATION.
EVALUATE RESULTS. CALCULATE BENEFITS AND COSTS. WRITE SUMMARIES
MAKE CHANGES TO THE TIME AND AMOUNT OF CHANGE, USING A RULE BASE.
EVALUATED ENOUGH ALTERNATIVES ?
NO
YES
A


A
CHOOSE BEST ALTERNATIVE AND WRITE PARAMETERS TO SUMMARY FILES.
RUN A 14 DAY STEP OF THE SIMULATION.
IS SIMULATION FINISHED?
NO
YES
RESET BEGINNING ELEVATIONS AND DISCHARGES.
EVALUATE SIMULATION RESULTS. CALCULATE BENEFITS AND COSTS.
B
END


TO BEGIN, CHOOSE AN AMOUNT TO CHANGE THE DISCHARGE, AND A TIME TO CHANGE THE DISCHARGE.
CREATE A DISCHARGE SCHEDULE WITH NO CHANGE IN DISCHARGE AT NOTIGI OR MISSI FALLS.
RUN SIMULATION.
FIND THE TIME OF VIOLATION OF MAXIMUM SIL LEVEL.
FROM THE TIME OF VIOLATION AND AN ESTIMATE OF THE LAG TIME, CALCULATE THE TIME TO CHANGE THE DISCHARGE.
FOR THE INITIAL ESTIMATE, USE THE MAXIMUM CHANGE IN DISCHARGE ALLOWABLE.

Appendix F

Calculations for Marginal Benefit-Cost Ratios for the Existing Network

Summarized in Table 15

Economic Evaluation of Discontinuing One or Two Lake Level Gauges on Southern Indian Lake

by Tim Lock

Feb. 11, 1995

Gauges:
1 S.I.L. Village
2 South Bay
3 Missi Falls
4 Opachuana

Accuracy: 2.576 x Std. Dev.
Worth: 1000000 /ft /year

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
<u>Base Case:</u>							
1,2,3,4	0	0.02579	0.066	0.000	$0		$0
<u>Possible Cases:</u>							
1,2,3	0.02117	0.02909	0.075	-0.009	-$8,501	-$180	
2,3,4	0.02152	0.02590	0.067	0.000	-$283	-$6	
1,2,4	0.15565	0.03805	0.098	-0.032	-$31,582	-$4,916	
1,3,4	0.02365	0.02842	0.073	-0.007	-$6,775	-$160	
1,2	0.00329	0.03959	0.102	-0.036	-$35,549	-$117	
1,3	0.00050	0.03790	0.098	-0.031	-$31,195	-$16	
1,4	0.00368	0.04321	0.111	-0.045	-$44,874	-$165	
2,3	0.00046	0.03373	0.087	-0.020	-$20,453	-$9	
2,4	0.00335	0.04282	0.110	-0.044	-$43,869	-$147	
3,4	0.00051	0.03396	0.087	-0.021	-$21,046	-$11	
1	0.00008	0.04700	0.121	-0.055	-$54,637	-$4	
2	0.00007	0.04600	0.118	-0.052	-$52,061	-$4	
3	0.00001	0.06800	0.175	-0.109	-$108,733	-$1	
4	0.00008	0.06100	0.157	-0.091	-$90,701	-$7	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$5,743	

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
<u>Changed Network:</u>							
1,2,3	1.00000	0.02909	0.075	-0.009	-$8,501		-$8,501
<u>Possible Cases:</u>							
1,2	0.15565	0.03959	0.102	-0.027	-$27,048	-$4,210	
1,3	0.02365	0.03790	0.098	-0.023	-$22,695	-$537	
2,3	0.02152	0.03373	0.087	-0.012	-$11,953	-$257	
1	0.00368	0.04700	0.121	-0.046	-$46,136	-$170	
2	0.00335	0.04600	0.118	-0.044	-$43,560	-$146	
3	0.00051	0.06800	0.175	-0.100	-$100,232	-$51	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$5,371	-$5,371
			Less Reliability Risk of Base Case:				$5,743
					Total:		-$8,128

Note: The words "reliability risk" should be replaced with the words "reliability cost" each time they occur.

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
2,3,4	1.00000	0.02590	0.067	0.000	-$283		-$283
Possible Cases:							
2,3	0.02117	0.03373	0.087	-0.020	-$20,170	-$427	
2,4	0.15565	0.04282	0.110	-0.044	-$43,586	-$6,784	
3,4	0.02365	0.03396	0.087	-0.021	-$20,763	-$491	
2	0.00329	0.04600	0.118	-0.052	-$51,778	-$171	
3	0.00050	0.06800	0.175	-0.108	-$108,450	-$54	
4	0.00368	0.06100	0.157	-0.090	-$90,418	-$333	
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						-$8,260	-$8,260
Less Reliability Risk of Base Case:							$5,743
Total:							-$2,800
Changed Network:							
1,2,4	1.00000	0.03805	0.098	-0.032	-$31,582		-$31,582
Possible Cases:							
1,2	0.02117	0.03959	0.102	-0.004	-$3,967	-$84	
1,4	0.02365	0.04321	0.111	-0.013	-$13,292	-$314	
2,4	0.02152	0.04282	0.110	-0.012	-$12,288	-$264	
1	0.00050	0.04700	0.121	-0.023	-$23,055	-$12	
2	0.00046	0.04600	0.118	-0.020	-$20,479	-$9	
4	0.00051	0.06100	0.157	-0.059	-$59,119	-$30	
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						-$714	-$714
Less Reliability Risk of Base Case:							$5,743
Total:							-$26,552
Changed Network:							
1,3,4	1.00000	0.02842	0.073	-0.007	-$6,775	-$6,775	-$6,775
Possible Cases:							
1,3	0.02117	0.03790	0.098	-0.024	-$24,420	-$517	
1,4	0.15565	0.04321	0.111	-0.038	-$38,099	-$5,930	
3,4	0.02152	0.03396	0.087	-0.014	-$14,271	-$307	
1	0.00329	0.04700	0.121	-0.048	-$47,862	-$158	
3	0.00046	0.06800	0.175	-0.102	-$101,958	-$46	
4	0.00335	0.06100	0.157	-0.084	-$83,926	-$281	
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						-$7,239	-$7,239
Less Reliability Risk of Base Case:							$5,743
Total:							-$8,271

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,2	1.00000	0.03959	0.102	-0.036	-$35,549		-$35,549
Possible Cases:							
1	0.02365	0.04700	0.121	-0.019	-$19,088	-$451	
2	0.02152	0.04600	0.118	-0.017	-$16,512	-$355	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$807	-$807
					Less Reliability Risk of Base Case:		$5,743
					Total:		-$30,612
Changed Network:							
1,3	1.00000	0.03790	0.098	-0.031	-$31,195		-$31,195
Possible Cases:							
1	0.15565	0.04700	0.121	-0.023	-$23,442	-$3,649	
3	0.02152	0.06800	0.175	-0.078	-$77,538	-$1,669	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$5,317	-$5,317
					Less Reliability Risk of Base Case:		$5,743
					Total:		-$30,769
Changed Network:							
1,4	1.00000	0.04321	0.111	-0.045	-$44,874		-$44,874
Possible Cases:							
1	0.02117	0.04700	0.121	-0.010	-$9,763	-$207	
4	0.02152	0.06100	0.157	-0.046	-$45,827	-$986	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$1,193	-$1,193
					Less Reliability Risk of Base Case:		$5,743
					Total:		-$40,324

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
<u>Changed Network:</u>							
2,3	1.00000	0.03373	0.087	-0.020	-$20,453		-$20,453
<u>Possible Cases:</u>							
2	0.15565	0.04600	0.118	-0.032	-$31,608	-$4,920	
3	0.02365	0.06800	0.175	-0.088	-$88,280	-$2,088	
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						-$7,008	-$7,008
Less Reliability Risk of Base Case:							$5,743
Total:							-$21,718
<u>Changed Network:</u>							
2,4	1.00000	0.04282	0.110	-0.044	-$43,869		-$43,869
<u>Possible Cases:</u>							
2	0.02117	0.04600	0.118	-0.008	-$8,192	-$173	
4	0.02365	0.06100	0.157	-0.047	-$46,832	-$1,108	
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						-$1,281	-$1,281
Less Reliability Risk of Base Case:							$5,743
Total:							-$39,407
<u>Changed Network:</u>							
3,4	1.00000	0.03396	0.087	-0.021	-$21,046		-$21,046
<u>Possible Cases:</u>							
3	0.02117	0.06800	0.175	-0.088	-$87,687	-$1,856	
4	0.15565	0.06100	0.157	-0.070	-$69,655	-$10,842	
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						-$12,698	-$12,698
Less Reliability Risk of Base Case:							$5,743
Total:							-$28,001

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
<u>Changed Network:</u>							
1	1.00000	0.04700	0.121	-0.055	-$54,637		-$54,637
<u>Possible Cases:</u>							
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				$0	$0
			Less Reliability Risk of Base Case:				$5,743
					Total:		-$48,894
<u>Changed Network:</u>							
2	1.00000	0.04600	0.118	-0.052	-$52,061		-$52,061
<u>Possible Cases:</u>							
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				$0	$0
			Less Reliability Risk of Base Case:				$5,743
					Total:		-$46,318
<u>Changed Network:</u>							
3	1.00000	0.06800	0.175	-0.109	-$108,733		-$108,733
<u>Possible Cases:</u>							
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				$0	$0
			Less Reliability Risk of Base Case:				$5,743
					Total:		-$102,990
<u>Changed Network:</u>							
4	1.00000	0.06100	0.157	-0.091	-$90,701		-$90,701
<u>Possible Cases:</u>							
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				$0	$0
			Less Reliability Risk of Base Case:				$5,743
					Total:		-$84,958

Marginal Benefit /Cost Ratio of Discontinuing Gauges on Southern Indian Lake

Gauges Discontinued:	Benefit (1) ($/year)	Benefit (2) ($/year)	Cost ($/year)	B/C Ratio (1)	B/C Ratio (2)
S.I.L. Village	$2,950	$5,900	$2,800	1.05	2.11
South Bay	$0	$5,900	$8,271	0.00	0.71
Missi Falls	$5,900	$5,900	$26,552	0.22	0.22
Opachuana	$5,900	$5,900	$8,128	0.73	0.73
S.I.L. Village and South Bay	$2,950	$11,800	$28,001	0.11	0.42
S.I.L. Village and Missi Falls	$8,850	$11,800	$39,407	0.22	0.30
S.I.L. Village and Opachuana	$8,850	$11,800	$21,718	0.41	0.54
South Bay and Missi Falls	$5,900	$11,800	$40,324	0.15	0.29
South Bay and Opachuana	$5,900	$11,800	$30,769	0.19	0.38
Missi Falls and Opachuana	$11,800	$11,800	$30,612	0.39	0.39
S.I.L. Village, South Bay, Missi Falls	$8,850	$17,700	$84,958	0.10	0.21
South Bay, Missi Falls, Opachuana	$11,800	$17,700	$48,894	0.24	0.36
S.I.L. Village, South Bay, Opachuana	$8,850	$17,700	$102,990	0.09	0.17
S.I.L. Village, Missi Falls, Opachuana	$14,750	$17,700	$46,318	0.32	0.38

Note: The benefit of discontinuing a gauge is the reduction in operating cost of that gauge.
The cost of discontinuing a gauge is the economic impact it has.
Case (1) is under current operating cost sharing agreements.
Case (2) is if the total operating cost was born by Manitoba Hydro.

Note: Probability is the probability of gauge failure of the gauge or gauges (probabilities are multiplied for more than one gauge)

1	S.I.L. Village	0.02152
2	South Bay	0.023653
3	Missi Falls	0.155648
4	Opachuana	0.021168

Appendix G

Calculations for Marginal Benefit-Cost Ratios After Repairing the Gauge at Missi Falls

Summarized in Table 18

Economic Evaluation
of Discontinuing One or More Lake Level Gauges
on Southern Indian Lake
After Repairing the Gauge at Missi Falls

by Tim Lock

Feb. 11, 1995

Gauges:				
1	S.I.L. Village	Accuracy:	2.576	x Std. Dev.
2	South Bay	Worth:	1000000	/ft /year
3	Missi Falls			
4	Opachuana			

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Base Case:							
1,2,3,4	0	0.02579	0.066	0.000	$0		$0
Possible Cases:							
1,2,3	0.02117	0.02909	0.075	-0.009	-$8,501	-$180	
2,3,4	0.02152	0.02590	0.067	0.000	-$283	-$6	
1,2,4	0.02200	0.03805	0.098	-0.032	-$31,582	-$695	
1,3,4	0.02365	0.02842	0.073	-0.007	-$6,775	-$160	
1,2	0.00047	0.03959	0.102	-0.036	-$35,549	-$17	
1,3	0.00050	0.03790	0.098	-0.031	-$31,195	-$16	
1,4	0.00052	0.04321	0.111	-0.045	-$44,874	-$23	
2,3	0.00046	0.03373	0.087	-0.020	-$20,453	-$9	
2,4	0.00047	0.04282	0.110	-0.044	-$43,869	-$21	
3,4	0.00051	0.03396	0.087	-0.021	-$21,046	-$11	
1	0.00001	0.04700	0.121	-0.055	-$54,637	-$1	
2	0.00001	0.04600	0.118	-0.052	-$52,061	-$1	
3	0.00001	0.06800	0.175	-0.109	-$108,733	-$1	
4	0.00001	0.06100	0.157	-0.091	-$90,701	-$1	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$1,141	

Changed Network:							
1,2,3	1.00000	0.02909	0.075	-0.009	-$8,501		-$8,501
Possible Cases:							
1,2	0.02200	0.03959	0.102	-0.027	-$27,048	-$595	
1,3	0.02365	0.03790	0.098	-0.023	-$22,695	-$537	
2,3	0.02152	0.03373	0.087	-0.012	-$11,953	-$257	
1	0.00052	0.04700	0.121	-0.046	-$46,136	-$24	
2	0.00047	0.04600	0.118	-0.044	-$43,560	-$21	
3	0.00051	0.06800	0.175	-0.100	-$100,232	-$51	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$1,485	-$1,485
					Less Reliability Risk of Base Case:		$1,141
					Total:		-$8,845

Note: The words "reliability risk" should be replaced with the words "reliability cost" each time they occur.

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
<u>Changed Network:</u>							
2,3,4	1.00000	0.02590	0.067	0.000	-$283		-$283
<u>Possible Cases:</u>							
2,3	0.02117	0.03373	0.087	-0.020	-$20,170	-$427	
2,4	0.02200	0.04282	0.110	-0.044	-$43,586	-$959	
3,4	0.02365	0.03396	0.087	-0.021	-$20,763	-$491	
2	0.00047	0.04600	0.118	-0.052	-$51,778	-$24	
3	0.00050	0.06800	0.175	-0.108	-$108,450	-$54	
4	0.00052	0.06100	0.157	-0.090	-$90,418	-$47	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$2,002	-$2,002
					Less Reliability Risk of Base Case:		$1,141
					Total:		-$1,145
<u>Changed Network:</u>							
1,2,4	1.00000	0.03805	0.098	-0.032	-$31,582		-$31,582
<u>Possible Cases:</u>							
1,2	0.02117	0.03959	0.102	-0.004	-$3,967	-$84	
1,4	0.02365	0.04321	0.111	-0.013	-$13,292	-$314	
2,4	0.02152	0.04282	0.110	-0.012	-$12,288	-$264	
1	0.00050	0.04700	0.121	-0.023	-$23,055	-$12	
2	0.00046	0.04600	0.118	-0.020	-$20,479	-$9	
4	0.00051	0.06100	0.157	-0.059	-$59,119	-$30	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$714	-$714
					Less Reliability Risk of Base Case:		$1,141
					Total:		-$31,155
<u>Changed Network:</u>							
1,3,4	1.00000	0.02842	0.073	-0.007	-$6,775	-$6,775	-$6,775
<u>Possible Cases:</u>							
1,3	0.02117	0.03790	0.098	-0.024	-$24,420	-$517	
1,4	0.02200	0.04321	0.111	-0.038	-$38,099	-$838	
3,4	0.02152	0.03396	0.087	-0.014	-$14,271	-$307	
1	0.00047	0.04700	0.121	-0.048	-$47,862	-$22	
3	0.00046	0.06800	0.175	-0.102	-$101,958	-$46	
4	0.00047	0.06100	0.157	-0.084	-$83,926	-$40	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$1,771	-$1,771
					Less Reliability Risk of Base Case:		$1,141
					Total:		-$7,405

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,2	1.00000	0.03959	0.102	-0.036	-$35,549		-$35,549
Possible Cases:							
1	0.02365	0.04700	0.121	-0.019	-$19,088	-$451	
2	0.02152	0.04600	0.118	-0.017	-$16,512	-$355	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$807	-$807
					Less Reliability Risk of Base Case:		$1,141
					Total:		-$35,215
Changed Network:							
1,3	1.00000	0.03790	0.098	-0.031	-$31,195		-$31,195
Possible Cases:							
1	0.02200	0.04700	0.121	-0.023	-$23,442	-$516	
3	0.02152	0.06800	0.175	-0.078	-$77,538	-$1,669	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$2,184	-$2,184
					Less Reliability Risk of Base Case:		$1,141
					Total:		-$32,239
Changed Network:							
1,4	1.00000	0.04321	0.111	-0.045	-$44,874		-$44,874
Possible Cases:							
1	0.02117	0.04700	0.121	-0.010	-$9,763	-$207	
4	0.02152	0.06100	0.157	-0.046	-$45,827	-$986	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$1,193	-$1,193
					Less Reliability Risk of Base Case:		$1,141
					Total:		-$44,926

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
<u>Changed Network:</u>							
2,3	1.00000	0.03373	0.087	-0.020	-$20,453		-$20,453
<u>Possible Cases:</u>							
2	0.02200	0.04600	0.118	-0.032	-$31,608	-$695	
3	0.02365	0.06800	0.175	-0.088	-$88,280	-$2,088	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$2,783	-$2,783
			Less Reliability Risk of Base Case:				$1,141
					Total:		-$22,096
<u>Changed Network:</u>							
2,4	1.00000	0.04282	0.110	-0.044	-$43,869		-$43,869
<u>Possible Cases:</u>							
2	0.02117	0.04600	0.118	-0.008	-$8,192	-$173	
4	0.02365	0.06100	0.157	-0.047	-$46,832	-$1,108	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,281	-$1,281
			Less Reliability Risk of Base Case:				$1,141
					Total:		-$44,010
<u>Changed Network:</u>							
3,4	1.00000	0.03396	0.087	-0.021	-$21,046		-$21,046
<u>Possible Cases:</u>							
3	0.02117	0.06800	0.175	-0.088	-$87,687	-$1,856	
4	0.02200	0.06100	0.157	-0.070	-$69,655	-$1,532	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$3,389	-$3,389
			Less Reliability Risk of Base Case:				$1,141
					Total:		-$23,294

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1	1.00000	0.04700	0.121	-0.055	-$54,637		-$54,637
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						$0	$0
Less Reliability Risk of Base Case:							$1,141
Total:							-$53,496
Changed Network:							
2	1.00000	0.04600	0.118	-0.052	-$52,061		-$52,061
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						$0	$0
Less Reliability Risk of Base Case:							$1,141
Total:							-$50,920
Changed Network:							
3	1.00000	0.06800	0.175	-0.109	-$108,733		-$108,733
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						$0	$0
Less Reliability Risk of Base Case:							$1,141
Total:							-$107,592
Changed Network:							
4	1.00000	0.06100	0.157	-0.091	-$90,701		-$90,701
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						$0	$0
Less Reliability Risk of Base Case:							$1,141
Total:							-$89,560

Marginal Benefit /Cost Ratio of Discontinuing Gauges on Southern Indian Lake

Gauges Discontinued:	Benefit (1) ($/year)	Benefit (2) ($/year)	Cost ($/year)	B/C Ratio (1)	B/C Ratio (2)
S.I.L. Village	$2,950	$5,900	$1,145	2.58	5.15
South Bay	$0	$5,900	$7,405	0.00	0.80
Missi Falls	$5,900	$5,900	$31,155	0.19	0.19
Opachuana	$5,900	$5,900	$8,845	0.67	0.67
S.I.L. Village and South Bay	$2,950	$11,800	$23,294	0.13	0.51
S.I.L. Village and Missi Falls	$8,850	$11,800	$44,010	0.20	0.27
S.I.L. Village and Opachuana	$8,850	$11,800	$22,096	0.40	0.53
South Bay and Missi Falls	$5,900	$11,800	$44,926	0.13	0.26
South Bay and Opachuana	$5,900	$11,800	$32,239	0.18	0.37
Missi Falls and Opachuana	$11,800	$11,800	$35,215	0.34	0.34
S.I.L. Village, South Bay, Missi Falls	$8,850	$17,700	$89,560	0.10	0.20
South Bay, Missi Falls, Opachuana	$11,800	$17,700	$53,496	0.22	0.33
S.I.L. Village, South Bay, Opachuana	$8,850	$17,700	$107,592	0.08	0.16
S.I.L. Village, Missi Falls, Opachuana	$14,750	$17,700	$50,920	0.29	0.35

Note: The benefit of discontinuing a gauge is the reduction in operating cost of that gauge.
The cost of discontinuing a gauge is the economic impact it has.
Case (1) is under current operating cost sharing agreements.
Case (2) is if the total operating cost was born by Manitoba Hydro.

Note: Probability is the probability of gauge failure of the gauge or gauges (probabilities are multiplied for more than one gauge)

1	S.I.L. Village	0.02152	
2	South Bay	0.023653	
3	Missi Falls	0.022	Repaired Gauge
4	Opachuana	0.021168	

Appendix H

Calculations for Marginal Benefit-Cost Ratios After Adding a Fifth Gauge

Summarized in Table 19

Economic Evaluation
of Discontinuing Lake Level Gauges on Southern Indian Lake After Adding a Fifth Gauge (Missi Falls Gauge not repaired)

by Tim Lock

Mar. 12, 1995

Gauges:		
	1	S.I.L. Village
	2	South Bay
	3	Missi Falls
	4	Opachuana
	5	North End

Accuracy: 2.576 x Std. Dev.
Worth: 1000000 /ft /year

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Base Case:							
1,2,3,4,5	0	0.02314	0.060	0	0		0
Possible Cases:							
1,2,3,4	0.02200	0.02579	0.066	-0.007	-$6,826	-$150	
2,3,4,5	0.02152	0.02427	0.063	-0.003	-$2,911	-$63	
1,3,4,5	0.02365	0.02691	0.069	-0.010	-$9,712	-$230	
1,2,4,5	0.15565	0.02800	0.072	-0.013	-$12,519	-$1,949	
1,2,3,5	0.02117	0.02880	0.074	-0.015	-$14,580	-$309	
1,2,3	0.00047	0.02909	0.075	-0.015	-$15,327	-$7	
2,3,4	0.00047	0.02590	0.067	-0.007	-$7,110	-$3	
1,2,4	0.00342	0.03805	0.098	-0.038	-$38,408	-$132	
1,3,4	0.00052	0.02842	0.073	-0.014	-$13,601	-$7	
1,2,5	0.00329	0.03107	0.080	-0.020	-$20,428	-$67	
1,3,5	0.00050	0.03795	0.098	-0.038	-$38,151	-$19	
1,4,5	0.00368	0.03081	0.079	-0.020	-$19,758	-$73	
2,3,5	0.00046	0.03471	0.089	-0.030	-$29,804	-$14	
2,4,5	0.00335	0.02884	0.074	-0.015	-$14,683	-$49	
3,4,5	0.00051	0.03260	0.084	-0.024	-$24,369	-$12	
1,2	0.00007	0.03590	0.092	-0.033	-$32,870	-$2	
1,3	0.00001	0.03790	0.098	-0.038	-$38,022	$0	
1,4	0.00008	0.04321	0.111	-0.052	-$51,700	-$4	
2,3	0.00001	0.03373	0.087	-0.027	-$27,280	$0	
2,4	0.00007	0.04282	0.110	-0.051	-$50,696	-$4	
3,4	0.00001	0.03396	0.087	-0.028	-$27,872	$0	
1,5	7.79E-05	0.03934	0.101	-0.042	-$41,731	-$3	
2,5	7.09E-05	0.03596	0.093	-0.033	-$33,024	-$2	
3,5	1.08E-05	0.05586	0.144	-0.084	-$84,287	-$1	
4,5	7.92E-05	0.03687	0.095	-0.035	-$35,368	-$3	
1	1.71E-06	0.04700	0.121	-0.061	-$61,463	$0	
2	1.56E-06	0.04600	0.118	-0.059	-$58,887	$0	
3	2.37E-07	0.06800	0.175	-0.116	-$115,559	$0	
4	1.74E-06	0.06100	0.157	-0.098	-$97,527	$0	
5	1.68E-06	0.06800	0.175	-0.116	-$115,559	$0	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$3,104	

Note: The words "reliability risk" should be replaced with the words "reliability cost" each time they occur.

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,2,3,4	1	0.02579	0.066	-0.007	-$6,826		-$6,826
Possible Cases:							
1,2,3	0.02117	0.02909	0.075	-0.009	-$8,501	-$180	
2,3,4	0.02152	0.02590	0.067	0.000	-$283	-$6	
1,2,4	0.15565	0.03805	0.098	-0.032	-$31,582	-$4,916	
1,3,4	0.02365	0.02842	0.073	-0.007	-$6,775	-$160	
1,2	0.00329	0.03959	0.102	-0.036	-$35,549	-$117	
1,3	0.00050	0.03790	0.098	-0.031	-$31,195	-$16	
1,4	0.00368	0.04321	0.111	-0.045	-$44,874	-$165	
2,3	0.00046	0.03373	0.087	-0.020	-$20,453	-$9	
2,4	0.00335	0.04282	0.110	-0.044	-$43,869	-$147	
3,4	0.00051	0.03396	0.087	-0.021	-$21,046	-$11	
1	0.00008	0.04700	0.121	-0.055	-$54,637	-$4	
2	0.00007	0.04600	0.118	-0.052	-$52,061	-$4	
3	0.00001	0.06800	0.175	-0.109	-$108,733	-$1	
4	0.00008	0.06100	0.157	-0.091	-$90,701	-$7	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$5,743	-$5,743
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$9,465
Changed Network:							
2,3,4,5	1	0.02427	0.063	-0.003	-$2,911		-$2,911
Possible Cases:							
2,3,4	0.02200	0.02590	0.067	-0.004	-$4,199	-$92	
2,3,5	0.02117	0.03471	0.089	-0.027	-$26,893	-$569	
2,4,5	0.15565	0.02884	0.074	-0.012	-$11,772	-$1,832	
3,4,5	0.02365	0.03260	0.084	-0.021	-$21,458	-$508	
2,3	0.00047	0.03373	0.087	-0.024	-$24,369	-$11	
2,4	0.00342	0.04282	0.110	-0.048	-$47,785	-$164	
3,4	0.00052	0.03396	0.087	-0.025	-$24,961	-$13	
2,5	0.003295	0.03596	0.093	-0.030	-$30,113	-$99	
3,5	0.000501	0.05586	0.144	-0.081	-$81,376	-$41	
4,5	0.003682	0.03687	0.095	-0.032	-$32,458	-$119	
2	7.25E-05	0.04600	0.118	-0.056	-$55,976	-$4	
3	1.1E-05	0.06800	0.175	-0.113	-$112,648	-$1	
4	8.1E-05	0.06100	0.157	-0.095	-$94,616	-$8	
5	7.79E-05	0.06800	0.175	-0.113	-$112,648	-$9	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$3,471	-$3,471
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$3,277

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,3,4,5	1	0.02691	0.069	-0.010	-$9,712		-$9,712
Possible Cases:							
1,3,4	0.02200	0.02842	0.073	-0.004	-$3,890	-$86	
1,3,5	0.02117	0.03795	0.098	-0.028	-$28,439	-$602	
1,4,5	0.15565	0.03081	0.079	-0.010	-$10,046	-$1,564	
3,4,5	0.02152	0.03260	0.084	-0.015	-$14,657	-$315	
1,3	0.00047	0.03790	0.098	-0.028	-$28,310	-$13	
1,4	0.00342	0.04321	0.111	-0.042	-$41,989	-$144	
3,4	0.00047	0.03396	0.087	-0.018	-$18,161	-$9	
1,5	0.003295	0.03934	0.101	-0.032	-$32,020	-$105	
3,5	0.000456	0.05586	0.144	-0.075	-$74,575	-$34	
4,5	0.00335	0.03687	0.095	-0.026	-$25,657	-$86	
1	7.25E-05	0.04700	0.121	-0.052	-$51,752	-$4	
3	1E-05	0.06800	0.175	-0.106	-$105,848	-$1	
4	7.37E-05	0.06100	0.157	-0.088	-$87,816	-$6	
5	7.09E-05	0.06800	0.175	-0.106	-$105,848	-$8	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$2,976	-$2,976
			Less Reliability Risk of Base Case:				$3,104
					Total:		-$9,584
Changed Network:							
1,2,4,5,	1	0.028	0.072	-0.013	-$12,519		-$12,519
Possible Cases:							
1,2,4	0.02200	0.03805	0.098	-0.026	-$25,889	-$570	
1,2,5	0.02117	0.03107	0.080	-0.008	-$7,908	-$167	
1,4,5	0.02365	0.03081	0.079	-0.007	-$7,239	-$171	
2,4,5	0.02152	0.02884	0.074	-0.002	-$2,164	-$47	
1,2	0.00047	0.03590	0.092	-0.020	-$20,350	-$9	
1,4	0.00052	0.04321	0.111	-0.039	-$39,181	-$20	
2,4	0.00047	0.04282	0.110	-0.038	-$38,176	-$18	
1,5	0.000501	0.03934	0.101	-0.029	-$29,212	-$15	
2,5	0.000456	0.03596	0.093	-0.021	-$20,505	-$9	
4,5	0.000509	0.03687	0.095	-0.023	-$22,849	-$12	
1	1.1E-05	0.04700	0.121	-0.049	-$48,944	-$1	
2	1E-05	0.04600	0.118	-0.046	-$46,368	$0	
4	1.12E-05	0.06100	0.157	-0.085	-$85,008	-$1	
5	1.08E-05	0.06800	0.175	-0.103	-$103,040	-$1	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,041	-$1,041
			Less Reliability Risk of Base Case:				$3,104
					Total:		-$10,456

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,2,3,5	1	0.0288	0.074	-0.015	-$14,580		-$14,580
Possible Cases:							
1,2,3	0.02200	0.02909	0.075	-0.001	-$747	-$16	
1,2,5	0.15565	0.03107	0.080	-0.006	-$5,848	-$910	
1,3,5	0.02365	0.03795	0.098	-0.024	-$23,570	-$558	
2,3,5	0.02152	0.03471	0.089	-0.015	-$15,224	-$328	
1,2	0.00342	0.03590	0.092	-0.018	-$18,290	-$63	
1,3	0.00052	0.03790	0.098	-0.023	-$23,442	-$12	
2,3	0.00047	0.03373	0.087	-0.013	-$12,700	-$6	
1,5	0.003682	0.03934	0.101	-0.027	-$27,151	-$100	
2,5	0.00335	0.03596	0.093	-0.018	-$18,444	-$62	
3,5	0.000509	0.05586	0.144	-0.070	-$69,707	-$35	
1	8.1E-05	0.04700	0.121	-0.047	-$46,883	-$4	
2	7.37E-05	0.04600	0.118	-0.044	-$44,307	-$3	
3	1.12E-05	0.06800	0.175	-0.101	-$100,979	-$1	
5	7.92E-05	0.06800	0.175	-0.101	-$100,979	-$8	
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						-$2,106	-$2,106
Less Reliability Risk of Base Case:							$3,104
Total:							-$13,582
Changed Network:							
1,2,3	1.00000	0.02909	0.075	-0.015	-$15,327		-$15,327
Possible Cases:							
1,2	0.15565	0.03959	0.102	-0.027	-$27,048	-$4,210	
1,3	0.02365	0.03790	0.098	-0.023	-$22,695	-$537	
2,3	0.02152	0.03373	0.087	-0.012	-$11,953	-$257	
1	0.00368	0.04700	0.121	-0.046	-$46,136	-$170	
2	0.00335	0.04600	0.118	-0.044	-$43,560	-$146	
3	0.00051	0.06800	0.175	-0.100	-$100,232	-$51	
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						-$5,371	-$5,371
Less Reliability Risk of Base Case:							$5,743
Total:							-$14,955
Changed Network:							
2,3,4	1.00000	0.02590	0.067	-0.007	-$7,110		-$7,110
Possible Cases:							
2,3	0.02117	0.03373	0.087	-0.020	-$20,170	-$427	
2,4	0.15565	0.04282	0.110	-0.044	-$43,586	-$6,784	
3,4	0.02365	0.03396	0.087	-0.021	-$20,763	-$491	
2	0.00329	0.04600	0.118	-0.052	-$51,778	-$171	
3	0.00050	0.06800	0.175	-0.108	-$108,450	-$54	
4	0.00368	0.06100	0.157	-0.090	-$90,418	-$333	
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						-$8,260	-$8,260
Less Reliability Risk of Base Case:							$3,104
Total:							-$12,265

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,2,4	1.00000	0.03805	0.098	-0.038	-$38,408		-$38,408
Possible Cases:							
1,2	0.02117	0.03959	0.102	-0.004	-$3,967	-$84	
1,4	0.02365	0.04321	0.111	-0.013	-$13,292	-$314	
2,4	0.02152	0.04282	0.110	-0.012	-$12,288	-$264	
1	0.00050	0.04700	0.121	-0.023	-$23,055	-$12	
2	0.00046	0.04600	0.118	-0.020	-$20,479	-$9	
4	0.00051	0.06100	0.157	-0.059	-$59,119	-$30	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$714	-$714
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$36,018
Changed Network:							
1,3,4	1.00000	0.02842	0.073	-0.014	-$13,601	-$13,601	-$13,601
Possible Cases:							
1,3	0.02117	0.03790	0.098	-0.024	-$24,420	-$517	
1,4	0.15565	0.04321	0.111	-0.038	-$38,099	-$5,930	
3,4	0.02152	0.03396	0.087	-0.014	-$14,271	-$307	
1	0.00329	0.04700	0.121	-0.048	-$47,862	-$158	
3	0.00046	0.06800	0.175	-0.102	-$101,958	-$46	
4	0.00335	0.06100	0.157	-0.084	-$83,926	-$281	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$7,239	-$7,239
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$17,736
Changed Network:							
1,2,5	1.00000	0.03107	0.080	-0.020	-$20,428	-$20,428	-$20,428
Possible Cases:							
1,2	0.02200	0.03590	0.092	-0.012	-$12,442	-$274	
1,5	0.02365	0.03934	0.101	-0.021	-$21,304	-$504	
2,5	0.02152	0.03596	0.093	-0.013	-$12,597	-$271	
1	0.00052	0.04700	0.121	-0.041	-$41,036	-$21	
2	0.000473	0.04600	0.118	-0.038	-$38,460	-$18	
5	0.000509	0.06800	0.175	-0.095	-$95,132	-$48	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$1,137	-$1,137
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$18,460

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,3,5	1.00000	0.03795	0.098	-0.038	-$38,151	-$38,151	-$38,151
Possible Cases:							
1,3	0.02200	0.03790	0.098	0.0001	$129	$3	
1,5	0.15565	0.03934	0.101	-0.004	-$3,581	-$557	
3,5	0.02152	0.05586	0.144	-0.046	-$46,136	-$993	
1	0.003424	0.04700	0.121	-0.023	-$23,313	-$80	
3	0.000473	0.06800	0.175	-0.077	-$77,409	-$37	
5	0.00335	0.06800	0.175	-0.077	-$77,409	-$259	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$1,923	-$1,923
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$36,969
Changed Network:							
1,4,5	1.00000	0.03081	0.079	-0.020	-$19,758	-$19,758	-$19,758
Possible Cases:							
1,4	0.02200	0.04321	0.111	-0.032	-$31,942	-$703	
1,5	0.02117	0.03934	0.101	-0.022	-$21,973	-$465	
4,5	0.02152	0.03687	0.095	-0.016	-$15,611	-$336	
1	0.000466	0.04700	0.121	-0.042	-$41,705	-$19	
4	0.000473	0.06100	0.157	-0.078	-$77,769	-$37	
5	0.000456	0.06800	0.175	-0.096	-$95,801	-$44	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$1,604	-$1,604
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$18,257
Changed Network:							
2,3,5	1.00000	0.03471	0.089	-0.030	-$29,804	-$29,804	-$29,804
Possible Cases:							
2,3	0.02200	0.03373	0.087	0.003	$2,524	$56	
2,5	0.15565	0.03596	0.093	-0.003	-$3,220	-$501	
3,5	0.02365	0.05586	0.144	-0.054	-$54,482	-$1,289	
2	0.003424	0.04600	0.118	-0.029	-$29,083	-$100	
3	0.00052	0.06800	0.175	-0.086	-$85,755	-$45	
5	0.003682	0.06800	0.175	-0.086	-$85,755	-$316	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$2,194	-$2,194
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$28,894

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
2,4,5	1.00000	0.02884	0.074	-0.015	-$14,683	-$14,683	-$14,683
Possible Cases:							
2,4	0.02200	0.04282	0.110	-0.036	-$36,012	-$792	
2,5	0.02117	0.03596	0.093	-0.018	-$18,341	-$388	
4,5	0.02365	0.03687	0.095	-0.021	-$20,685	-$489	
2	0.000466	0.04600	0.118	-0.044	-$44,204	-$21	
4	0.00052	0.06100	0.157	-0.083	-$82,844	-$43	
5	0.000501	0.06800	0.175	-0.101	-$100,876	-$51	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,784	-$1,784
			Less Reliability Risk of Base Case:				$3,104
					Total:		-$13,363
Changed Network:							
3,4,5	1.00000	0.03260	0.084	-0.024	-$24,369	-$24,369	-$24,369
Possible Cases:							
3,4	0.02200	0.03396	0.087	-0.004	-$3,503	-$77	
3,5	0.02117	0.05586	0.144	-0.060	-$59,918	-$1,268	
4,5	0.15565	0.03687	0.095	-0.011	-$11,000	-$1,712	
3	0.000466	0.06800	0.175	-0.091	-$91,190	-$42	
4	0.003424	0.06100	0.157	-0.073	-$73,158	-$251	
5	0.003295	0.06800	0.175	-0.091	-$91,190	-$300	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$3,651	-$3,651
			Less Reliability Risk of Base Case:				$3,104
					Total:		-$24,915
Changed Network:							
1,2	1.00000	0.03959	0.102	-0.042	-$42,375		-$42,375
Possible Cases:							
1	0.02365	0.04700	0.121	-0.019	-$19,088	-$451	
2	0.02152	0.04600	0.118	-0.017	-$16,512	-$355	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$807	-$807
			Less Reliability Risk of Base Case:				$3,104
					Total:		-$40,078
Changed Network:							
1,3	1.00000	0.03790	0.098	-0.038	-$38,022		-$38,022
Possible Cases:							
1	0.15565	0.04700	0.121	-0.023	-$23,442	-$3,649	
3	0.02152	0.06800	0.175	-0.078	-$77,538	-$1,669	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$5,317	-$5,317
			Less Reliability Risk of Base Case:				$3,104
					Total:		-$40,235

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,4	1.00000	0.04321	0.111	-0.052	-$51,700		-$51,700
Possible Cases:							
1	0.02117	0.04700	0.121	-0.010	-$9,763	-$207	
4	0.02152	0.06100	0.157	-0.046	-$45,827	-$986	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,193	-$1,193
		Less Reliability Risk of Base Case:					$3,104
		Total:					-$49,789
Changed Network:							
2,3	1.00000	0.03373	0.087	-0.020	-$20,453		-$20,453
Possible Cases:							
2	0.15565	0.04600	0.118	-0.032	-$31,608	-$4,920	
3	0.02365	0.06800	0.175	-0.088	-$88,280	-$2,088	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$7,008	-$7,008
		Less Reliability Risk of Base Case:					$3,104
		Total:					-$24,357
Changed Network:							
2,4	1.00000	0.04282	0.110	-0.044	-$43,869		-$43,869
Possible Cases:							
2	0.02117	0.04600	0.118	-0.008	-$8,192	-$173	
4	0.02365	0.06100	0.157	-0.047	-$46,832	-$1,108	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,281	-$1,281
		Less Reliability Risk of Base Case:					$3,104
		Total:					-$42,046
Changed Network:							
3,4	1.00000	0.03396	0.087	-0.021	-$21,046		-$21,046
Possible Cases:							
3	0.02117	0.06800	0.175	-0.088	-$87,687	-$1,856	
4	0.15565	0.06100	0.157	-0.070	-$69,655	-$10,842	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$12,698	-$12,698
		Less Reliability Risk of Base Case:					$3,104
		Total:					-$30,639
Changed Network:							
1,5	1.00000	0.03934	0.101	-0.035	-$34,905		-$34,905
Possible Cases:							
1	0.02200	0.04700	0.121	-0.020	-$19,732	-$434	
5	0.02152	0.06800	0.175	-0.074	-$73,828	-$1,589	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$2,023	-$2,023
		Less Reliability Risk of Base Case:					$3,104
		Total:					-$33,823

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
2,5	1.00000	0.03596	0.093	-0.026	-$26,198		-$26,198
Possible Cases:							
2	0.02200	0.04600	0.118	-0.026	-$25,863	-$569	
5	0.02365	0.06800	0.175	-0.083	-$82,535	-$1,952	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$2,521	-$2,521
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$25,615
Changed Network:							
3,5	1.00000	0.05586	0.144	-0.077	-$77,460		-$77,460
Possible Cases:							
3	0.02200	0.06800	0.175	-0.031	-$31,273	-$688	
5	0.15565	0.06800	0.175	-0.031	-$31,273	-$4,868	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$5,556	-$5,556
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$79,911
Changed Network:							
4,5	1.00000	0.03687	0.095	-0.029	-$28,542		-$28,542
Possible Cases:							
4	0.02200	0.06100	0.157	-0.062	-$62,159	-$1,367	
5	0.02117	0.06800	0.175	-0.080	-$80,191	-$1,697	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$3,065	-$3,065
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$28,503
Changed Network:							
1	1.00000	0.04700	0.121	-0.055	-$54,637		-$54,637
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	$0	$0
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$51,533
Changed Network:							
2	1.00000	0.04600	0.118	-0.052	-$52,061		-$52,061
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	$0	$0
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$48,957
Changed Network:							
3	1.00000	0.06800	0.175	-0.109	-$108,733		-$108,733
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	$0	$0
					Less Reliability Risk of Base Case:		$3,104
					Total:		-$105,629

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
4	1.00000	0.06100	0.157	-0.091	-$90,701		-$90,701
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				$0	$0
			Less Reliability Risk of Base Case:				$3,104
					Total:		-$87,597
Changed Network:							
5	1.00000	0.06800	0.175	-0.109	-$108,733		-$108,733
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				$0	$0
			Less Reliability Risk of Base Case:				$3,104
					Total:		-$105,629

Economic Evaluation of Discontinuing Lake Level Gauges on Southern Indian Lake After Adding a Fifth Gauge (Missi Falls Gauge not repaired)

Gauges Discontinued:	Benefit (1) ($/year)	Benefit (2) ($/year)	Cost ($/year)	B/C Ratio (1)	B/C Ratio (2)
North End	$7,665	$7,665	$9,465	0.81	0.81
S.I.L. Village	$2,950	$5,900	$3,277	0.90	1.80
South Bay	$0	$5,900	$9,584	0.00	0.62
Missi Falls	$5,900	$5,900	$10,456	0.56	0.56
Opachuana	$5,900	$5,900	$13,582	0.43	0.43
Opachuana and North End	$13,565	$13,565	$14,955	0.91	0.91
S.I.L. Village and North End	$10,615	$13,565	$12,265	0.87	1.11
Missi Falls and North End	$13,565	$13,565	$36,018	0.38	0.38
South Bay and North End	$7,665	$13,565	$17,736	0.43	0.76
Missi Falls and Opachuana	$11,800	$11,800	$18,460	0.64	0.64
South Bay and Opachuana	$5,900	$11,800	$36,969	0.16	0.32
South Bay and Missi Falls	$5,900	$11,800	$18,257	0.32	0.65
S.I.L. Village and Opachuana	$8,850	$11,800	$28,894	0.31	0.41
S.I.L. Village and Missi Falls	$8,850	$11,800	$13,363	0.66	0.88
S.I.L. Village and South Bay	$2,950	$11,800	$24,915	0.12	0.47
Missi Falls, Opachuana, North End	$19,465	$19,465	$40,078	0.49	0.49
South Bay, Opachuana, North End	$13,565	$19,465	$40,235	0.34	0.48
South Bay, Missi Falls, North End	$13,565	$19,465	$49,789	0.27	0.39
S.I.L. Village, Opachuana, North End	$16,515	$19,465	$24,357	0.68	0.80
S.I.L. Village, Missi Falls, North End	$16,515	$19,465	$42,046	0.39	0.46
S.I.L. Village, South Bay, North End	$10,615	$19,465	$30,639	0.35	0.64
South Bay, Missi Falls, Opachuana	$11,800	$17,700	$33,823	0.35	0.52
S.I.L. Village, Missi Falls, Opachuana	$14,750	$17,700	$25,615	0.58	0.69
S.I.L. Village, South Bay, Opachuana	$8,850	$17,700	$79,911	0.11	0.22
S.I.L. Village, South Bay, Missi Falls	$8,850	$17,700	$28,503	0.31	0.62
S.Bay, Missi Falls, Opach., N.End	$19,465	$25,365	$51,533	0.38	0.49
S.I.L. Village, Missi, Opach., N.End	$22,415	$25,365	$48,957	0.46	0.52
S.I.L. Village, S.Bay, Opach., N.End	$16,515	$25,365	$105,629	0.16	0.24
S.I.L. Village, S.Bay, Missi, N.End	$16,515	$25,365	$87,597	0.19	0.29
S.I.L. Village, S.Bay, Missi, Opach.	$14,750	$23,600	$105,629	0.14	0.22

Notes: The benefit of discontinuing a gauge is the reduction in operating cost of that gauge. The benefit of discontinuing the porposed gauge is also not having to incur the installation cost ($22,000 over a 20 year life at a 5% discount rate is $1,765 per year). The cost of discontinuing a gauge is the reduction in hydro-power production it causes.

Case (1) is under current operating cost sharing agreements.
Case (2) is if the total operating cost was born by Manitoba Hydro.

Probability is the probability of gauge failure of the gauge or gauges (probabilities are multiplied for more than one gauge)

1	S.I.L. Villag	0.02152	
2	South Bay	0.02365	
3	Missi Falls	0.15565	
4	Opachuana	0.02117	
5	North End	0.02200	Proposed Gauge

Appendix I

Calculations for Marginal Benefit-Cost Ratios After Repairing the Gauge at Missi Falls and Adding a Fifth Gauge

Summarized in Table 20

Economic Evaluation of Discontinuing Lake Level Gauges on Southern Indian Lake After Repairing the Missi Falls Gauge and Adding a Fifth Gauge

by Tim Lock

Mar. 12, 1995

Gauges:		
	1	S.I.L. Village
	2	South Bay
	3	Missi Falls
	4	Opachuana
	5	North End

Accuracy: 2.576 x Std. Dev.
Worth: 1000000 /ft /year

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Base Case:							
1,2,3,4,5	0	0.02314	0.060	0	0		0
Possible Cases:							
1,2,3,4	0.02200	0.02579	0.066	-0.007	-$6,826	-$150	
2,3,4,5	0.02152	0.02427	0.063	-0.003	-$2,911	-$63	
1,3,4,5	0.02365	0.02691	0.069	-0.010	-$9,712	-$230	
1,2,4,5	0.02200	0.02800	0.072	-0.013	-$12,519	-$275	
1,2,3,5	0.02117	0.02880	0.074	-0.015	-$14,580	-$309	
1,2,3	0.00047	0.02909	0.075	-0.015	-$15,327	-$7	
2,3,4	0.00047	0.02590	0.067	-0.007	-$7,110	-$3	
1,2,4	0.00048	0.03805	0.098	-0.038	-$38,408	-$19	
1,3,4	0.00052	0.02842	0.073	-0.014	-$13,601	-$7	
1,2,5	0.00047	0.03107	0.080	-0.020	-$20,428	-$10	
1,3,5	0.00050	0.03795	0.098	-0.038	-$38,151	-$19	
1,4,5	0.00052	0.03081	0.079	-0.020	-$19,758	-$10	
2,3,5	0.00046	0.03471	0.089	-0.030	-$29,804	-$14	
2,4,5	0.00047	0.02884	0.074	-0.015	-$14,683	-$7	
3,4,5	0.00051	0.03260	0.084	-0.024	-$24,369	-$12	
1,2	0.00001	0.03590	0.092	-0.033	-$32,870	$0	
1,3	0.00001	0.03790	0.098	-0.038	-$38,022	$0	
1,4	0.00001	0.04321	0.111	-0.052	-$51,700	-$1	
2,3	0.00001	0.03373	0.087	-0.027	-$27,280	$0	
2,4	0.00001	0.04282	0.110	-0.051	-$50,696	-$1	
3,4	0.00001	0.03396	0.087	-0.028	-$27,872	$0	
1,5	1.1E-05	0.03934	0.101	-0.042	-$41,731	$0	
2,5	1E-05	0.03596	0.093	-0.033	-$33,024	$0	
3,5	1.08E-05	0.05586	0.144	-0.084	-$84,287	-$1	
4,5	1.12E-05	0.03687	0.095	-0.035	-$35,368	$0	
1	2.42E-07	0.04700	0.121	-0.061	-$61,463	$0	
2	2.2E-07	0.04600	0.118	-0.059	-$58,887	$0	
3	2.37E-07	0.06800	0.175	-0.116	-$115,559	$0	
4	2.46E-07	0.06100	0.157	-0.098	-$97,527	$0	
5	2.37E-07	0.06800	0.175	-0.116	-$115,559	$0	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,139	

Note: The words "reliability risk" should be replaced with the words "reliability cost" each time they occur.

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,2,3,4	1	0.02579	0.066	-0.007	-$6,826		-$6,826
Possible Cases:							
1,2,3	0.02117	0.02909	0.075	-0.009	-$8,501	-$180	
2,3,4	0.02152	0.02590	0.067	0.000	-$283	-$6	
1,2,4	0.02200	0.03805	0.098	-0.032	-$31,582	-$695	
1,3,4	0.02365	0.02842	0.073	-0.007	-$6,775	-$160	
1,2	0.00047	0.03959	0.102	-0.036	-$35,549	-$17	
1,3	0.00050	0.03790	0.098	-0.031	-$31,195	-$16	
1,4	0.00052	0.04321	0.111	-0.045	-$44,874	-$23	
2,3	0.00046	0.03373	0.087	-0.020	-$20,453	-$9	
2,4	0.00047	0.04282	0.110	-0.044	-$43,869	-$21	
3,4	0.00051	0.03396	0.087	-0.021	-$21,046	-$11	
1	0.00001	0.04700	0.121	-0.055	-$54,637	-$1	
2	0.00001	0.04600	0.118	-0.052	-$52,061	-$1	
3	0.00001	0.06800	0.175	-0.109	-$108,733	-$1	
4	0.00001	0.06100	0.157	-0.091	-$90,701	-$1	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$1,141	-$1,141
					Less Reliability Risk of Base Case:		$1,139
					Total:		-$6,828
Changed Network:							
2,3,4,5	1	0.02427	0.063	-0.003	-$2,911		-$2,911
Possible Cases:							
2,3,4	0.02200	0.02590	0.067	-0.004	-$4,199	-$92	
2,3,5	0.02117	0.03471	0.089	-0.027	-$26,893	-$569	
2,4,5	0.02200	0.02884	0.074	-0.012	-$11,772	-$259	
3,4,5	0.02365	0.03260	0.084	-0.021	-$21,458	-$508	
2,3	0.00047	0.03373	0.087	-0.024	-$24,369	-$11	
2,4	0.00048	0.04282	0.110	-0.048	-$47,785	-$23	
3,4	0.00052	0.03396	0.087	-0.025	-$24,961	-$13	
2,5	0.000466	0.03596	0.093	-0.030	-$30,113	-$14	
3,5	0.000501	0.05586	0.144	-0.081	-$81,376	-$41	
4,5	0.00052	0.03687	0.095	-0.032	-$32,458	-$17	
2	1.02E-05	0.04600	0.118	-0.056	-$55,976	-$1	
3	1.1E-05	0.06800	0.175	-0.113	-$112,648	-$1	
4	1.14E-05	0.06100	0.157	-0.095	-$94,616	-$1	
5	1.1E-05	0.06800	0.175	-0.113	-$112,648	-$1	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$1,551	-$1,551
					Less Reliability Risk of Base Case:		$1,139
					Total:		-$3,323

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,3,4,5	1	0.02691	0.069	-0.010	-$9,712		-$9,712
Possible Cases:							
1,3,4	0.02200	0.02842	0.073	-0.004	-$3,890	-$86	
1,3,5	0.02117	0.03795	0.098	-0.028	-$28,439	-$602	
1,4,5	0.02200	0.03081	0.079	-0.010	-$10,046	-$221	
3,4,5	0.02152	0.03260	0.084	-0.015	-$14,657	-$315	
1,3	0.00047	0.03790	0.098	-0.028	-$28,310	-$13	
1,4	0.00048	0.04321	0.111	-0.042	-$41,989	-$20	
3,4	0.00047	0.03396	0.087	-0.018	-$18,161	-$9	
1,5	0.000466	0.03934	0.101	-0.032	-$32,020	-$15	
3,5	0.000456	0.05586	0.144	-0.075	-$74,575	-$34	
4,5	0.000473	0.03687	0.095	-0.026	-$25,657	-$12	
1	1.02E-05	0.04700	0.121	-0.052	-$51,752	-$1	
3	1E-05	0.06800	0.175	-0.106	-$105,848	-$1	
4	1.04E-05	0.06100	0.157	-0.088	-$87,816	-$1	
5	1E-05	0.06800	0.175	-0.106	-$105,848	-$1	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,331	-$1,331
			Less Reliability Risk of Base Case:				$1,139
					Total:		-$9,903
Changed Network:							
1,2,4,5	1	0.028	0.072	-0.013	-$12,519		-$12,519
Possible Cases:							
1,2,4	0.02200	0.03805	0.098	-0.026	-$25,889	-$570	
1,2,5	0.02117	0.03107	0.080	-0.008	-$7,908	-$167	
1,4,5	0.02365	0.03081	0.079	-0.007	-$7,239	-$171	
2,4,5	0.02152	0.02884	0.074	-0.002	-$2,164	-$47	
1,2	0.00047	0.03590	0.092	-0.020	-$20,350	-$9	
1,4	0.00052	0.04321	0.111	-0.039	-$39,181	-$20	
2,4	0.00047	0.04282	0.110	-0.038	-$38,176	-$18	
1,5	0.000501	0.03934	0.101	-0.029	-$29,212	-$15	
2,5	0.000456	0.03596	0.093	-0.021	-$20,505	-$9	
4,5	0.000509	0.03687	0.095	-0.023	-$22,849	-$12	
1	1.1E-05	0.04700	0.121	-0.049	-$48,944	-$1	
2	1E-05	0.04600	0.118	-0.046	-$46,368	$0	
4	1.12E-05	0.06100	0.157	-0.085	-$85,008	-$1	
5	1.08E-05	0.06800	0.175	-0.103	-$103,040	-$1	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,041	-$1,041
			Less Reliability Risk of Base Case:				$1,139
					Total:		-$12,421

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,2,3,5	1	0.0288	0.074	-0.015	-$14,580		-$14,580
Possible Cases:							
1,2,3	0.02200	0.02909	0.075	-0.001	-$747	-$16	
1,2,5	0.02200	0.03107	0.080	-0.006	-$5,848	-$129	
1,3,5	0.02365	0.03795	0.098	-0.024	-$23,570	-$558	
2,3,5	0.02152	0.03471	0.089	-0.015	-$15,224	-$328	
1,2	0.00048	0.03590	0.092	-0.018	-$18,290	-$9	
1,3	0.00052	0.03790	0.098	-0.023	-$23,442	-$12	
2,3	0.00047	0.03373	0.087	-0.013	-$12,700	-$6	
1,5	0.00052	0.03934	0.101	-0.027	-$27,151	-$14	
2,5	0.000473	0.03596	0.093	-0.018	-$18,444	-$9	
3,5	0.000509	0.05586	0.144	-0.070	-$69,707	-$35	
1	1.14E-05	0.04700	0.121	-0.047	-$46,883	-$1	
2	1.04E-05	0.04600	0.118	-0.044	-$44,307	$0	
3	1.12E-05	0.06800	0.175	-0.101	-$100,979	-$1	
5	1.12E-05	0.06800	0.175	-0.101	-$100,979	-$1	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,119	-$1,119
			Less Reliability Risk of Base Case:				$1,139
					Total:		-$14,560
Changed Network:							
1,2,3	1.00000	0.02909	0.075	-0.015	-$15,327		-$15,327
Possible Cases:							
1,2	0.02200	0.03959	0.102	-0.027	-$27,048	-$595	
1,3	0.02365	0.03790	0.098	-0.023	-$22,695	-$537	
2,3	0.02152	0.03373	0.087	-0.012	-$11,953	-$257	
1	0.00052	0.04700	0.121	-0.046	-$46,136	-$24	
2	0.00047	0.04600	0.118	-0.044	-$43,560	-$21	
3	0.00051	0.06800	0.175	-0.100	-$100,232	-$51	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,485	-$1,485
			Less Reliability Risk of Base Case:				$1,141
					Total:		-$15,671
Changed Network:							
2,3,4	1.00000	0.02590	0.067	-0.007	-$7,110		-$7,110
Possible Cases:							
2,3	0.02117	0.03373	0.087	-0.020	-$20,170	-$427	
2,4	0.02200	0.04282	0.110	-0.044	-$43,586	-$959	
3,4	0.02365	0.03396	0.087	-0.021	-$20,763	-$491	
2	0.00047	0.04600	0.118	-0.052	-$51,778	-$24	
3	0.00050	0.06800	0.175	-0.108	-$108,450	-$54	
4	0.00052	0.06100	0.157	-0.090	-$90,418	-$47	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$2,002	-$2,002
			Less Reliability Risk of Base Case:				$1,139
					Total:		-$7,973

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,2,4	1.00000	0.03805	0.098	-0.038	-$38,408		-$38,408
Possible Cases:							
1,2	0.02117	0.03959	0.102	-0.004	-$3,967	-$84	
1,4	0.02365	0.04321	0.111	-0.013	-$13,292	-$314	
2,4	0.02152	0.04282	0.110	-0.012	-$12,288	-$264	
1	0.00050	0.04700	0.121	-0.023	-$23,055	-$12	
2	0.00046	0.04600	0.118	-0.020	-$20,479	-$9	
4	0.00051	0.06100	0.157	-0.059	-$59,119	-$30	
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						-$714	-$714
Less Reliability Risk of Base Case:							$1,139
Total:							-$37,983
Changed Network:							
1,3,4	1.00000	0.02842	0.073	-0.014	-$13,601	-$13,601	-$13,601
Possible Cases:							
1,3	0.02117	0.03790	0.098	-0.024	-$24,420	-$517	
1,4	0.02200	0.04321	0.111	-0.038	-$38,099	-$838	
3,4	0.02152	0.03396	0.087	-0.014	-$14,271	-$307	
1	0.00047	0.04700	0.121	-0.048	-$47,862	-$22	
3	0.00046	0.06800	0.175	-0.102	-$101,958	-$46	
4	0.00047	0.06100	0.157	-0.084	-$83,926	-$40	
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						-$1,771	-$1,771
Less Reliability Risk of Base Case:							$1,139
Total:							-$14,233
Changed Network:							
1,2,5	1.00000	0.03107	0.080	-0.020	-$20,428	-$20,428	-$20,428
Possible Cases:							
1,2	0.02200	0.03590	0.092	-0.012	-$12,442	-$274	
1,5	0.02365	0.03934	0.101	-0.021	-$21,304	-$504	
2,5	0.02152	0.03596	0.093	-0.013	-$12,597	-$271	
1	0.00052	0.04700	0.121	-0.041	-$41,036	-$21	
2	0.000473	0.04600	0.118	-0.038	-$38,460	-$18	
5	0.000509	0.06800	0.175	-0.095	-$95,132	-$48	
none	possible	?!	?!	?!	?!	?!	
Subtotal of Reliability Risk of Possible Cases:						-$1,137	-$1,137
Less Reliability Risk of Base Case:							$1,139
Total:							-$20,425

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,3,5	1.00000	0.03795	0.098	-0.038	-$38,151	-$38,151	-$38,151
Possible Cases:							
1,3	0.02200	0.03790	0.098	0.0001	$129	$3	
1,5	0.02200	0.03934	0.101	-0.004	-$3,581	-$79	
3,5	0.02152	0.05586	0.144	-0.046	-$46,136	-$993	
1	0.000484	0.04700	0.121	-0.023	-$23,313	-$11	
3	0.000473	0.06800	0.175	-0.077	-$77,409	-$37	
5	0.000473	0.06800	0.175	-0.077	-$77,409	-$37	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,153	-$1,153
		Less Reliability Risk of Base Case:					$1,139
		Total:					-$38,165
Changed Network:							
1,4,5	1.00000	0.03081	0.079	-0.020	-$19,758	-$19,758	-$19,758
Possible Cases:							
1,4	0.02200	0.04321	0.111	-0.032	-$31,942	-$703	
1,5	0.02117	0.03934	0.101	-0.022	-$21,973	-$465	
4,5	0.02152	0.03687	0.095	-0.016	-$15,611	-$336	
1	0.000466	0.04700	0.121	-0.042	-$41,705	-$19	
4	0.000473	0.06100	0.157	-0.078	-$77,769	-$37	
5	0.000456	0.06800	0.175	-0.096	-$95,801	-$44	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,604	-$1,604
		Less Reliability Risk of Base Case:					$1,139
		Total:					-$20,222
Changed Network:							
2,3,5	1.00000	0.03471	0.089	-0.030	-$29,804	-$29,804	-$29,804
Possible Cases:							
2,3	0.02200	0.03373	0.087	0.003	$2,524	$56	
2,5	0.02200	0.03596	0.093	-0.003	-$3,220	-$71	
3,5	0.02365	0.05586	0.144	-0.054	-$54,482	-$1,289	
2	0.000484	0.04600	0.118	-0.029	-$29,083	-$14	
3	0.00052	0.06800	0.175	-0.086	-$85,755	-$45	
5	0.00052	0.06800	0.175	-0.086	-$85,755	-$45	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,407	-$1,407
		Less Reliability Risk of Base Case:					$1,139
		Total:					-$30,072

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
2,4,5	1.00000	0.02884	0.074	-0.015	-$14,683	-$14,683	-$14,683
Possible Cases:							
2,4	0.02200	0.04282	0.110	-0.036	-$36,012	-$792	
2,5	0.02117	0.03596	0.093	-0.018	-$18,341	-$388	
4,5	0.02365	0.03687	0.095	-0.021	-$20,685	-$489	
2	0.000466	0.04600	0.118	-0.044	-$44,204	-$21	
4	0.00052	0.06100	0.157	-0.083	-$82,844	-$43	
5	0.000501	0.06800	0.175	-0.101	-$100,876	-$51	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,784	-$1,784
			Less Reliability Risk of Base Case:				$1,139
					Total:		-$15,328
Changed Network:							
3,4,5	1.00000	0.03260	0.084	-0.024	-$24,369	-$24,369	-$24,369
Possible Cases:							
3,4	0.02200	0.03396	0.087	-0.004	-$3,503	-$77	
3,5	0.02117	0.05586	0.144	-0.060	-$59,918	-$1,268	
4,5	0.02200	0.03687	0.095	-0.011	-$11,000	-$242	
3	0.000466	0.06800	0.175	-0.091	-$91,190	-$42	
4	0.000484	0.06100	0.157	-0.073	-$73,158	-$35	
5	0.000466	0.06800	0.175	-0.091	-$91,190	-$42	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,708	-$1,708
			Less Reliability Risk of Base Case:				$1,139
					Total:		-$24,937
Changed Network:							
1,2	1.00000	0.03959	0.102	-0.042	-$42,375		-$42,375
Possible Cases:							
1	0.02365	0.04700	0.121	-0.019	-$19,088	-$451	
2	0.02152	0.04600	0.118	-0.017	-$16,512	-$355	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$807	-$807
			Less Reliability Risk of Base Case:				$1,139
					Total:		-$42,043
Changed Network:							
1,3	1.00000	0.03790	0.098	-0.038	-$38,022		-$38,022
Possible Cases:							
1	0.02200	0.04700	0.121	-0.023	-$23,442	-$516	
3	0.02152	0.06800	0.175	-0.078	-$77,538	-$1,669	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$2,184	-$2,184
			Less Reliability Risk of Base Case:				$1,139
					Total:		-$39,067

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
1,4	1.00000	0.04321	0.111	-0.052	-$51,700		-$51,700
Possible Cases:							
1	0.02117	0.04700	0.121	-0.010	-$9,763	-$207	
4	0.02152	0.06100	0.157	-0.046	-$45,827	-$986	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,193	-$1,193
		Less Reliability Risk of Base Case:					$1,139
		Total:					-$51,754
Changed Network:							
2,3	1.00000	0.03373	0.087	-0.020	-$20,453		-$20,453
Possible Cases:							
2	0.02200	0.04600	0.118	-0.032	-$31,608	-$695	
3	0.02365	0.06800	0.175	-0.088	-$88,280	-$2,088	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$2,783	-$2,783
		Less Reliability Risk of Base Case:					$1,139
		Total:					-$22,098
Changed Network:							
2,4	1.00000	0.04282	0.110	-0.044	-$43,869		-$43,869
Possible Cases:							
2	0.02117	0.04600	0.118	-0.008	-$8,192	-$173	
4	0.02365	0.06100	0.157	-0.047	-$46,832	-$1,108	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$1,281	-$1,281
		Less Reliability Risk of Base Case:					$1,139
		Total:					-$44,011
Changed Network:							
3,4	1.00000	0.03396	0.087	-0.021	-$21,046		-$21,046
Possible Cases:							
3	0.02117	0.06800	0.175	-0.088	-$87,687	-$1,856	
4	0.02200	0.06100	0.157	-0.070	-$69,655	-$1,532	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$3,389	-$3,389
		Less Reliability Risk of Base Case:					$1,139
		Total:					-$23,295
Changed Network:							
1,5	1.00000	0.03934	0.101	-0.035	-$34,905		-$34,905
Possible Cases:							
1	0.02200	0.04700	0.121	-0.020	-$19,732	-$434	
5	0.02152	0.06800	0.175	-0.074	-$73,828	-$1,589	
none	possible	?!	?!	?!	?!	?!	
		Subtotal of Reliability Risk of Possible Cases:				-$2,023	-$2,023
		Less Reliability Risk of Base Case:					$1,139
		Total:					-$35,788

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
2,5	1.00000	0.03596	0.093	-0.026	-$26,198		-$26,198
Possible Cases:							
2	0.02200	0.04600	0.118	-0.026	-$25,863	-$569	
5	0.02365	0.06800	0.175	-0.083	-$82,535	-$1,952	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$2,521	-$2,521
					Less Reliability Risk of Base Case:		$1,139
					Total:		-$27,580
Changed Network:							
3,5	1.00000	0.05586	0.144	-0.077	-$77,460		-$77,460
Possible Cases:							
3	0.02200	0.06800	0.175	-0.031	-$31,273	-$688	
5	0.02200	0.06800	0.175	-0.031	-$31,273	-$688	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$1,376	-$1,376
					Less Reliability Risk of Base Case:		$1,139
					Total:		-$77,697
Changed Network:							
4,5	1.00000	0.03687	0.095	-0.029	-$28,542		-$28,542
Possible Cases:							
4	0.02200	0.06100	0.157	-0.062	-$62,159	-$1,367	
5	0.02117	0.06800	0.175	-0.080	-$80,191	-$1,697	
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	-$3,065	-$3,065
					Less Reliability Risk of Base Case:		$1,139
					Total:		-$30,468
Changed Network:							
1	1.00000	0.04700	0.121	-0.055	-$54,637		-$54,637
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	$0	$0
					Less Reliability Risk of Base Case:		$1,139
					Total:		-$53,498
Changed Network:							
2	1.00000	0.04600	0.118	-0.052	-$52,061		-$52,061
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	$0	$0
					Less Reliability Risk of Base Case:		$1,139
					Total:		-$50,922
Changed Network:							
3	1.00000	0.06800	0.175	-0.109	-$108,733		-$108,733
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	$0	$0
					Less Reliability Risk of Base Case:		$1,139
					Total:		-$107,594

Remaining Gauges in Network	Probability of Case Occurring	Std. Dev. of Gauge Data	Accuracy (+or-feet)	Change in Accuracy (feet)	Change in Benefits $/year	Risk of Unrelialbe Gauges $/year	Expected Change in Benefits $/year
Changed Network:							
4	1.00000	0.06100	0.157	-0.091	-$90,701		-$90,701
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	$0	$0
					Less Reliability Risk of Base Case:		$1,139
					Total:		-$89,562
Changed Network:							
5	1.00000	0.06800	0.175	-0.109	-$108,733		-$108,733
Possible Cases:							
none	possible	?!	?!	?!	?!	?!	
					Subtotal of Reliability Risk of Possible Cases:	$0	$0
					Less Reliability Risk of Base Case:		$1,139
					Total:		-$107,594

Economic Evaluation of Discontinuing Lake Level Gauges on Southern Indian Lake After Repairing the Missi Falls Gauge and Adding a Fifth Gauge

Gauges Discontinued:	Benefit (1) ($/year)	Benefit (2) ($/year)	Cost ($/year)	B/C Ratio (1)	B/C Ratio (2)
North End	$7,665	$7,665	$6,828	1.12	1.12
S.I.L. Village	$2,950	$5,900	$3,323	0.89	1.78
South Bay	$0	$5,900	$9,903	0.00	0.60
Missi Falls	$5,900	$5,900	$12,421	0.47	0.47
Opachuana	$5,900	$5,900	$14,560	0.41	0.41
Opachuana and North End	$13,565	$13,565	$15,671	0.87	0.87
S.I.L. Village and North End	$10,615	$13,565	$7,973	1.33	1.70
Missi Falls and North End	$13,565	$13,565	$37,983	0.36	0.36
South Bay and North End	$7,665	$13,565	$14,233	0.54	0.95
Missi Falls and Opachuana	$11,800	$11,800	$20,425	0.58	0.58
South Bay and Opachuana	$5,900	$11,800	$38,165	0.15	0.31
South Bay and Missi Falls	$5,900	$11,800	$20,222	0.29	0.58
S.I.L. Village and Opachuana	$8,850	$11,800	$30,072	0.29	0.39
S.I.L. Village and Missi Falls	$8,850	$11,800	$15,328	0.58	0.77
S.I.L. Village and South Bay	$2,950	$11,800	$24,937	0.12	0.47
Missi Falls, Opachuana, North End	$19,465	$19,465	$42,043	0.46	0.46
South Bay, Opachuana, North End	$13,565	$19,465	$39,067	0.35	0.50
South Bay, Missi Falls, North End	$13,565	$19,465	$51,754	0.26	0.38
S.I.L. Village, Opachuana, North End	$16,515	$19,465	$22,098	0.75	0.88
S.I.L. Village, Missi Falls, North End	$16,515	$19,465	$44,011	0.38	0.44
S.I.L. Village, South Bay, North End	$10,615	$19,465	$23,295	0.46	0.84
South Bay, Missi Falls, Opachuana	$11,800	$17,700	$35,788	0.33	0.49
S.I.L. Village, Missi Falls, Opachuana	$14,750	$17,700	$27,580	0.53	0.64
S.I.L. Village, South Bay, Opachuana	$8,850	$17,700	$77,697	0.11	0.23
S.I.L. Village, South Bay, Missi Falls	$8,850	$17,700	$30,468	0.29	0.58
S.Bay, Missi Falls, Opach., N.End	$19,465	$25,365	$53,498	0.36	0.47
S.I.L. Village, Missi, Opach., N.End	$22,415	$25,365	$50,922	0.44	0.50
S.I.L. Village, S.Bay, Opach., N.End	$16,515	$25,365	$107,594	0.15	0.24
S.I.L. Village, S.Bay, Missi, N.End	$16,515	$25,365	$89,562	0.18	0.28
S.I.L. Village, S.Bay, Missi, Opach.	$14,750	$23,600	$107,594	0.14	0.22

Notes: The benefit of discontinuing a gauge is the reduction in operating cost of that gauge. The benefit of discontinuing the proposed gauge is also not having to incur the installation cost ($22,000 over a 20 year life at a 5% discount rate is $1,765 per year). The cost of discontinuing a gauge is the reduction in hydro-power production it causes.

Case (1) is under current operating cost sharing agreements.
Case (2) is if the total operating cost was born by Manitoba Hydro.

Probability is the probability of gauge failure of the gauge or gauges (probabilities are multiplied for more than one gauge)

1	S.I.L. Village	0.02152	
2	South Bay	0.02365	
3	Missi Falls	0.02200	Repaired Gauge
4	Opachuana	0.02117	
5	North End	0.02200	Proposed Gauge