THE UNIVERSITY OF MANITOBA

APPLICATION OF OPTIMIZATION TECHNIQUES FOR RESERVOIR MANAGEMENT IN CONJUNCTION WITH THERMAL POWER GENERATION

by

Mohamed Imran Latheef

A Thesis

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A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

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ABSTRACT

The thesis develops an approach for obtaining reservoir management policies that explicitly consider the dilution needs for heated effluent of downstream thermal generating stations. A relationship is developed which relates the allowable power generation to the river flow at the discharge point as a function of the background stream temperature, the temperature standard in the stream, the physical characteristics of the river, and the ambient atmospheric conditions. This relationship is linearized and incorporated in a linear goal programming model in which the objective is to minimize deviations from power generation and reservoir storage targets. The goal programming model may be used to assist in the development of management policies for the reservoir that accommodate the downstream thermal generation needs.

The latter part of the thesis investigates seasonal operating strategies for a cooling tower for a thermal generating station downstream of a reservoir. A linear relationship between river flow and allowable generation is obtained for the situation in which a cooling tower operates to reduce the effluent temperature. This relationship is incorporated in a mixed integer programming model which identifies the optimal periods in which a cooling tower may operate given that dilution of heated effluent may also be achieved with reservoir releases.

These models are applied to a realistic case study based on the Shellmouth Reservoir and Dam in Southwestern Manitoba. The results yield a reservoir management strategy for the case study, seasonal operating strategies for a potential cooling tower, and identification of the trade-offs between power generation and reservoir storage levels for such systems.

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1 INTRODUCTION

1.1 Statement of the Problem

Many coal fired thermal power plants operate using a once through direct cooling system. This cooling system withdraws cooling water from an external source such as a river or a lake, circulates the cooling water through the heat exchanger in the thermal power plant, and transfers heat from the power generation process to the cooling water, thereby elevating the temperature of the cooling water. The resulting hot water (or thermal effluent) is discharged into a stream or a cooling pond.

Thermal effluent discharged into a river can have a negative effect on the ecology of the river. It accelerates biological processes thus increasing oxygen consumption, it decreases the solubility of atmospheric oxygen in surface water thus decreasing the DO concentration, it increases the minimum requirement of dissolved oxygen concentration for fish to survive, and it decreases the waste load handling capability of the river. In addition, the area of thermal discharge often acts as a thermal block preventing the migration of fish. Moreover extreme temperatures can be lethal to fish and other aquatic organisms and sublethal impacts on these organisms such as effects on metabolism, behavior, reproduction, feeding rate, growth, and migration may also occur. Nevertheless, these adverse effects can be reduced or eliminated by diluting the heated effluent in the river as long as a feasible source of dilution water exists. Such an approach may be practical if the effluent is discharged to a regulated waterway.

This thesis addresses the problem of diluting a discharge of thermal effluent in a regulated waterway. Efficient management strategies for operating a

multipurpose reservoir which regulate the waterway are identified using optimization techniques. The general approach is to develop a constraint set which relates the allowable power generation to river flow and consequently reservoir releases, and to incorporate this constraint set into a reservoir management model. The reservoir management model may then be used to select an optimal release strategy which accommodates the dilution needs of the the thermal effluent from the power plant.

Should the optimal release strategy be inadequate for meeting all of the uses of the reservoir, alternative cooling facilities for the power plant may need to be examined. The latter part of the thesis employs a mixed integer programming technique to investigate cooling facility alternatives for a downstream power plant. Seasonal management strategies for a cooling tower for the power plant are identified.

The models developed in this thesis are applied to a case study based on the Shellmouth Reservoir and Dam which regulate the Assiniboine River in Southern Manitoba. The power plant of interest is the thermal generating station at Brandon, Manitoba which is operated by Manitoba Hydro.

The management of a multipurpose reservoir is a very complex issue. The reservoir has many uses and these uses may be conflicting. For example, releases required to meet water supply demands may conflict with storage targets which are set to provide recreation in the reservoir. Only an efficient operation of the reservoir may ensure the satisfaction of all the uses of the reservoir. When introducing a new use for the reservoir, such as the need to provide dilution water to maintain a temperature standard in a river, additional release requirements must be considered. In order to satisfy this new requirement shortfalls in other goals such as desired storage levels for recreation may occur. Thus the identification of management

strategies which satisfy all the existing users and also satisfy the dilution requirements of the new use becomes even more complicated.

The amount of water which should be released for dilution of thermal effluent depends primarily on the amount of tributary inflow in the river, the temperature of the river, the magnitude of power generation required, and the relationship between the power generation of the thermal power plant and its cooling water temperature. If the reservoir operator does not know the precise amount of water required for dilution of the thermal effluent at any given time, an unnecessary wastage of water could occur, thus affecting the other users of the water system. One of the goals of this thesis is to explicitly identify the amount of water required for dilution given the power generation goals of the thermal power plant and to incorporate the required dilution demand into an optimization based management model of the reservoir. The approach used is to develop a relationship between river flow at the point of thermal discharge and power generation at any time in the year.

This relationship can also be used to investigate other cooling alternatives for the thermal power plant. In the latter part of the thesis an integer programming model is developed which uses the relationship between river flow and power generation to analyze the alternative of building and operating a cooling tower. A cooling tower is a cooling system used to transfer part of the heat generated in the power generation process to the atmosphere, thus reducing the temperature of the discharge of thermal effluent into the river.

The effective use of optimization techniques in dealing with such problems is also demonstrated. The needs of the various users may be conflicting and may occur at different times. Optimization techniques are used to obtain a management policy for multipurpose reservoirs and to identify the inherent trade-offs between

various conflicting uses. The overall methodology is best applied when obtaining a management strategy for an existing multipurpose reservoir with conflicting users and when considering new users downstream of the reservoir.

Several alternate policies are identified with these optimization models. Simulation and multiobjective compromise programming techniques are then used to select the most preferred policy. Simulation techniques may also be used for checking the performance of the optimal management policies in a realistic situation and to identify trade-offs in the reservoir system that are not obvious from the optimization results.

1.2 Scope of the Work

This thesis develops a method for identifying operating policies for multipurpose reservoirs which consider the needs of a downstream thermal generation station and ensure temperature control in the river. The method employs the use of optimization techniques. Simulation techniques are used to validate the results of the optimization models.

Chapter 2 provides a literature review of water resources systems applications of optimization models. It also provides a review of literature regarding temperature modelling in a river. Chapter 3 provides the development and formulation of an optimization based reservoir management model which explicitly accounts for thermal power generation and temperature control in the river. The relationship between river flow and thermal power generation as a function of the upstream river temperature and the temperature standard in the river is developed and incorporated in the optimization model.

Next, the modelling approach developed in Chapter 3 is illustrated with a case study of the Shellmouth Reservoir and Dam. In Chapter 5 the optimization results are analyzed and a simulation model is applied to validate these results and to evaluate the preferred operating policy for the case study.

Chapter 6 develops a mixed integer program for obtaining optimal operating policies for reservoirs in conjunction with seasonal operating strategies for a cooling tower. In Chapter 7 this model is applied to the Shellmouth case study and the model results are analyzed. Chapter 8 discusses the conclusions, recommendations, and suggestions for future research.

2. LITERATURE REVIEW

The management and operation of multipurpose reservoirs requires release decisions to be determined in order to efficiently fulfill the purposes for which the reservoir is built. To assist in making these release decisions many mathematical models exist. *Yeh* (1985) reviews the state-of-the-art of mathematical models developed for reservoir operations. The algorithms and methods surveyed in the paper include various optimization techniques such as linear programming (LP), dynamic programming (DP), nonlinear programming (NLP), and simulation. He summarized that the application of a particular model or algorithm to a reservoir system depends on the reservoir system characteristics and on the availability of data for that system.

Optimization models have been extensively used in reservoir management and operation studies. These models can be formulated for either a stochastic or a deterministic environment. Stochastic programming models are used for making decisions while explicitly considering the stochasticity on which these decisions depend (see e.g., *Tintner*, 1972). Deterministic models are more simple in their formulation. They incorporate the expected values or best estimates of uncertain input data such as inflow into a reservoir, tributary inflow into a river, and rainfall.

The most common and valuable optimization technique used in reservoir operation, management, and design is LP. A linear program consists of an objective function and a constraint set in which the preferences, objectives, and requirements of the problem can be incorporated. The constraint set defines the strict requirements for meeting specified goals whereas the objective function defines the goal of the model. The advantages of LP are that its concept and solution procedure is simple and

straightforward. Moreover there are plenty of software packages which can solve even very large LP problems in very little time.

ReVelle and Gundelach (1975) present a straightforward deterministic LP model for designing a reservoir. The objective is to minimize the capacity of the reservoir while meeting the user requirements which are incorporated in the constraint set of the model. *Fitch et al.* (1970) formulates a deterministic LP model to identify the best trade-off between the conflicting objectives of hydro-electric power generation (i.e., desired storage levels in a reservoir) and low flow augmentation (i.e., water quality downstream) for a multiple multipurpose reservoir system.

Loucks (1967) shows different deterministic and stochastic LP models for management of water resources systems. The models are structured for determining the reservoir releases and allocation of water for satisfying consumptive uses and low flow augmentation downstream of the reservoir. Although deterministic models incorporate stochasticity by using expected values of uncertain input, these models may not always lead to satisfactory results. A stochastic LP model is developed by *Loucks* (1968) for a single reservoir which is subject to random serially correlated net inflows. He concludes that in real situations this type of model would have a dimensionality problem and could easily require several thousands of constraints. Stochastic DP and LP models incorporating first order Markov chains are also reviewed and compared by *Loucks and Falkson* (1970).

A second type of stochastic programming is stochastic programming with recourse or two stage linear programming. Under this approach the final optimal solution is obtained by two separate interrelated linear programs in two stages. In the first stage an optimal solution is found from an LP which uses the estimated value of the random event such as the predicted inflow into a reservoir. In the second stage,

once the random event has occurred, a corrective action is taken so as to minimize the error in further decisions associated with the random event, and an overall optimal solution for the problem is obtained. *Dantzig* (1955) gives a complete computational procedure for two stage LP models. He illustrates the use of two stage LP to obtain the minimum cost of shipping items from a factory to meet an uncertain demand at a specified outlet. *Loucks* (1967) applies two stage LP in formulating a water resources related problem. This approach has the advantage of penalizing the constraint violation in the second stage when the estimated value of the random event (associated with the constraint) is not predicted correctly in the first stage. However the linear programs required are large in size and are expensive in terms of computational burden.

A third type of stochastic programming is called chance constrained programming (CCP). In this case, the constraint associated with the random event is converted into its deterministic equivalent using the probability distribution function of the random variable. This method has the ability to incorporate the probability of satisfying a given need such as flood protection, water supply, storage level in the reservoir, or low flow augmentation. CCP is introduced by *Charnes et al.* (1958) and illustrated with a model developed to determine refinery rates for heating oils where the weather dependent demands are stochastic. *Loucks et al.* (1981) demonstrates that in terms of precision of the optimal solution value, CCP does an inferior job when compared to stochastic programming with recourse. Furthermore, CCP unlike stochastic programming with recourse, does not explicitly penalize the constraint violation nor does it provide recourse action to correct realized constraint violations (*Yeh* , 1985). The major advantage of chance constrained programming over stochastic programming with recourse is its relatively smaller model size.

Another method of incorporating stochasticity into reservoir management models is called reliability programming (RP). Unlike chance constrained programming, the risk or reliability of a certain function of the system to be modelled is incorporated as a decision variable and not fixed *a priori* (*Sengupta*, 1972). Hence, an RP model can be constructed in such a way as to explicitly account for the trade-offs between the objective of a system and its associated risk.

Colorni and Fronza (1976) apply RP for reservoir management. The objective of their model is to maximize the net benefit associated with reservoir operation and to minimize the yearly risk associated with satisfying the constraint which specifies the release to meet the contract volume. *Simonovic and Marino* (1980) formulate a similar but more detailed RP model. Unlike *Colorni and Fronza* (1976) who express the reliability of the system through a single reliability constraint, *Simonovic and Marino* (1980) use two reliability constraints to incorporate the yearly risk associated with the objective of the model. These are functions of the flood risk and drought risk. They apply their model to a hypothetical single multipurpose reservoir. The detailed methodology for obtaining risk-loss functions associated with flood risk and drought risk and its application to a real life multipurpose reservoir is explained in the work by *Simonovic and Marino* (1981). They state that a similar approach could also be employed in obtaining risk-loss functions for other reservoir purposes.

Marino and Mohammadi (1983) use an RP model based on the chance constrained linear programming (CCLP) and the DP approach. The CCLP approach is used to define the flood and drought reliabilities in the form of chance constraints and the reliabilities are varied parametrically. The solution procedure employed in the DP approach is used to determine the trade-offs between flood and drought

reliabilities. They apply their model to the Folsom Reservoir of the California Central Valley project.

In comparison with deterministic LP models, more time and effort are usually spent on stochastic programming models due to the process of explicitly incorporating the stochasticity of the random event in the model. The availability of data is another factor which limits the use of stochastic programming models.

Most of the aforementioned research used optimization models with objective functions that are primarily designed for a single purpose, and that incorporate the other purposes as strict constraints. However, recent applications in water resources systems have been directed towards selecting or identifying trade-offs between several conflicting goals. Goal programming (GP) is a very useful method when the objective of a model is to obtain solutions which are as close as possible to a specified value of several conflicting objectives. The concept of GP is initiated by *Charnes and Cooper* (1961). Under this method the objective function minimizes deviations from specified target values. GP seems very promising when the most ideally suited values of the goals are known. It also allows the various goals to be ranked according to their relative importance by assigning suitable weights to the deviations from the respective goals. GP formulations can easily incorporate the preferences of the decision makers in the specified values of the goals.

Changchit and Terrell (1989) present a chance constrained GP model to achieve target values of several conflicting objectives such as providing flood protection and municipal and industrial water supply, and maintaining sufficient water in a reservoir for hydro-electric power generation and recreation. *Goulter and Castenson* (1988) present a mixed integer goal programming model to minimize the deviations below the recommended levels of Lake Sommen in Sweden. The

objective of the model is to satisfy the conflicting uses of fishing and boating on the lake, hydro-electric power generation, and irrigation and urban water supply. However, this model is unable to achieve a satisfactory solution due to the restrictiveness of the operation of the reservoir. *Can and Houck* (1984) use GP for real time daily reservoir system operation and apply it to the Green River Basin, in Kentucky. The objective of the GP model is to minimize deviations from a predefined storage zone while achieving the most desirable downstream flows. *Datta and Burges* (1984) also use a GP model to examine the trade-offs between conflicting storage and release targets in hypothetical river basins.

The major advantage of the GP technique is its ability to find a solution in most circumstances where a feasible solution may not exist, by relaxing the constraint which causes infeasibility. Furthermore, the GP approach tends to result in solutions that are relatively more appealing to the decision maker since it may explicitly incorporate the decision maker's preference. In addition, it may also be used with nonlinear programming techniques.

One of the primary criticisms of the GP approach in multiobjective analysis of water resources projects is the difficulty in obtaining appropriate levels for the goals and in assigning appropriate weights to deviations from these goals (see e.g., *Goulter and Castenson,* 1988). Hence when sufficient data is available in terms of costs and benefits for the objectives of the problem, it may be better to use an objective function which incorporates these costs and benefit functions as long as this function is linear or may be linearized.

The major drawback of LP is its inability to precisely incorporate nonlinear functions. On the other hand, although there are quite a few software packages available for solving nonlinear programs, they are not as efficient as their counterparts

used in solving linear programs. Moreover, most of these software packages have a tendency to decrease in accuracy as the size of the nonlinear model increases. They are also incapable of handling very large models. Fortunately, under suitable conditions a nonlinear function can be linearized, using various linearization techniques, such as piecewise linearization and first-order Taylor Series expansion.

ReVelle et al. (1967) presents an LP model which determines the degrees of treatment of wastewater in a waterway based on a least cost objective and the oxygen sag equation. The objective function is to minimize the total treatment cost, which requires a piecewise linearization of the relationship between the total annual cost and the treatment plant efficiency. *Dagli and Miles* (1980) propose a simple solution approach for analysis of a series of reservoirs. The objective function is to maximize the total head of water retained in the reservoirs. Since the hydraulic head is a nonlinear function of the volume of water stored in the reservoirs, the objective function and some constraints of this problem are nonlinear. Therefore, the relationship between storage volume and head is linearized in order to satisfactorily solve this problem. *Houck and Cohon* (1978) design a management policy for a multipurpose multiple-reservoir system by using a special algorithm to solve a nonlinear program. The nonlinearity is caused by the benefit, loss, and cost functions in the objective and the products of the joint probabilities of some random variables in the constraint set. The approximate solution to the nonlinear program is obtained by sequentially solving two linear programs which are subsets of the nonlinear program. However, the authors conclude that the huge computational burden was one of the major weaknesses of the model.

Alternatively, dynamic programming (DP) may be used to solve some nonlinear programs. DP is a procedure for optimizing a multistage decision process, where complex problems are effectively decomposed into a series of subproblems

which are solved recursively (see e.g., *Bellman*, 1957). DP has proved to be very practical and helpful in solving water resources problems that require the precise incorporation of nonlinear functions. It also has been shown to be helpful when applied to problems requiring a series of interrelated decisions (*Dreyfus and Law*, 1977). *Yeh* (1985) provides a review of DP as applied to reservoir optimization problems (see e.g., *Little*, 1955; *Young* , 1967; *Meir and Bleighter*, 1967; *Hall et al* , 1968; *Schweig and Cole*, 1968; *Fitch et al.*, 1970; *Hall and Buras* , 1961; *Liu and Tedrow*, 1973; *Opricovic and Djordjivic*, 1976; and *Collins*, 1977) and states that dynamic programming is well suited to handle the following types of water resources problems: progressive directed networks for capacity expansion problems, deterministic dynamic programming for short-range operation, and stochastic dynamic programming for long-range operation.

DP can also be effectively used for linear problems. *Becker and Yeh* (1974) suggest a combined solution methodology of LP and DP for determining optimal real time reservoir operations associated with the California Central Valley Project. *Takeuchi and Moreau* (1974) describe a similar idea where a combination of LP with stochastic DP was developed.

Optimization based management models structured for multiobjective problems can generate many management policies, while identifying the trade-offs between the conflicting objectives. Simulation models can prove to be very useful in determining the most preferred management policy. Simulation models may also be used for checking the validity of the policies in realistic situations and for identifying the long-term benefits or costs of implementing a particular operating policy. *Simonovic* (1991) presents a methodology for evaluating operating policies for a multipurpose reservoir and applies it to the same case study as that of this thesis. His methodology is quite similar to that used in selecting a preffered operating policy for

the case study. *Evenson and Moseley* (1970) show how valuable information can be obtained in the development and operation of a complex water resource system using a set of simulation and optimization techniques. *Jacoby and Loucks* (1972) describe the combined use of optimization models for screening models to obtain high valued alternatives which are then evaluated using simulation models in river basin planning.

The literature regarding the application of optimization techniques for managing reservoirs for downstream water quality needs is limited. *Rhode and Naparaxawong* (1981) present an optimization model of an existing two reservoir system in Thailand in which one of the objectives of the model is to regulate the supply of water for salinity control. *Gordon* (1983) considers the construction of special reservoirs for waste water dilution. Although he did not use optimization techniques to solve the problem of the conflicting uses of wastewater dilution and hydroelectric power generation, he shows that reservoirs built for these two objectives are complex to manage. *Simonovic and Orlob* (1984) develop a risk-reliability approach for optimal reservoir releases for downstream water quality control of total dissolved solids. Their model accounts for agricultural production losses and risk losses associated with other water uses and is applied to the New Melones Multipurpose Reservoir in California.

Shafer et al. (1981) presents an approach for accounting for a new demand placed on available water resources in a river basin. The new demand is for water supply for a cooling pond at a coal fired electric generation facility in the Cache la Poudre River basin in North Central Colorado. The goals are to ensure delivery of a physically and legally feasible firm water supply to the power plant without causing injury to the established water users in the river basin. The model does not include the goal of controlling temperature at any point in the river. Moreover, the water required for supplying cooling water does not compete greatly with the other uses,

since the system of this case study is flexible due to a series of interconnected reservoirs.

Yang (1991) uses a GP model to identify optimal seasonal operating policies for a multipurpose reservoir. The objective of the model is to minimize the deviations from the target values of the conflicting uses of storage for recreation in the reservoir and cooling water supply. The cooling water ensures a monthly supply of water to a once through direct cooling facility of a downstream thermal power plant. However, the cooling water supply is modelled as a fixed constant demand for each month of the year. It does not represent the monthly amount of power that could be generated nor does it represent the dilution required to meet a temperature standard in the river.

No work has been reported on explicitly modelling the relationship between maintaining a temperature standard in a river and the operation of a reservoir. The major contribution of this thesis is the development of equations that represent the relationship between reservoir releases and temperature controls in the river and the incorporation of this relationship in optimization models for generating efficient reservoir management policies.

Modelling the temperature in a river is a very complex issue. River temperatures depend on the climatic conditions of the regions through which the river flows, on hydraulic characteristics of the river, and on the temperature of the water inputs. The major factors causing changes in the thermal regime of the river are the exchange of energy to the surrounding atmosphere and river banks, man made or natural obstructions such as weirs, rapids or waterfalls across the path of river flow; the magnitude and nature of heat input into the river; evaporation and condensation;

internal heat dissipation by friction; and convection and diffusion in the water mass (*Jacquet*, 1983).

The resulting temperature in a river due to heated effluent may be simulated with mathematical models. *Edinger et al.* (1974) developed a relationship for predicting stream temperature at any distance downstream from the point of thermal discharge, as a function of various parameters such as stream velocity, depth of flow, dew point temperature in the region, wind velocity, and upstream temperature. These authors also provide a full and detailed treatment of heat balance, heat exchange, and resulting temperature in water bodies. Most applications of temperature modelling have been based on this relationship (for example, *Thomann et al.* (1975), and *DiToro and Connolly* (1980) have applied finite difference models based on the same relationship for complex lake and estuarine settings).

Part of the work presented in this thesis identifies management strategies for reducing the heat input from thermal power plants by diluting it with water released from an upstream reservoir. This may prove unpopular with the other users since the reservoir manager might have to sacrifice other water demands in order to meet this dilution requirement. In such cases, other more efficient cooling systems may be necessary. The most widely used alternative cooling systems are :

i) once through direct cooling systems,

ii) cooling ponds,

iii) spray ponds, and

iv) cooling towers.

A discussion of these various heat control methods is presented in *Oleson and Boyle* (1972), *Jimeson and Adkins* (1972), and *Krenkel and Novotny* (1980). The most efficient of these are the cooling towers, but they have higher capital and

operation and maintenance costs. A comparison of the costs of these different cooling methods can be found in the work of *Jimeson and Adkins* (1972). This thesis employs a mixed integer programming model to identify the optimal strategy for operating once through direct cooling systems in conjunction with cooling towers in regulated river basins. No previous work on this topic has been reported in the literature.

3. THE RESERVOIR MANAGEMENT MODEL THAT ACCOUNTS FOR POWER GENERATION

This chapter describes a linear GP model which incorporates the dilution needs of thermal effluent from a downstream thermal power plant in a reservoir management program. This model minimizes deviations from power generation and reservoir storage and release targets while meeting constraints on downstream temperature standards. It requires a constraint set that relates the magnitude of river flow at the point of discharge to the allowable power generation, as a function of the upstream temperature, the specified temperature standard, ambient parameters such as wind velocity and dew point temperature, the velocity and depth of flow, and the physical characteristics of the thermal generating station. The detailed development of this constraint set is also described in this chapter.

3.1 The Reservoir Management Model

The reservoir optimization model developed in this research is:

$$\text{Minimize } Z = \sum_{j=1}^{m} \sum_{i=1}^{n} (US_i^j + LS_i^j + UR_i^j + LR_i^j) + w \sum_{j=1}^{m} \sum_{i=1}^{n} u_i^j \quad (3.1)$$

subject to:

continuity:

$$S_i^j - S_{i-1}^j - I_i^j + R_i^j + E_i^j = 0 \qquad \forall\ i = 1, 2, \ldots, n,\ j = 1, 2, \ldots, m \qquad (3.2)$$

initial storage in each year equal to the ending storage in the previous year:

$$S_0^j - S_n^{j-1} = 0 \qquad \forall\, j = 1, 2, \ldots, m \qquad (3.3)$$

initial storage in the first year equal to the ending storage in the final year:

$$S_0^1 - S_n^m = 0 \qquad (3.4)$$

limits on storage and release volume:

$$Smin \le S_i^j \le Smax \qquad \forall\, i = 1, 2, \ldots, n, j = 1, 2, \ldots, m \qquad (3.5)$$

$$Rmin \le R_i^j \le Rmax \qquad \forall\, i = 1, 2, \ldots, n, j = 1, 2, \ldots, m \qquad (3.6)$$

definition of deviations from the targets of storage and release:

$$S_i^j + LS_i^j - US_i^j - STARGET_i^j = 0 \qquad \forall\, i = 1, 2, \ldots, n, j = 1, 2, \ldots, m \qquad (3.7)$$

$$R_i^j + LR_i^j - UR_i^j - RTARGET_i^j = 0 \qquad \forall\, i = 1, 2, \ldots, n, j = 1, 2, \ldots, m \qquad (3.8)$$

magnitude of river flow at the site of the thermal power plant:

$$R_i^j + TI_i^j - DM_i^j - Q_i^j = 0 \qquad \forall\, i = 1, 2, \ldots, n, j = 1, 2, \ldots, m \qquad (3.9)$$

allowable power generation:

$$G_i^j - g(T_i, Q_i^j, STD_i) \le 0 \qquad \forall\, i = 1, 2, \ldots, n, j = 1, 2, \ldots, m \qquad (3.10)$$

definition of deficit in meeting the target power generation:

$$G_i^j + u_i^j - GDES_i^j \geq 0 \qquad \forall\ i = 1, 2, \ldots, n, j = 1, 2, \ldots, m \qquad (3.11)$$

where :

i	=	time period in a year (for example weeks, months, or seasons);
j	=	year;
n	=	total number of time periods in a year;
m	=	total number of years;
LS_i^j	=	deviation below the target of storage volume in period i and year j, in m^3;
US_i^j	=	deviation above the target of storage volume in period i and year j, in m^3;
LR_i^j	=	deviation below the target of release volume in period i and year j, in m^3;
UR_i^j	=	deviation above the target of release volume in period i and year j, in m^3;
u_i^j	=	deviations below the desired power generation target in period i and year j, in Gwhr;
w	=	weight on the deviations from the desired power generation targets;
S_i^j	=	ending storage in period i of year j, in m^3;
S_0^j	=	initial storage in year j, in m^3;
I_i^j	=	inflow into the reservoir during period i of year j, in m^3;
R_i^j	=	water released from the reservoir during period i of year j, in m^3;

E_i^j = evaporation from the reservoir during period i of year j, in m^3;

$Smin$ = lower physical limit of the reservoir storage, in m^3;

$Smax$ = upper physical limit of the reservoir storage, in m^3;

$Rmin$ = lower physical limit on the release from the reservoir, in m^3;

$Rmax$ = upper physical limit on the release from the reservoir, in m^3;

Q_i^j = river flow at the point of discharge of the thermal power plant in period i of year j, in m^3;

TI_i^j = sum of the tributary inflows in the reach of the river from the reservoir to the point just upstream of the thermal power plant during period i of year j, in m^3;

DM_i^j = sum of the withdrawals of water in the reach of the river from the reservoir to the point just upstream of the thermal power plant during period i of year j, in m^3;

$STARGET_i^j$ = reservoir volume target during period i of year j, in m^3;

$RTARGET_i^j$ = release target during period i of year j, in m^3;

G_i^j = generation in period i of year j, in Gwhr;

$GDES_i^j$ = desired power generation during period i of year j, in Gwhr;

$g(T_i, Q_i^j, STD_i)$ = relationship which defines the maximum allowable power that can be generated as a function of stream temperature, T_i, river flow, Q_i^j, and the temperature standard, STD_i, in period i of year j.

The objective function (*Equation* 3.1) minimizes the deviations from the target values for the specified goals of the reservoir storage levels and the release requirements, and the deficits below the targets of thermal power generation. Usually the storage targets represent a specified value or a specified range of storage volume for recreation or flood control. *Equation* 3.1 assumes a situation where the storage

target represents a specified value. The storage targets can also represent the head of water in the reservoir for hydroelectric power generation, in a situation where the reservoir is used to provide hydroelectricity. The release targets usually represent the water requirements of the river basin serviced by the reservoir, or a threshold value of flooding. The deficits below the targets of thermal power generation are a function of the river flow which is related to the release from the reservoir.

Equation 3.2 ensures continuity in the consecutive time periods, i, in terms of the inflow, release, evaporation, and storage volume of the reservoir. *Equation* 3.3 ensures continuity in storage levels between the years of the model. *Equation* 3.4 ensures that the storage at the end of the nine year period is equal to the initial storage. *Equations* 3.5 and 3.6 define the lower and upper limits of storage and release, respectively. These limits are based on the physical characteristics of the reservoir and on management concerns such as the minimum required volume in the reservoir and low flow requirements.

The model is structured assuming that deficits or a surpluses in storage and release targets are considered undesirable. *Equations* 3.7 and 3.8 define the deficits and surpluses. The magnitude of river flow at the point of thermal discharge is calculated in the model by *Equation* 3.9. *Equation* 3.10 defines the allowable power that can be generated as a function of the river flow and *Equation* 3.11 defines the deficit in the desired generation value. *Equations* 3.1, 3.9, 3.10, and 3.11 determine the release to be made from the reservoir in order to minimize the deviations below the target generation level. The following sections in this chapter describe the development of the function $g(T_i, Q_i^j, STD_i)$ used in *Equation* 3.10.

3.2 Relationship Between River Flow and Allowable Power Generation

Consider a stream receiving heated discharge from a thermal power plant which is using a once through direct cooling system. The heated discharge raises the river temperature immediately and this temperature subsequently degrades following the first-order relationship illustrated in Figure 3.1. Here T_o is the average stream temperature immediately downstream of the point of emission, in °C, T_x is the average stream temperature X meters downstream of the point of emission, in °C; and T_b is the average stream temperature immediately upstream of the point of emission, in °C.

If the river temperature, T_x, at a point X meters downstream from the thermal power plant is known, then the temperature in the river immediately downstream of the point of thermal discharge may be defined by a modified version of the relationship developed by *Edinger et al.* (1974):

$$T_o = (T_x - T_b) \exp\left(\frac{K_r X}{V}\right) + T_b \qquad (3.12)$$

where:

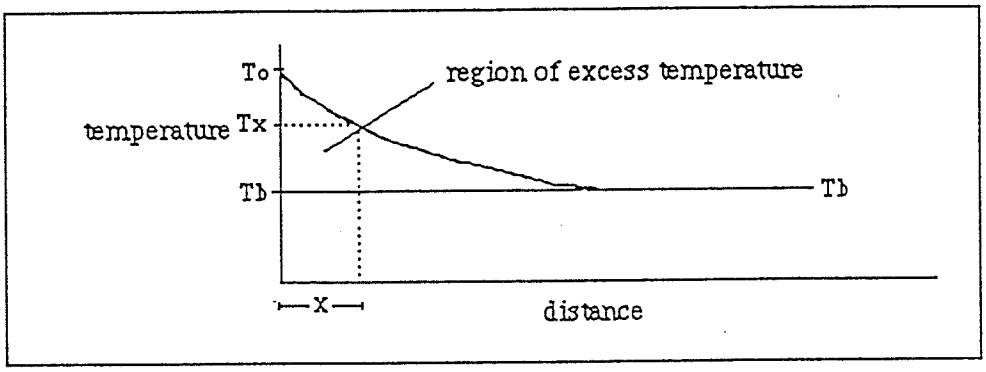
X = distance between the point of emission and the downstream point where the temperature, T_x, is known, in meters;

V = average stream velocity for the length of the river between the point of emission and the point X meters downstream, in meters/day;

K_r = heat exchange coefficient, in days^{-1}; and

all other variables are defined above.

If the temperature standard is set equal to T_x, then this equation can also be used to calculate the allowable temperature immediately downstream of the point of emission.



To = average stream temperature immediately downstream of the point of emission, in °C

Tx = average stream temperature X meters downstream of the point of emission, in °C

Tb = average stream temperature immediately upstream of the point of emission, in °C

Figure 3.1 Temperature pattern in a river receiving heated discharge.

In the development of *Equation* 3.12 *Edinger et al.* (1974) assumes homogeneity in temperature throughout a cross section of the river (i.e., one-dimensional temperature models). Although this assumption is not always verified, it only results in appreciable errors in exceptional cases (*Jacquet,* 1983). The heat exchange coefficient for the river, K_r, is calculated with the following relationship taken from *Thomann and Mueller* (1987):

$$K_r = \frac{K}{\rho \; C_p \; H} \tag{3.13}$$

where:

K	=	approximate average heat exchange coefficient, in cal / cm^2 day °C;
ρ	=	water density, in g/cm^3;
C_p	=	specific heat of water, in cal / g °C; and
H	=	river depth, in cms.

The velocity and depth of river flow, V and H, respectively, vary with the river discharge and play a significant role in the above equations. The value of K in *Equation* 3.13 is calculated using the following relationship (see, e.g., *Thomann and Mueller,* 1987):

$$K = 2.066 \left\{ 4.5 + 0.05\,T + [0.82 + 0.0075\,(T + T_{dew}) + 0.0012\,(T + T_{dew})^2]\,[9.2 + 0.46\,U^2] \right\} \tag{3.14}$$

where:

T = average water temperature in the reach of the river of interest, i.e., between the point of emission and X meters downstream, in °C;

T_{dew} = dew point temperature in the region in which the river reach of interest is located, in °C; and

U = wind speed in the region in which the river reach of interest is located, in m/sec.

Having calculated the allowable temperature in the river at the point of thermal discharge using *Equations* 3.12 - 3.14, the allowable temperature of the thermal effluent can be found with the following mass balance equation:

$$T_d = \frac{T_o\, Q - T_b\, [Q - Q_d]}{Q_d} \tag{3.15}$$

where:

T_d = allowable temperature of the thermal effluent, in °C;

Q = total river flow immediately downstream of the point of discharge of the thermal effluent, in m^3/sec;

Q_d = amount of water withdrawn from the river for cooling, in m^3/sec; and

all other variables are described above.

The assumptions on which *Equation* 3.15 is based are that the amount of coolant water lost in the cooling process is negligible and that complete mixing occurs at the point of thermal discharge. The latter assumption is typical of one dimensional models where homogeneity is assumed throughout a cross section of a river. This simple mass balance in conjunction with *Equations* 3.12 - 3.14 would adequately determine the allowable effluent temperature in cases of turbulent streamflows. However, it may cause appreciable errors by overpredicting the allowable effluent temperature in rivers having very low flows. Usually under low flow circumstances, the thermal effluent forms a plume and thermal stratification is produced in the river. Although several multidimensional models exist for modelling the different temperatures of the plume and the other thermal layers of the river, these models are efficient only if highly accurate data is available on the river flow characteristics. The

computational burden of these models is also relatively large. For these reasons, for purposes of this thesis *Equation* 3.15 is assumed to be valid.

The allowable electric power that can be generated by the thermal power plant can be related to the allowable effluent temperature, T_d, using the following relationship (see, e.g., *Thomann and Mueller,* 1987):

$$G = \frac{\gamma Q_d \ \mathrm{CF} \ (T_d - T_b)}{\mathrm{R_g}} \tag{3.16}$$

where:

G	=	amount of power generated, in Gwhr;
$\mathrm{R_g}$	=	heat rejection per unit generation, in million BTU/Gwhr;
γ	=	specific weight of water, in lb/ft^3;
CF	=	a conversion factor having a value of 5.493; and

all other variables are defined above.

Equations 3.12, 3.15, and 3.16 can be summarized by the following equation:

$$\mathrm{G} = \frac{\gamma Q \ \mathrm{CF} \left[(T_x - T_b) \exp\left(\frac{K_r X}{V}\right) \right]}{\mathrm{R_g}} \tag{3.17}$$

If T_x is set equal to the stream temperature standard, STD_i, and T_b is set equal to the temperature upstream of the plant, T_i, for a given time period i, then *Equation* 3.17 may be used to evaluate the allowable power generation in time period i as a function of the background stream temperature, the stream discharge, and the temperature standard $g(T_i, Q_i^j, STD_i)$. This function is typically nonlinear but may be approximated as linear.

4. APPLICATION OF THE RESERVOIR MANAGEMENT MODEL

The reservoir management model is applied to a case study based on the Shellmouth Reservoir and Dam, which is located on the Assiniboine River in south-western Manitoba. This multipurpose reservoir was constructed in 1969 and is currently managed and operated by the Water Resources Branch of the Manitoba Department of Natural Resources. The power plant of interest is the thermal generating station in the City of Brandon, Manitoba. This power plant is owned and operated by Manitoba Hydro.

Yang (1991) presents a linear GP model for identifying seasonal operating strategies for the same case study. The objective of his model is to minimize the sum of the deviations from storage targets and target values of the release required to meet the cooling water supply for the thermal power plant at Brandon. However, the target values for cooling water supply do not relate to the magnitude of power production, nor do they relate to the temperature standard a kilometer downstream from the point of thermal emission. The model presented in this thesis explicitly incorporates the thermal generation needs in an extension of Yang's GP model.

The data for the physical characteristics of the reservoir and the hydrological data for the river basin were obtained from the case study of *Yang* (1991). The Shellmouth Dam was constructed in the period from 1969 to 1971. Although it was initially designed for flood control, it also regulates water for different uses such as municipal, industrial, and irrigation supplies and dilution of municipal and industrial waste. It has a full supply level (FSL) of 477.36 million m^3 at a corresponding elevation of 429.42 m, and is approximately 1.28 km wide and 56.5 km long, at the FSL. The dead pool capacity is 12.33 million m^3 and the maximum outlet capacity is 198.1 m^3 per second. For the sake of simplicity, in this case study the Assiniboine

River is divided into three reaches. The first reach of the river extends from the Shellmouth Reservoir to the City of Brandon, the second from the City of Brandon to the City of Portage La Prairie, and the third from the City of Portage La Prairie to the City of Winnipeg.

4.1 Objectives of the Shellmouth Reservoir and Dam

Flood Protection: The dam provides flood protection to the entire river basin downstream of the Shellmouth Reservoir. The threshold value of river flow which causes flooding is assumed to be 1800 cfs based on communication with the Water Resources Branch of the Department of Natural Resources.

Water Supply: The reservoir should ensure a continued supply of water for municipal and industrial use throughout the year for the Cities of Brandon and Portage LaPrairie, Manitoba. It should also provide water for the seasonal demands for irrigation and farm water supplies in the Assiniboine River. A third demand is for the dilution of effluent from the various industries downstream of the reservoir and from the Cities of Brandon, Portage LaPrairie, and Winnipeg, Manitoba. Table 4.1 shows the total monthly requirement of water supply for municipal and industrial use, dilution of waste effluent, and irrigation and farm water supply which were obtained from *Yang* (1991).

Recreation: The reservoir should retain a sufficient volume of water, during the late spring and summer months, to maintain a sport fishery and to provide recreation. It should also achieve a specified volume during early spring (i.e., on April 1) for flood control. Table 4.2 shows the upper and lower targets for storage volume in each month which were also obtained from *Yang* (1991).

Table 4.1 Monthly Water Supply Demands (all units are in 10^3 m^3)†

Month	Municipal and Industrial,* Reach 1	Irrigation,# Reach 1	Municipal and Industrial, Reach 2	Irrigation, Reach 2	Dilution,** Reach 3
January	881.35	0.0	1145.39	0.0	7437.6
February	933.42	0.0	1123.08	0.0	7437.6
March	933.42	0.0	1145.39	0.0	7437.6
April	963.17	0.0	1145.39	0.0	7437.6
May	1097.05	81.81	1249.5	3205.6	7437.6
June	1521.0	238.04	1204.9	6277.3	7437.6
July	1201.17	788.39	1160.3	6277.3	7437.6
August	1201.17	394.19	1160.3	6277.3	7437.6
September	1015.23	81.81	1190.0	3205.6	7437.6
October	933.42	0.0	1197.5	2975.0	7437.6
November	903.67	0.0	1137.95	0.0	7437.6
December	881.35	0.0	1093.32	0.0	7437.6

† Obtained from *Yang* (1991).

* Water required for municipal and industrial use.

Water required for irrigation and farm water supplies.

** Water required for dilution of waste effluent for the City of Winnipeg.

Table 4.2 Monthly Upper and Lower Targets for Storage Volume (all units are in 10^3 m^3)†*

Month	Upper Storage Target	Lower Storage Target
January	no target	no target
February	no target	no target
March	no target	no target
April	200000.0	200000.0
May	413222.5	333045.0
June	413222.5	333045.0
July	413222.5	333045.0
August	413222.5	333045.0
September	no target	no target
October	no target	no target
November	no target	no target
December	no target	no target

† Obtained from the Water Resources Branch of the Department of Natural Resources.

* The storage targets in the month of April are for flood protection. The storage targets in the months of May through August are for recreation in the reservoir.

Dilution of Heated Effluent: The thermal generating station at Brandon has mandatory and desired target values for power generation in each month. The power plant is operated to provide local area support during winter months and it is also used to supplement local power generation for the hydroelectric generating stations in dry years. The mandatory target of power generation occurs in all years whereas the desired target of power generation occurs only in the dry years. The mandatory target denotes the level of power generation required when operated for local area support. The desired target denotes the level of power generation required to supplement the shortage in hydroelectric power in dry years, in addition to providing power to support the mandatory needs. Table 4.3 shows the monthly target values of the mandatory and desired level of power generation, which were determined by the Thermal Generation Production Division of Manitoba Hydro, Winnipeg.

4.2 The Reservoir Management Model for the Case Study

The reservoir management model is applied to this case study in order to obtain an operating policy which would meet the water supply and flood mitigation needs of the Shellmouth Reservoir as well as accommodate power production at a downstream generating station. The model divides each year into twelve monthly time periods. The operating policy that is obtained from the reservoir management model identifies the optimal monthly storage volume for each of three types of years (i.e., wet, average or dry years).

4.2.1 The Hydrologic Input for the Model

Yang (1991) develops four hydrologic scenarios and uses these as the inputs to his optimization models. Each hydrologic scenario consists of nine years of

Table 4.3 Monthly Mandatory and Desired Targets for Power Generation (all units are in Gwhr)†

Month	Mandatory Target*	Desired Target#
Jan	97.8	145.0
Feb	97.8	131.0
Mar	97.8	145.0
Apr	0.0	140.0
May	0.0	38.0
Jun	0.0	31.0
Jul	0.0	19.0
Aug	0.0	27.0
Sep	0.0	42.0
Oct	0.0	60.0
Nov	97.8	141.0
Dec	97.8	145.0

† Obtained from the Thermal Generation and Production Division, Manitoba Hydro.

* The mandatory targets for power generation occur only in the winter months of all types of years.

The desired targets for power generation occur only in the dry years.

historical inflow data, selected from forty years of inflow data from 1948 to 1987. These nine years of hydrologic data consist of three wet years (1975, 1976, and 1979), three average years (1967, 1970, and 1983), and three dry years (1961, 1963, and 1968). *Yang* (1991) employed this method in order to account for the stochastic nature of the inflows. The same input data is used for the optimization model presented herein. For the four scenarios, the hydrologic data is compiled as follows :

Scenario 1: Three wet years, three average years, and three dry years

Scenario 2: Three dry years, three average years, and three wet years

Scenario 3: One dry year, one average year, one wet year, etc.

Scenario 4: One wet year, one average year, one dry year, etc.

4.2.2 Formulation of the Management Model

As mentioned earlier the Assiniboine River is divided into three reaches. The thermal generating station is located at the beginning of the second reach. It is assumed that the sum of the tributary inflows into each reach contribute collectively to the river flow at the junction of that reach and to the successive downstream reaches. The sum of the withdrawals of water from the river in each reach is assumed to be collectively withdrawn at the beginning of each reach. These assumptions were made in order to avoid increasing the size of the model and to reduce the relative computational burden. Since the reservoir receives the major portion of the inflow in early spring, the year is assumed to begin with the month of April. Hence, month 1 in the reservoir management model corresponds to the month of April.

The objective of the model is to minimize the sum of the deviations from the flood protection and recreation storage targets and the sum of the deficits in mandatory and desired generation levels while meeting release demands for water supply, irrigation, and waste dilution. The flood protection storage target is required

only during the month of April. The recreation storage targets are represented as a range of storage values and are required during the months of May to August (i.e., month 2 through 4). The mandatory generation levels are seasonal and exist during the winter months of November through March only (i.e., month 8 through 12), whereas the desired generation levels exist throughout the year, in dry years only.

$$\text{Minimize } Z = \sum_{j=1}^{9} \sum_{i=1}^{5} (US_i^j + LS_i^j) + C_w \sum_{j=1}^{9} \sum_{i=8}^{12} D_i^j + w \sum_{j \in L} \sum_{i=1}^{12} u_i^j \tag{4.1}$$

subject to:

continuity:

$$S_i^j - S_{i-1}^j - I_i^j + R_i^j + E_i^j = 0 \qquad \forall\, i = 1, 2, \ldots, 12,\ j = 1, 2, \ldots, 9 \tag{4.2}$$

initial storage in each year equal to the ending storage in the previous year:

$$S_0^j - S_{12}^{j-1} = 0 \qquad \forall\, j = 1, 2, \ldots, 9 \tag{4.3}$$

initial storage in the first year equal to the ending storage in the final year:

$$S_0^1 - S_{12}^9 = 0 \tag{4.4}$$

limits on storage and release volume:

$$S_{min} \le S_i^j \le S_{max} \qquad \forall\, i = 1, 2, \ldots, 12,\ j = 1, 2, \ldots, 9 \tag{4.5}$$

$$R_{min} \le R_i^j \le R_{max} \qquad \forall\, i = 1, 2, \ldots, 12,\ j = 1, 2, \ldots, 9 \tag{4.6}$$

limits on the available water at a downstream site, e.g., for irrigation, water supply, etc.

for the individual reaches of the river:

$$F_i^{jk} + \sum_{n=1}^{k-1} TI_i^{jn} - \sum_{n=1}^{k} DM_i^{jn} = 0$$

$$\forall\, i = 1, 2, \ldots, 12,\ j = 1, 2, \ldots, 9,\ k = 2, 3 \qquad (4.7)$$

for the first reach of the river:

$$F_i^{j\,1} + DM_i^{j\,1} = 0 \qquad \forall\, i = 1, 2, \ldots, 12,\ j = 1, 2, \ldots, 9 \qquad (4.8)$$

for the entire river:

$$R_i^j - \sum_{k=1}^{3} F_i^{jk} \geq 0 \qquad \forall\, i = 1, 2, \ldots, 12,\ j = 1, 2, \ldots, 9 \qquad (4.9)$$

magnitude of river flow at the point of thermal discharge:

$$R_i^j + TI_i^{j\,1} - DM_i^{j\,1} - Q_i^j = 0 \qquad \forall\, i = 1, 2, \ldots, 12,\ j = 1, 2, \ldots, 9 \qquad (4.10)$$

defining of deviations from upper and lower storage targets, respectively:

$$US_i^j - S_i^j + SUP_i \geq 0 \qquad \forall\, i = 1, 2, \ldots, 5,\ j = 1, 2, \ldots, 9 \qquad (4.11)$$

$$LS_i^j + S_i^j - SLO_i \geq 0 \qquad \forall\, i = 1, 2, \ldots, 5,\ j = 1, 2, \ldots, 9 \qquad (4.12)$$

allowable power generation:

$$G_i^j - g(T_i, Q_i^j, STD_i) \leq 0 \qquad \forall\, i = 1, 2, \ldots, 12,\ j = 1, 2, \ldots, 9 \qquad (4.13)$$

definition of deficit in meeting the mandatory power generation:

$$G_i^j + D_i^j - GMAN_i \geq 0 \qquad \forall\ i = 8, 9, \ldots, 12,\ j = 1, 2, \ldots, 9 \qquad (4.14)$$

definition of deficit in meeting the desired power generation:

$$G_i^j + u_i^j - GDES_i \geq 0 \qquad \forall\ i = 1, 2, \ldots, 12,\ j\ \varepsilon\ L \qquad (4.16)$$

Also, in order to obtain a general management strategy, the storage volume is constrained to be the same in the same month of the same type of year.

where :

L = number of dry years in a given scenario, typically 3;

i = month;

D_i^j = deviation below the mandatory power generation target in month i and year j, in Gwhr;

Cw = weight on the deviations from the mandatory power generation targets;

k = reach of the river;

SUP_i = upper storage target in month i, in 10^3 m^3;

SLO_i = lower storage target in month i, in 10^3 m^3;

Q_i^j = river flow at Brandon Thermal Generating Station in month i of year j, in 10^3 m^3;

F_i^{jk} = total amount of water required to meet the demand for water in river reach k during month i of year j, in 10^3 m^3;

TI_i^{jn} = total tributary inflow in river reach n during month i of year j, in 10^3 m^3;

DM_i^{jn} = total demand for water in river reach n during month i of year j, in 10^3 m^3;

$GMAN_i$ = mandatory power generation during month i, in Gwhr; and all other variables are defined in Section 3.1.

The mandatory generation targets are very important. Therefore, it is preferred that D_i^j be as close to zero as possible. If D_i^j were constrained to be equal to zero however, an infeasibility would result for models under hydrologic Scenarios 1 and 2. Hence D_i^j is incorporated in the objective function with a very high weight, C_w, assigned to it. The value of C_w is chosen to be 10^6 for this case study.

Equations 4.2 - 4.6 are the same as *Equations* 3.2 - 3.6 described in Section 3.1. *Equations* 4.7 - 4.9 calculate the release required to meet the demands for water such as municipal and industrial supplies and waste effluent dilution in each reach, given the tributary inflows into the Assiniboine River. *Equation* 4.10 calculates the amount of available water at the point of thermal discharge. *Equation* 4.11 defines the deviations above the upper storage target and *Equation* 4.12 defines the deviations below the lower storage target. Since the month of April has only one storage target (see Table 4.2), the upper and lower storage target for April are considered the same.

The result of the model is the operating policy which is composed of the monthly storage volumes in a given type of year (i.e., wet, average, or dry). To achieve this the model has an additional constraint not shown here, requiring that the storage volume in each month be the same for all years for a similar type of year. For example, the month of September is required to have a storage level that is the same for all average years. *Yang* (1991) used these constraints in his management models in order to obtain a management policy for this case study.

Equation 4.13 limits the generation level of the power plant, in order to meet the given temperature standard in the river. The relationship between river flow

and power generation forms the important part of this constraint. The following sections of this chapter explain in detail the development of the relationship between river flow and allowable generation for the case study. This relationship is typically non-linear but is approximated as a linear function. *Equations* 4.15 and 4.16 define the deviations in mandatory and desired generation targets, respectively.

4.3 The Relationship Between River Flow and Allowable Power Generation

The thermal generating station at Brandon consists of five steam driven generating units. Generating Units 1 - 4 each have an ultimate capacity of 33 Mw, and a maximum sustainable output of 28 Mw. Generating Unit 5 has an ultimate capacity of 105 Mw and a maximum sustainable output of 88 Mw. Generating Units 1 - 4 were commissioned in 1958 and are less efficient than Unit 5, which was commissioned in 1969. The facility employs a once through direct cooling system and transfers the heat from the power generation process to the Assiniboine River, at Brandon.

The general form of the relationship between river flow and allowable generation as mentioned in Chapter 3 is as follows:

$$G = \frac{\gamma Q \ \mathrm{CF} \left[(T_x - T_b) \exp\left(\frac{K_r X}{V}\right) \right]}{R_g} \tag{4.17}$$

The data that are required for utilizing this equation are the background stream temperature, the stream temperature standard, the dew point temperature, the wind velocity, and the depth of flow and velocity corresponding to a given stream discharge,

in a given month, and the waste heat rejection of the power plant, R_g. (For a complete description of the variables and the development of *Equation* 4.17, see Section 3.2).

For the case study the allowable thermal effluent from the Manitoba Hydro power plant is constrained to meet a monthly temperature standard at a checkpoint one kilometer downstream from the point of thermal discharge on the Assiniboine River. The values of these monthly temperature standards represent the value of T_x in *Equation* 4.17. These values were derived by the Thermal Generation Production Division of Manitoba Hydro, Winnipeg, based on the estimated spawning periods and available thermal tolerance data for the key fish species inhabiting the Assiniboine River. The second column of Table 4.4 shows these monthly temperature standards.

Daily background river temperature values were obtained from the Thermal Generation Production Division of Manitoba Hydro, Winnipeg, for the twenty year record from 1949 to 1968. The distributions for these temperatures were evaluated and the mean monthly temperatures listed in column 3 of Table 4.4 were chosen to represent the value of T_b in *Equation* 4.17. It was found for the month of May, the mean background temperature is greater than the stream temperature standard (see Table 4.4). Hence, it is assumed in this case study that no generation is possible in the month of May.

The mean monthly wind velocities and dew point temperatures at Brandon were calculated from the available eleven year monthly record from 1978 to 1988. These data were obtained from the Water Resources Branch of the Department of Natural Resources, Winnipeg. The average monthly values for each year of the historical record were similar. Hence, the calculated mean monthly value for the wind velocity and dew point temperature were used. Column 4 and 5 of Table 4.4

Table 4.4 Monthly Values of Temperature Standard, Background Stream Temperature, Wind Velocity, and Dew Point Temperature

Month	Temperature* Standard, °C	Background* Stream Temperature, °C	Wind# Velocity, m/sec	Dew Point# Temperature,°C
January	6.0	0.97	4.48	-20.5
February	6.0	0.99	4.14	-17.0
March	6.0	1.05	4.24	-9.7
April	8.0	3.65	4.61	-3.2
May	12.0	13.27	4.67	2.8
June	23.0	19.28	4.27	8.8
July	25.0	23.06	3.54	12.8
August	25.0	21.49	3.71	10.7
September	25.0	15.16	4.37	5.4
October	20.0	8.46	4.40	-0.4
November	6.0	2.26	4.05	-8.6
December	6.0	1.06	4.47	-17.0

* Obtained from the Thermal Generation and Production Division of Manitoba Hydro, Winnipeg.

Obtained from the Water Resources Branch of the Natural Resources Department, Winnipeg.

shows these monthly values.

The available data for velocity and depth of flow were for a location just upstream of the power plant. These data were obtained from the Data Survey Department of Environment Canada, Winnipeg. They are comprised of the depth of flow, velocity of flow, and river discharge, measured at different times during the period from 1955 to 1973. Relationships between river discharge and depth of flow and river discharge and velocity of flow were determined based on these data. For these relationships only the data for ice-free periods were used. This is because in this case study it is assumed that the power plant operates continuously throughout the month. It has been shown that ice cover formation downstream of the plant is prevented during thermal discharge and for at least two days after the time that the discharge stops (*Bergman,* 1978). Furthermore, *Donald* (1975) recorded no ice cover for an approximate distance of 5.5 miles downstream from the point of thermal discharge during the winter of 1973 - 1974.

The relationships between velocity and discharge, and depth and discharge were found by using regression techniques and logarithmic transformations of the available data. Figures 4.1 and 4.2 show these relationships plotted along with the raw data. Figure 4.1 shows the comparison for the velocity - discharge relationship and Figure 4.2 shows the comparison for the depth - discharge relationship. The relationships calculated are as follows :

$$V = 0.1197\, Q^{0.41} \tag{4.18}$$

$$H = 0.2931\, Q^{0.379} \tag{4.19}$$

where:

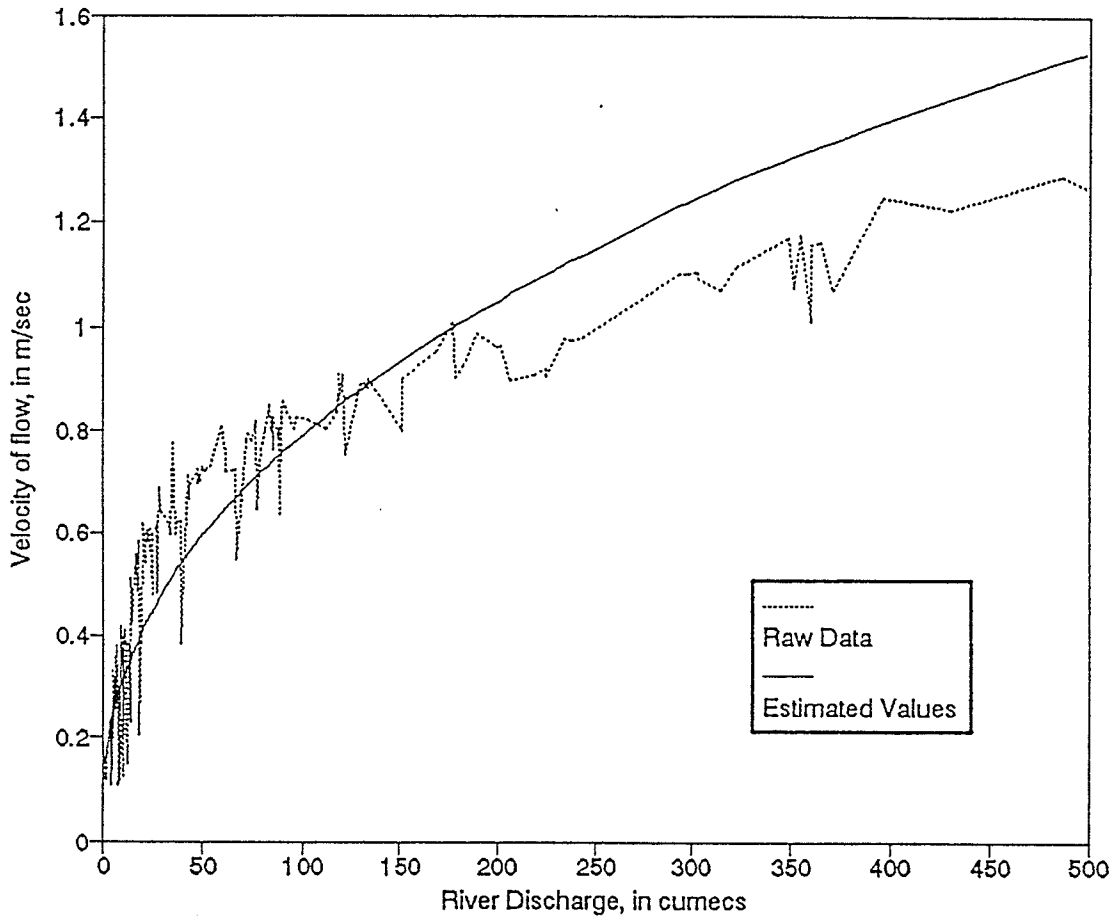


Figure 4.1 Raw data and estimated relationship between river flow and velocity of flow.

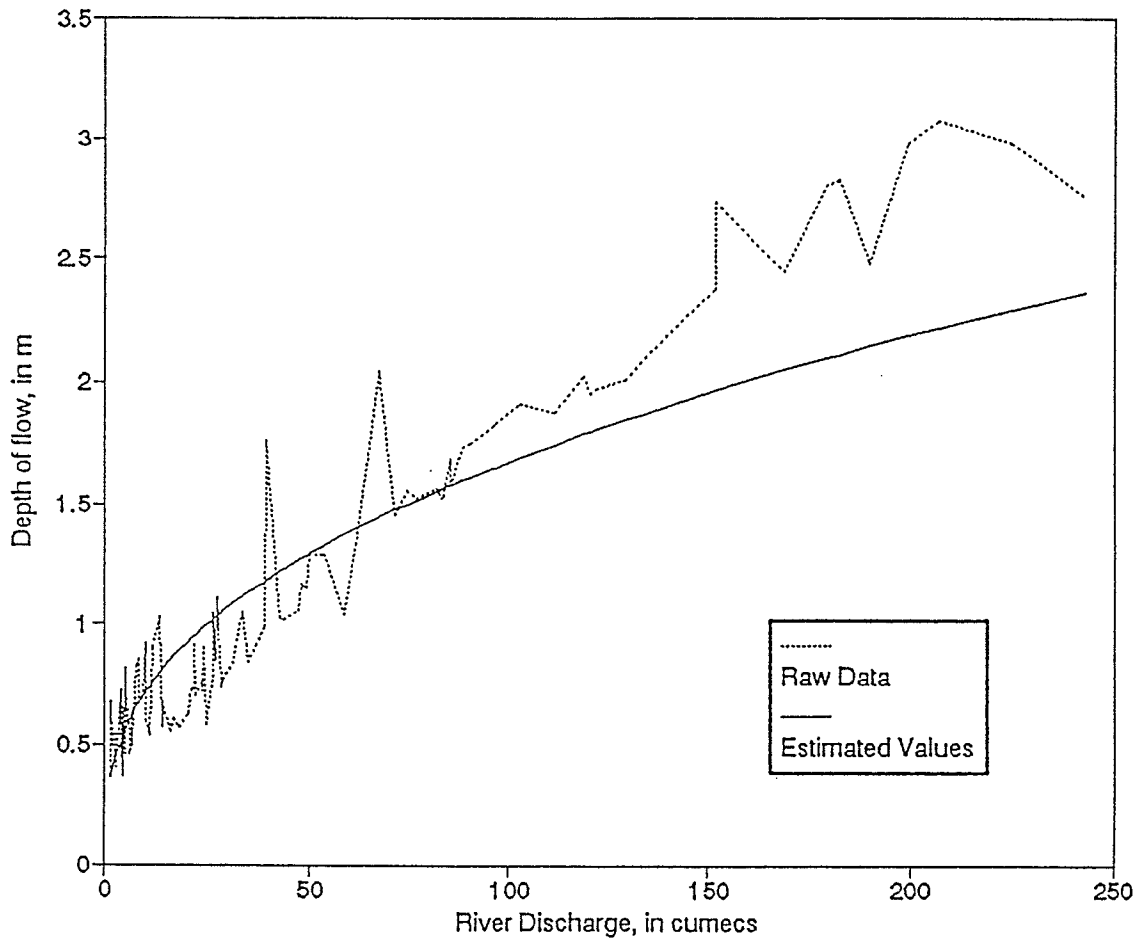


Figure 4.2 Raw data and estimated relationship between river flow and depth of flow.

V = velocity of flow, in m/sec;

Q = discharge, in m3/sec; and

H = depth of flow, in m.

The correlation coefficients for *Equations* 4.17 and 4.18 are 0.922 and 0.904, respectively.

The rate of heat rejection for the power plant is a function of the power generated. The heat rejection per unit generation for the five individual generating units are as follows :

Generating Units 1 - 4 have a heat rejection of 7195 million BTU / Gwhr, and Generating Unit 5 has a heat rejection of 5694 million BTU / Gwhr.

4.4 Verification of the Relationship Between River Flow and Allowable Power Generation for the Assiniboine River

In order to evaluate the performance of the equations used to model temperature, field data for the Assiniboine River were compared with model results. During the months of November 1989 to March 1990 and the month of November 1990 the Thermal Generation Production Division of Manitoba Hydro monitored the river temperature and plant characteristics for the Brandon power plant. The monitoring data include daily values for: the amount of power generated by each Generating Unit at the plant, the rate of effluent discharge, the river temperature upstream of the power plant and at a point 1.6 km downstream of the power plant, and the temperature of the plant effluent. The downstream river temperature and the thermal effluent temperature were measured every eight hours, but the power generated was recorded as the total for each day, i.e., the total amount produced by

each generating unit. Daily river flow values were sparse, so additional river flows at Brandon were also obtained from the Data Survey Branch of Environment Canada, Winnipeg. Since daily values of wind velocity and dew point temperatures were not available, the calculated mean monthly values from the eleven year period of record previously mentioned were used. The specific times of operation of each individual Generating Unit were not available. Hence it was assumed that for a given day the operating Generating Units were in operation for twenty four hours, and the mean of the three daily readings of the effluent and downstream temperatures was the corresponding daily mean effluent and downstream temperature, respectively.

Substituting the daily values of river flow, upstream river temperature and power generation for each Generating Unit, into the *Equations* 3.12 - 3.17, the stream temperature 1.6 km downstream from the point of thermal effluent discharge was estimated. Figures 4.3 to 4.8 show plots of the the river temperature 1.6 km downstream from the point of thermal effluent discharge for each month, for estimates based on *Equations* 3.12 - 3.17 and for the mean measured values. For example, Figure 4.4 shows the plot of the estimated and mean measured downstream temperatures for the month of December, 1989. The two values are in agreement during the latter part of the month. The estimated value seems to be slightly more than the measured value for most days. This observation shows that the *Equations* 3.12 - 3.17 are relatively conservative in predicting the downstream temperature when compared to the measured values. The estimated value also follows the same trend as the mean measured value. These observations may be made for most of these figures except those for November, 1989 and 1990. No explanation could be determined for the poor verification for November, 1989. The results for November, 1990 were somewhat more encouraging because the pattern of temperature variation for the estimated and monitored values were consistent.

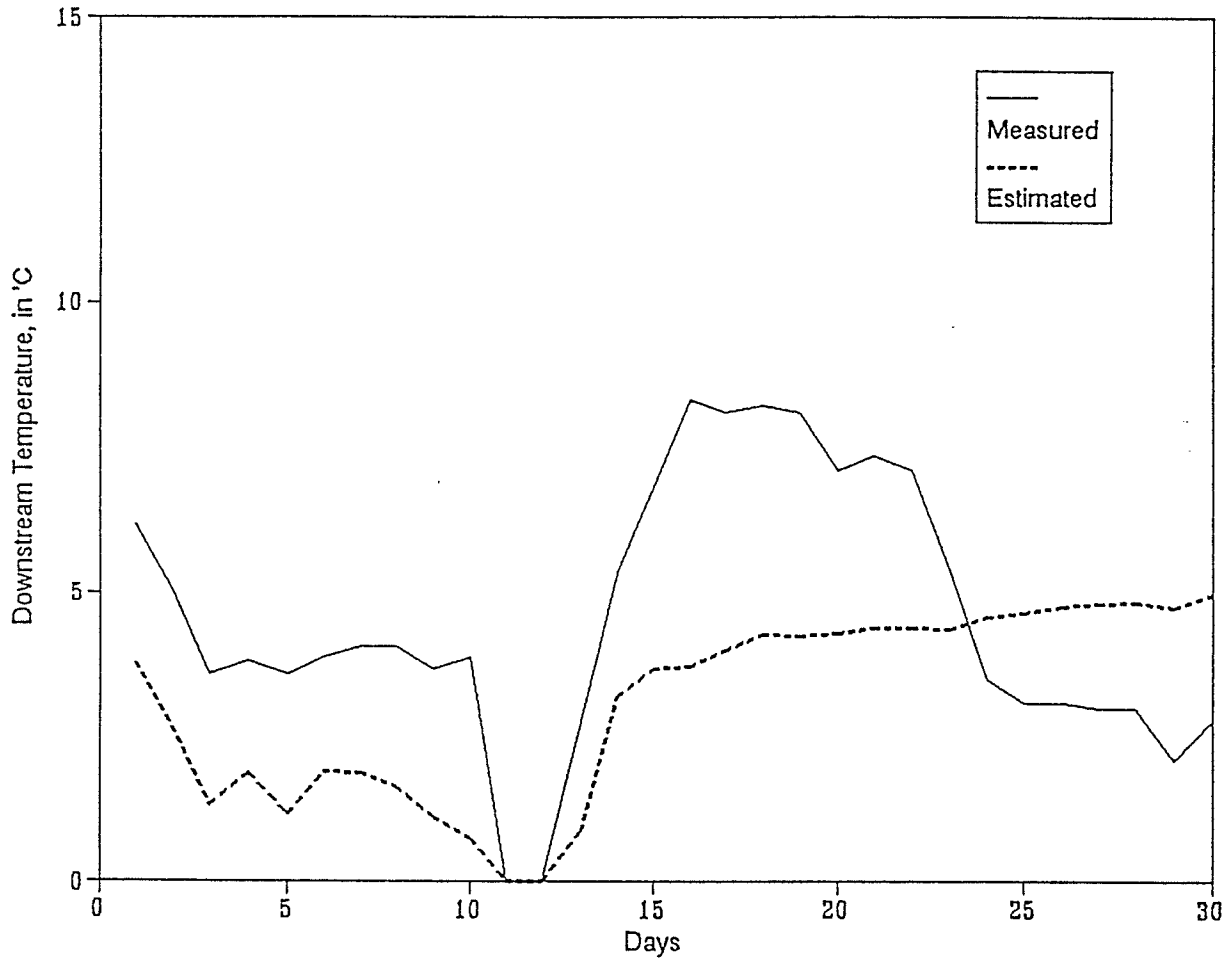


Figure 4.3 Measured field data and estimated value for the river temperature 1.6 km downstream from the Brandon thermal power plant for the month of November 1989.

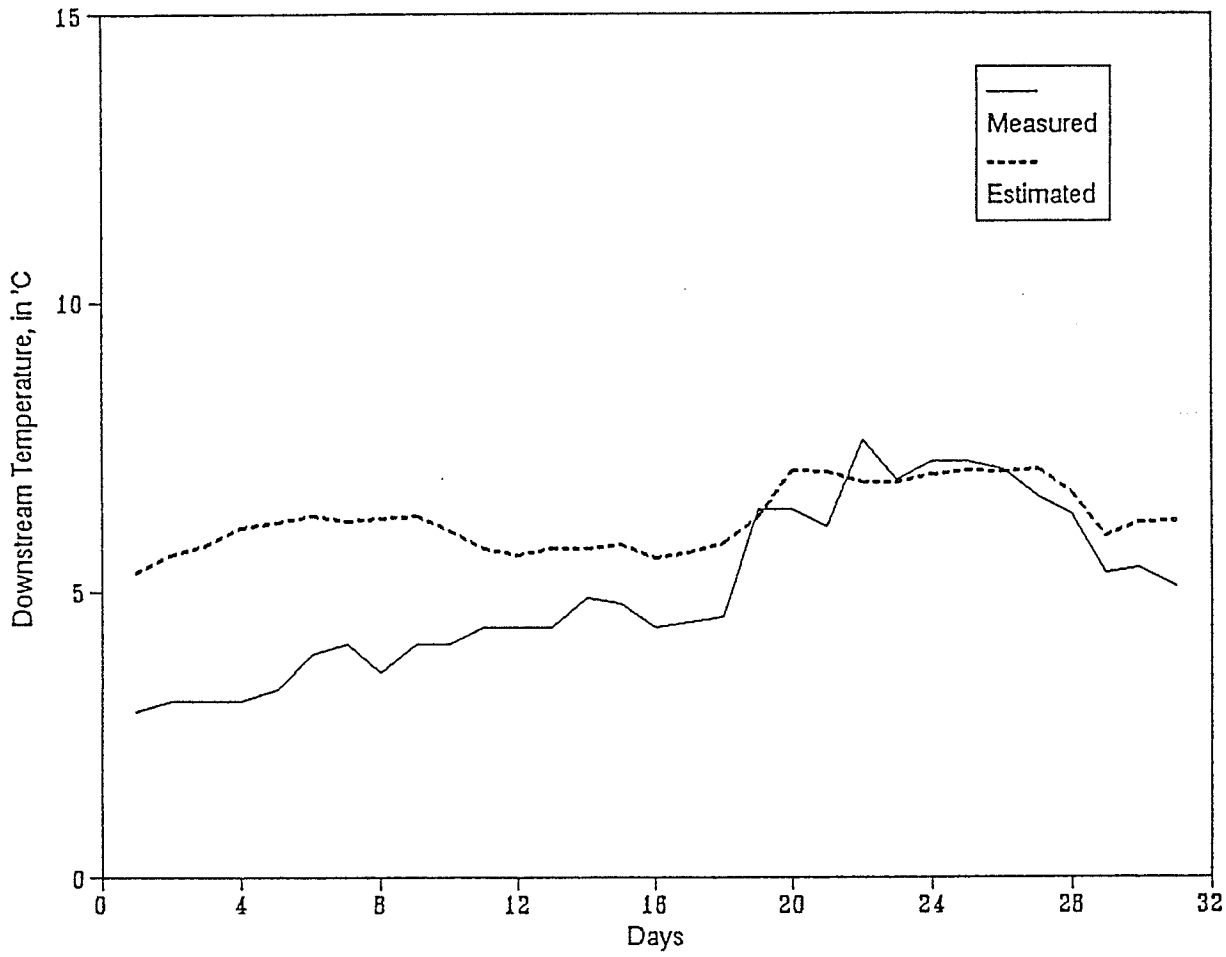


Figure 4.4 Measured field data and estimated value for the river temperature 1.6 km downstream from the Brandon thermal power plant for the month of December 1989.

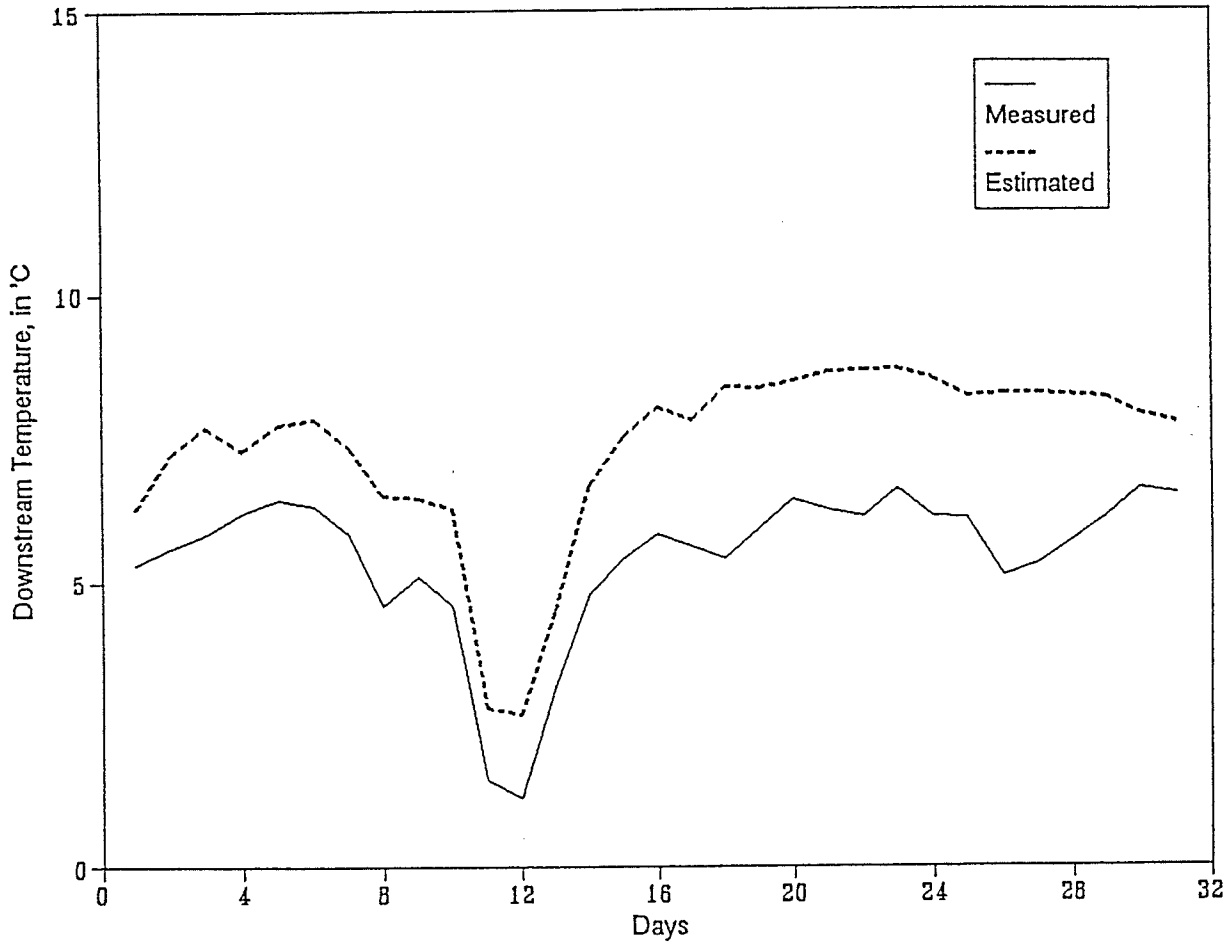


Figure 4.5 Measured field data and estimated value for the river temperature 1.6 km downstream from the Brandon thermal power plant for the month of January 1990.

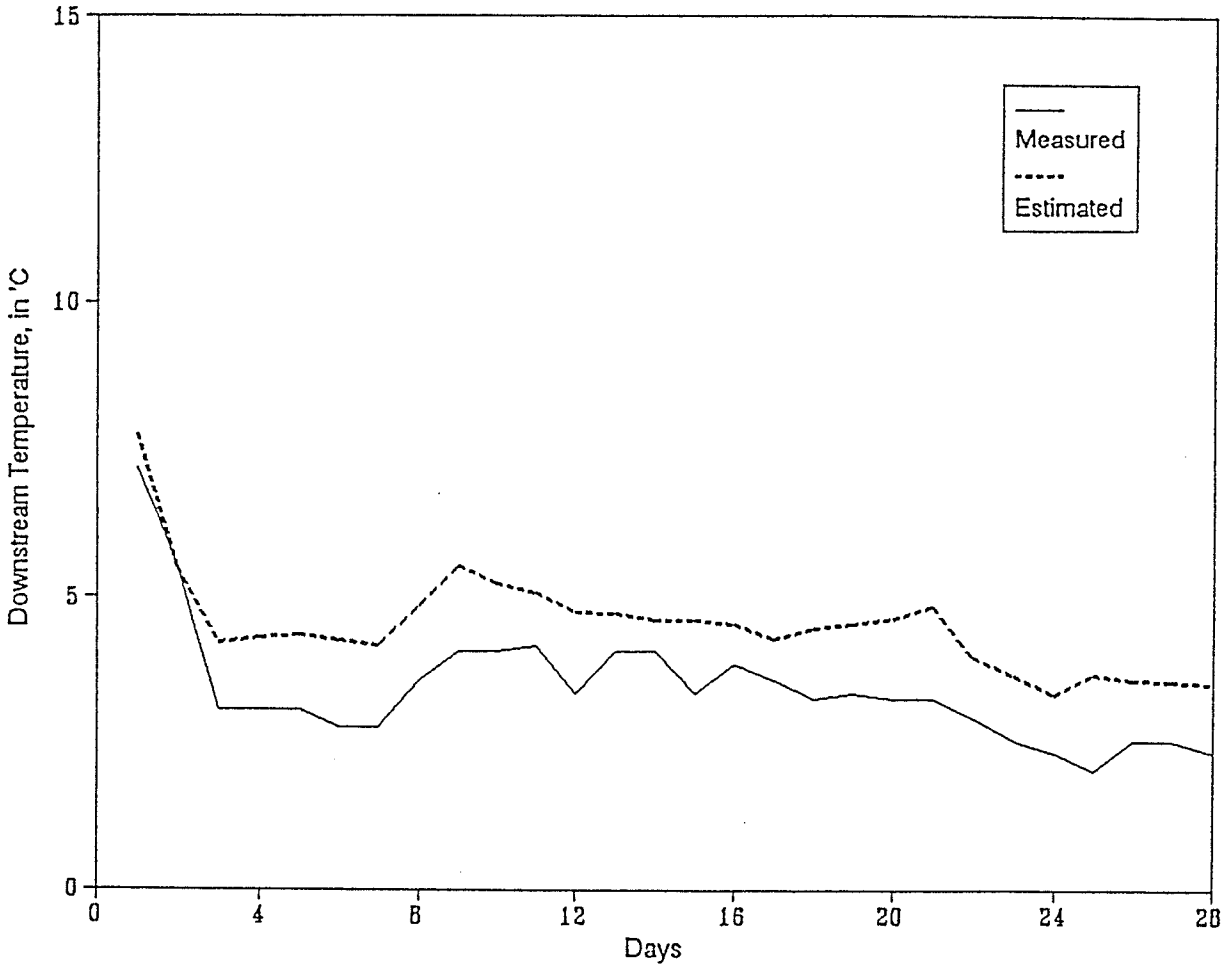


Figure 4.6 Measured field data and estimated value for the river temperature 1.6 km downstream from the Brandon thermal power plant for the month of February 1990.

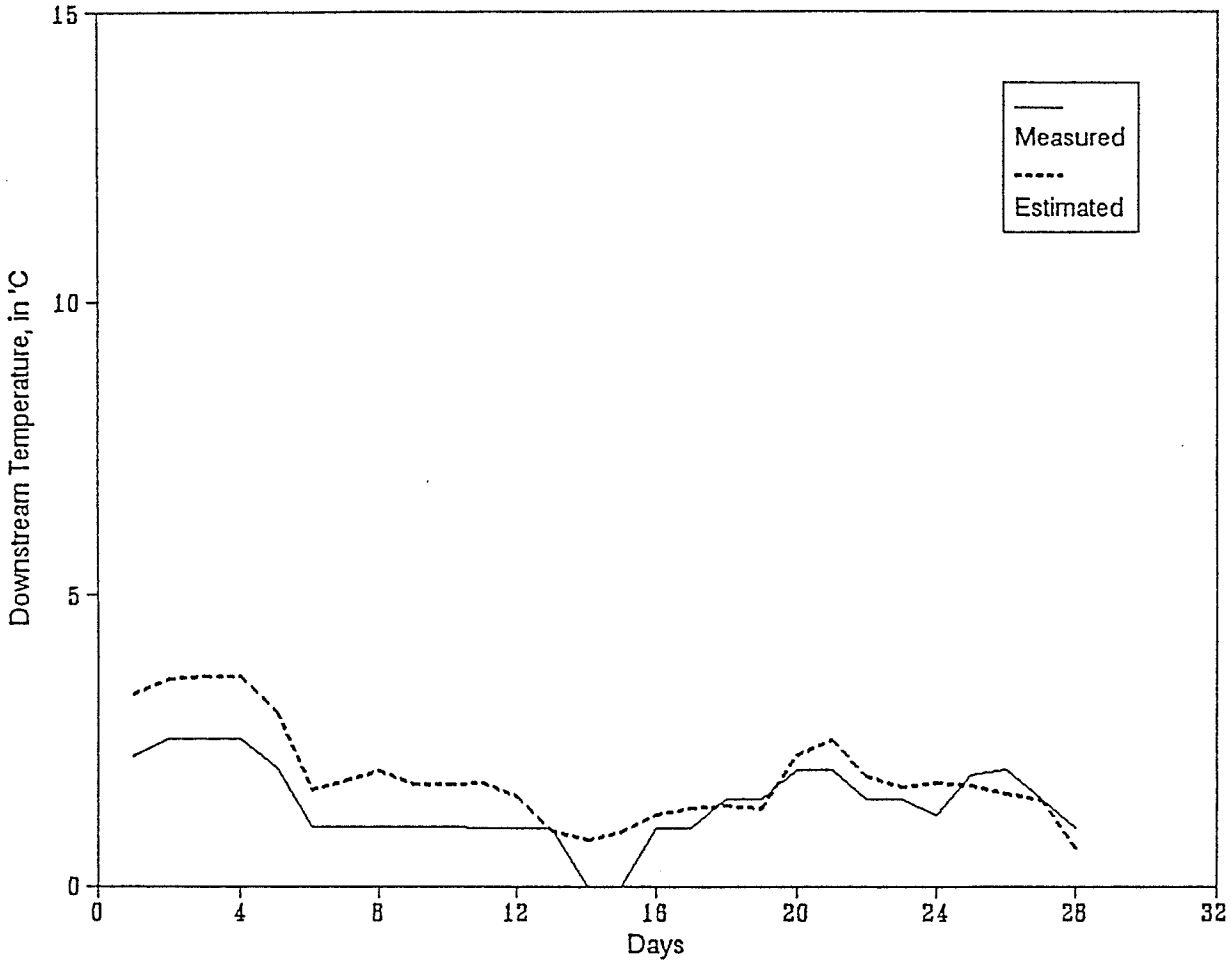


Figure 4.7 Measured field data and estimated value for the river temperature 1.6 km downstream from the Brandon thermal power plant for the month of March 1990.

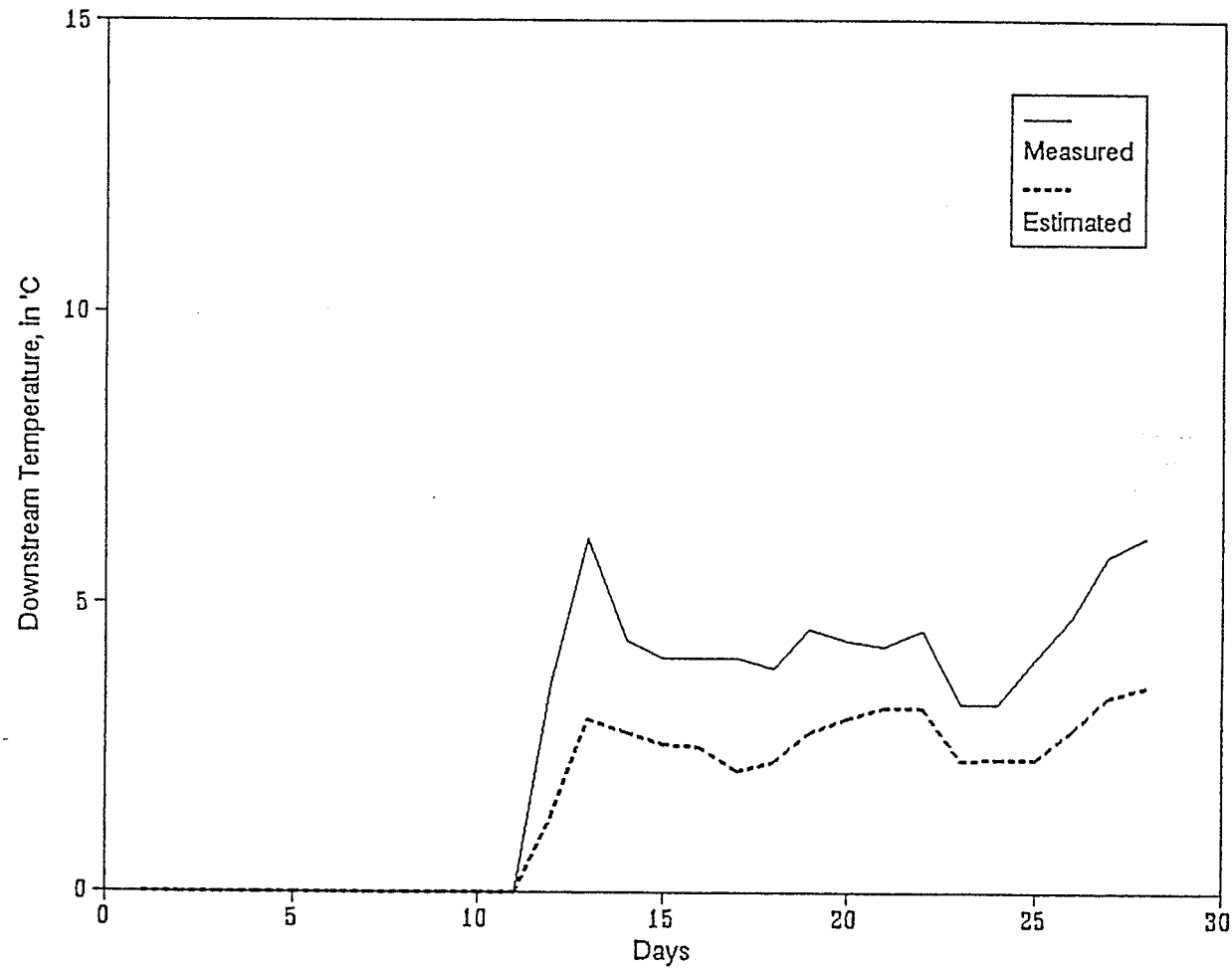


Figure 4.8 Measured field data and estimated value for the river temperature 1.6 km downstream from the Brandon thermal power plant for the month of November 1990.

The difference between the measured and estimated temperatures may be attributed mainly to monitoring error and/or lack of precise data. The most important missing data are the specific times of operation of each Generating Unit. This makes it difficult to link actual power generation to river temperature at any given time since these values are averaged over a day. The approximate depth of flow during the monitoring period was 2.5 ft. The monitoring location of the measured downstream temperature is roughly 2 ft from the surface and therefore closer to the river bed. Hence, the measured temperature has a tendency to be relatively cooler than the upper layer of the river. This may be the reason for the consistently lower values for the measured downstream temperatures. Other sources of error may be attributed to the lack of daily data for the wind velocity and dew point temperature.

4.5 Linearization of the Relationship Between River Flow and Allowable Power Generation

In order to incorporate the relationship between river flow and allowable power generation (*Equation* 4.17) into the linear GP problem defined by *Equations* 4.1 - 4.16, a linear approximation of this function was obtained for the Assiniboine River System for each month of the year. The process for linearizing the relationship between river flow and allowable generation is described by the following steps.

Step 1: Calculate the velocity of flow and depth of flow from *Equations* 4.18 and 4.19 for an initial low discharge value, Q, for the river (i.e., close to zero), and monthly parameters such as the values of the wind velocity, the dew point temperature, the temperature standard, and the background stream temperature.

Step 2: Calculate the value of the allowable generation, G, using *Equation* 4.17.

Step 3: If the calculated value of G is greater than or equal to the maximum possible capacity of the power plant, then stop the calculation; if not increase the value of Q by an increment and continue the procedure from Step 1.

To evaluate the allowable power generation, in Step 2, the relationship for the heat exchange coefficient, R_g, must be incorporated based on an assumption of which Generating Units are operating. Since Generating Unit 5 is the most efficient unit for the Brandon Power Plant, it is always operated first in all months except November. In the month of November, the power generation requirement is not uniform throughout each day of the month. In early November the power generation requirement is small, and as winter approaches in the latter part of the month, the power generation requirement increases. Hence, Manitoba Hydro finds it more suitable to employ one of the smaller generating units first. Therefore in November, one of the smaller generating units (for example, Generating Unit 1) is operated before Generating Unit 5.

Figures 4.9 - 4.19 show plots of the relationship between river flow and allowable power generation for January through December, respectively. The X-axis represents the river discharge, in m^3/second, and the Y-axis represents the maximum allowable generation possible, in Gwhr, at the corresponding discharge. The figure for the month of May is missing since it was assumed that no generation is possible in May because of a low temperature standard in that month.

These plots were linearized using first order linear regression. The general form of the equation is:

$$g(T_i, Q_i^j, STD_i) = a_i + b_i (Q_i^j) \tag{4.20}$$

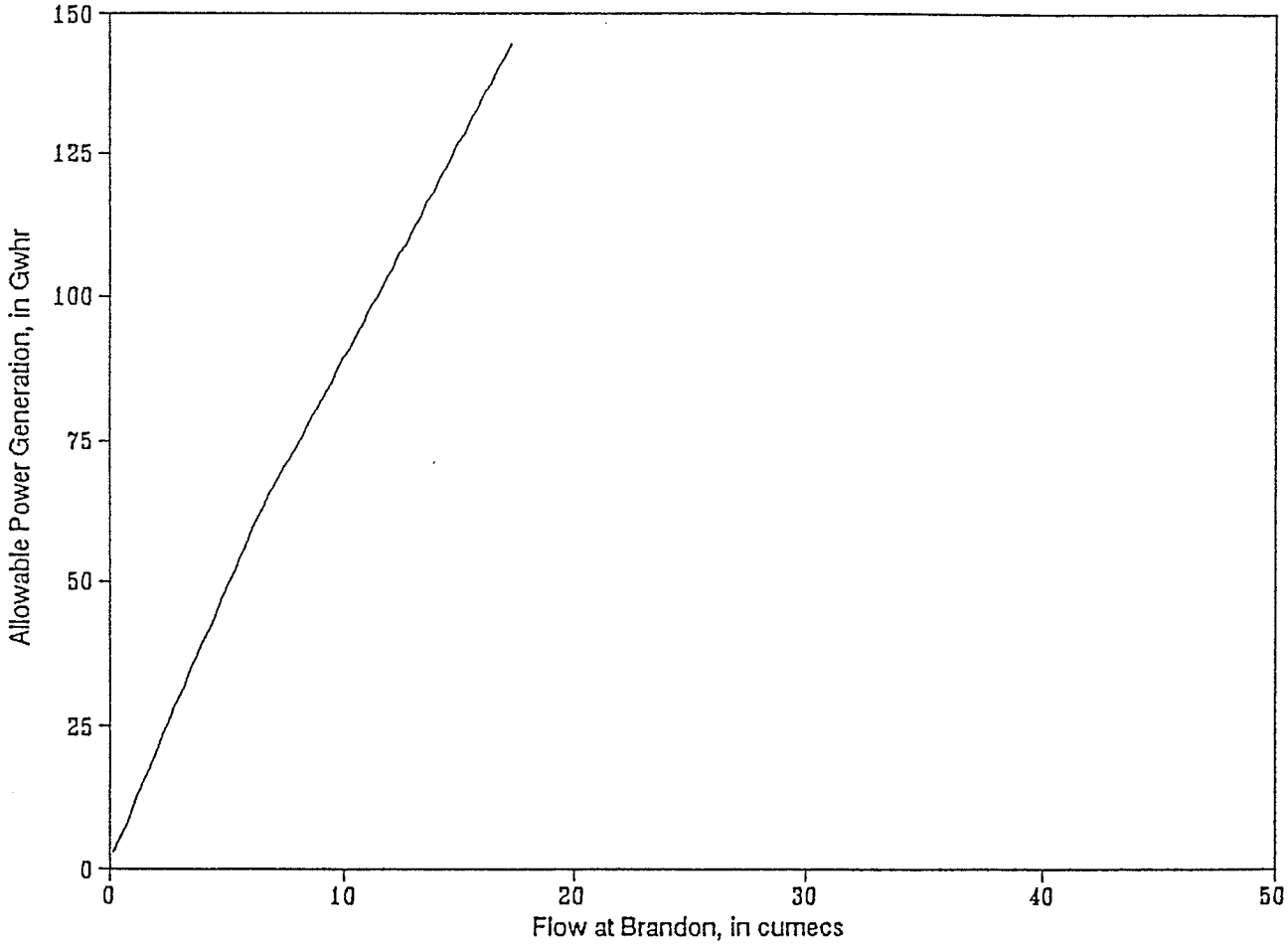


Figure 4.9 Relationship between river flow and allowable power generation for the month of January.

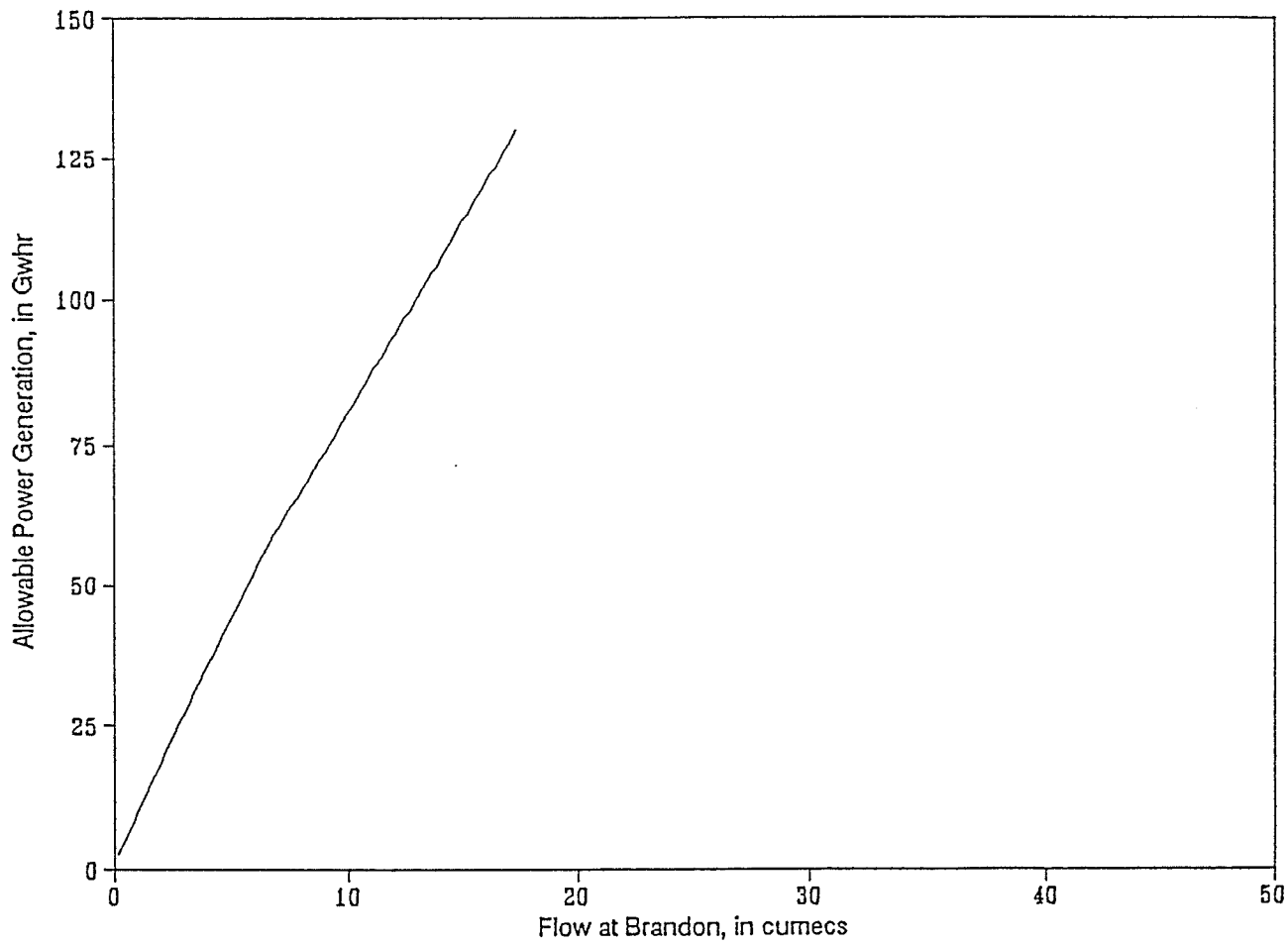


Figure 4.10 Relationship between river flow and allowable power generation for the month of February.

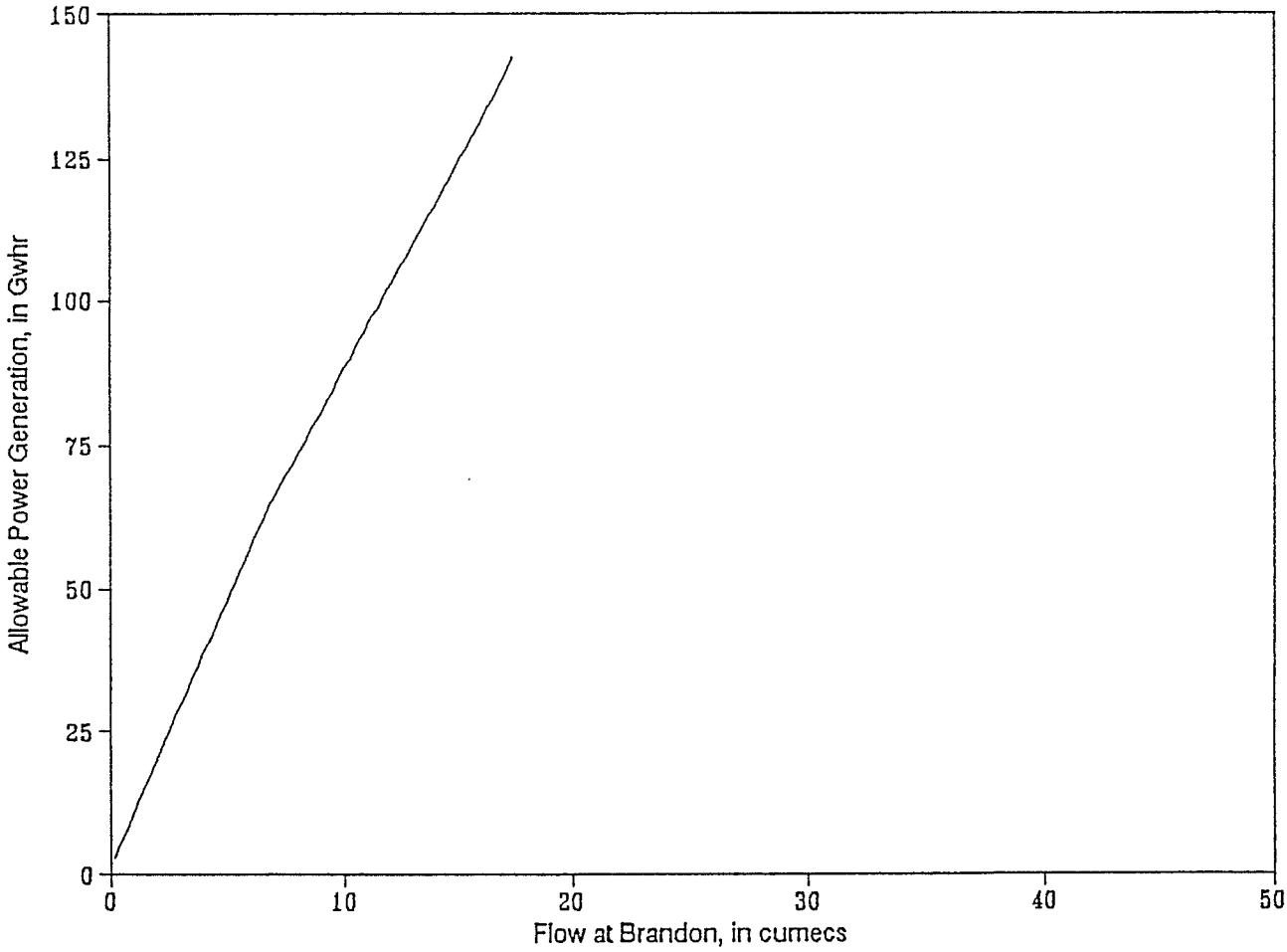


Figure 4.11 Relationship between river flow and allowable power generation for the month of March.

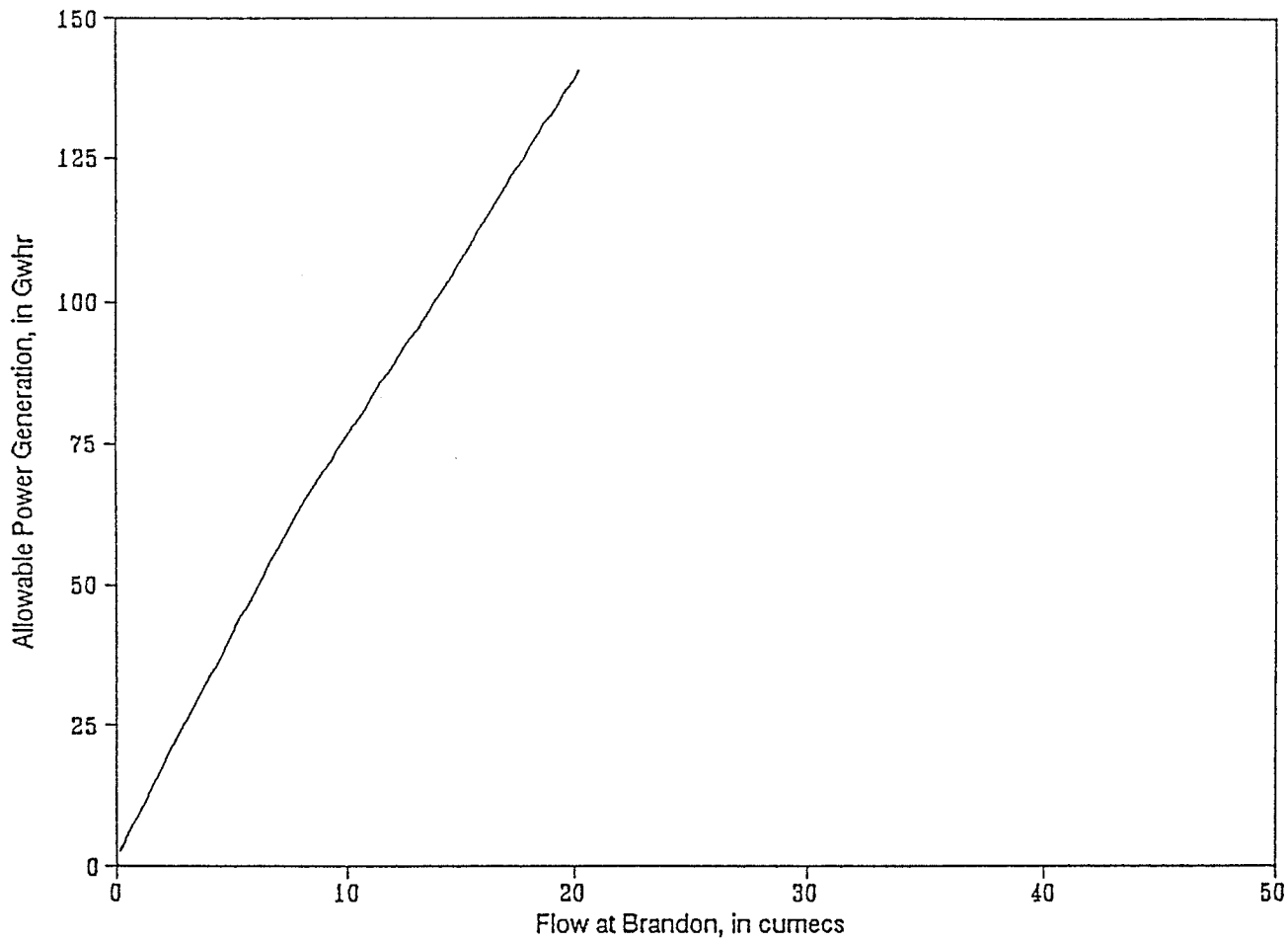


Figure 4.12 Relationship between river flow and allowable power generation for the month of April.

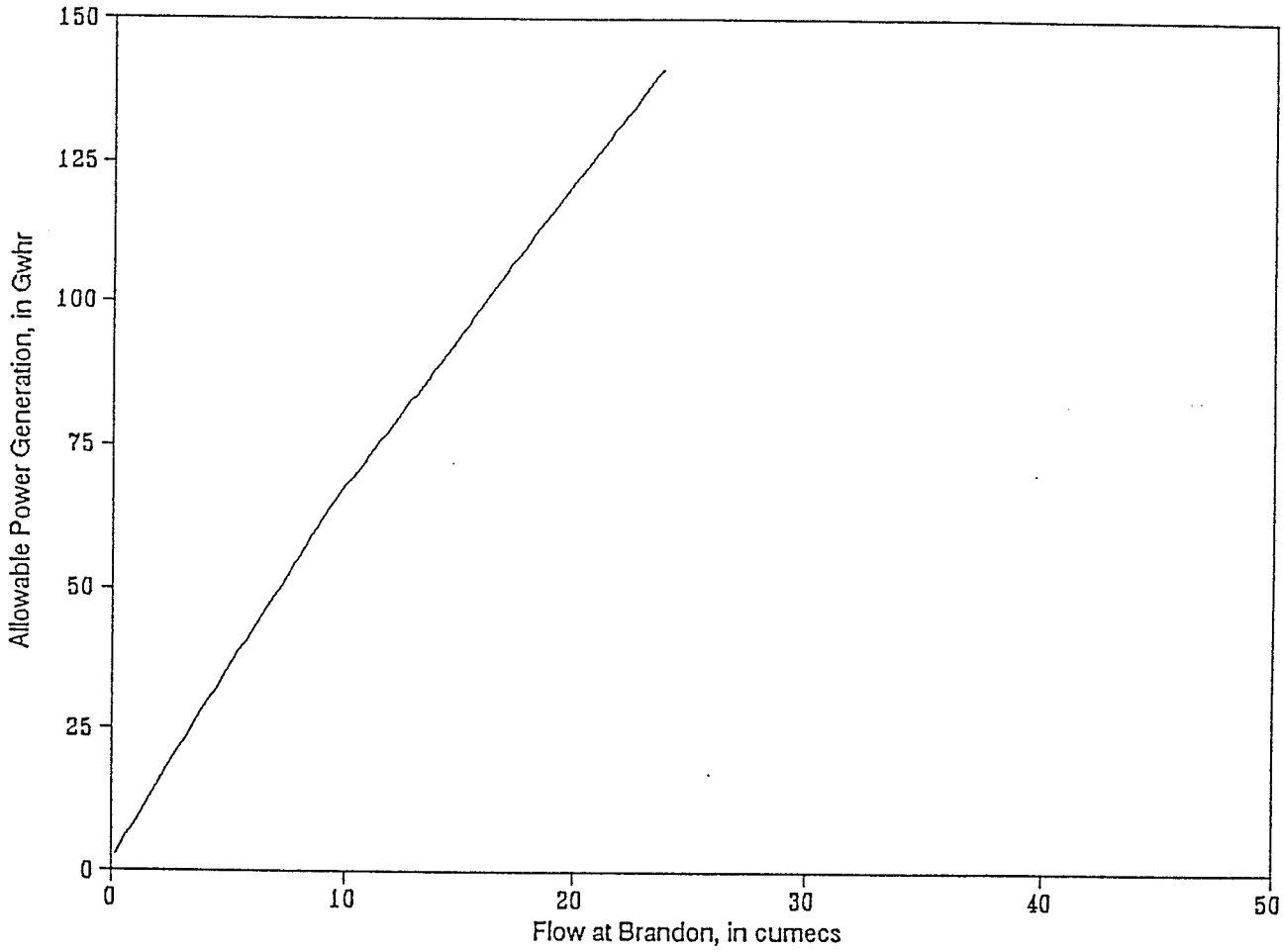


Figure 4.13 Relationship between river flow and allowable power generation for the month of June.

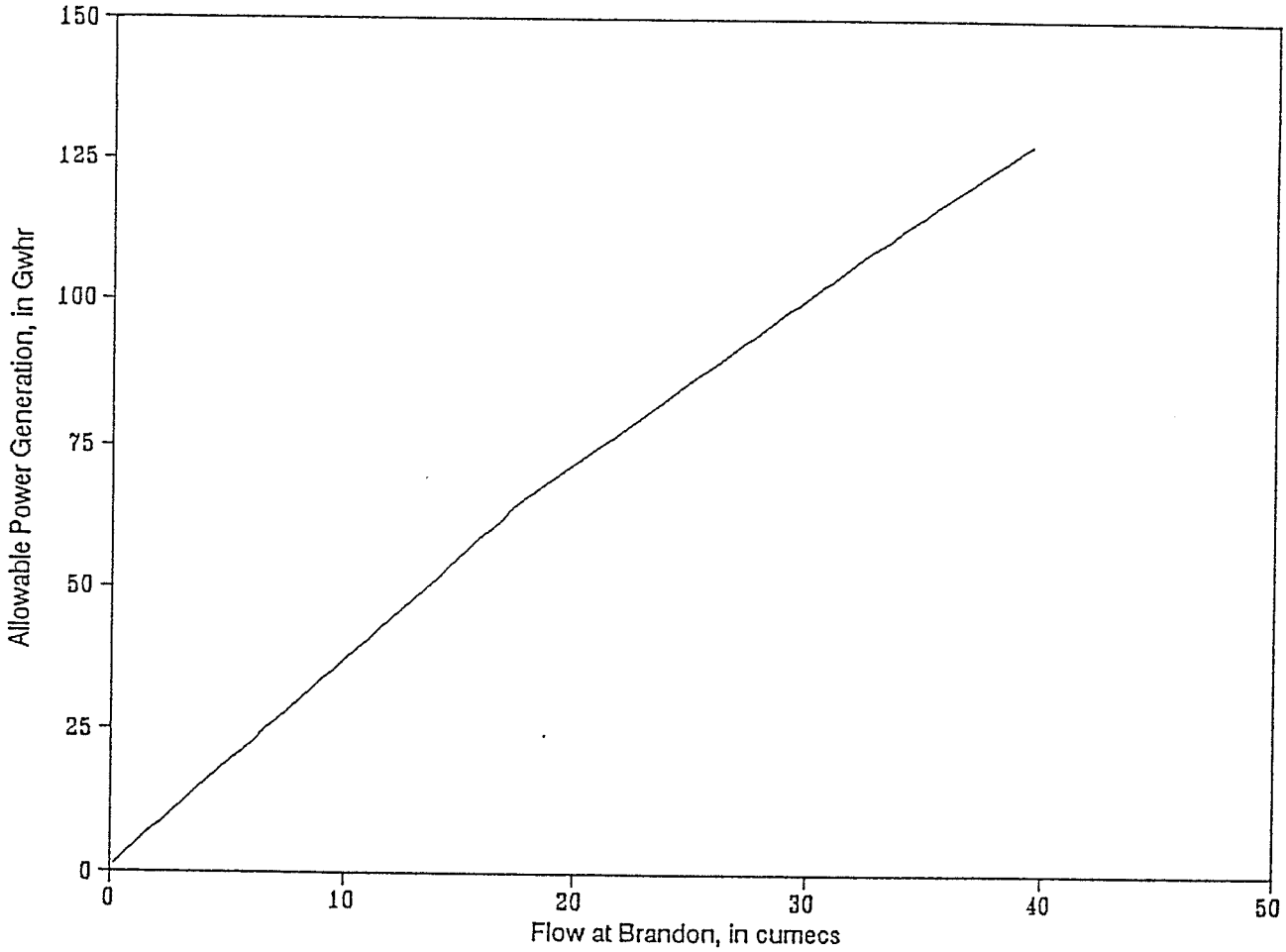


Figure 4.14 Relationship between river flow and allowable power generation for the month of July.

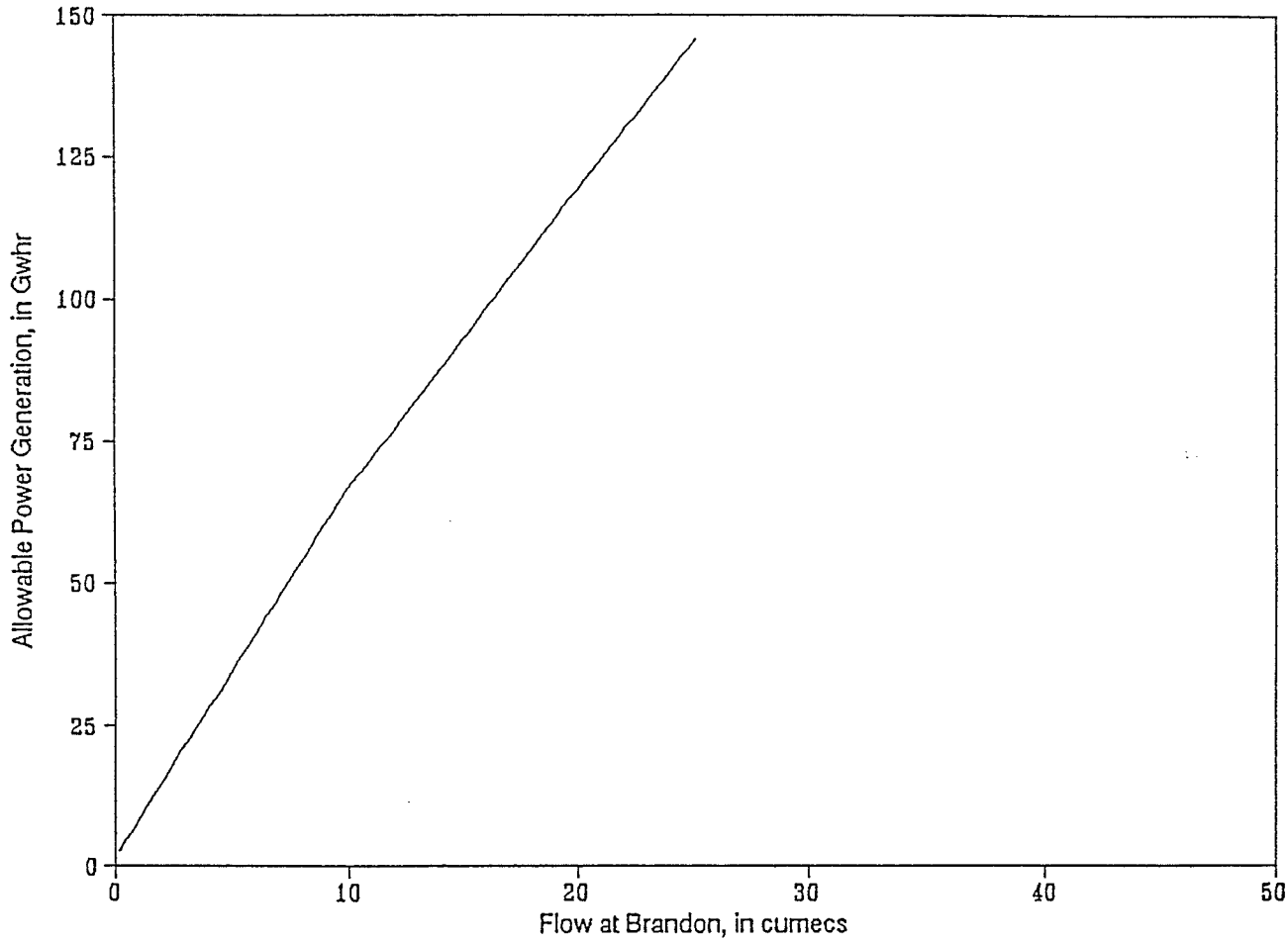


Figure 4.15 Relationship between river flow and allowable power generation for the month of August.

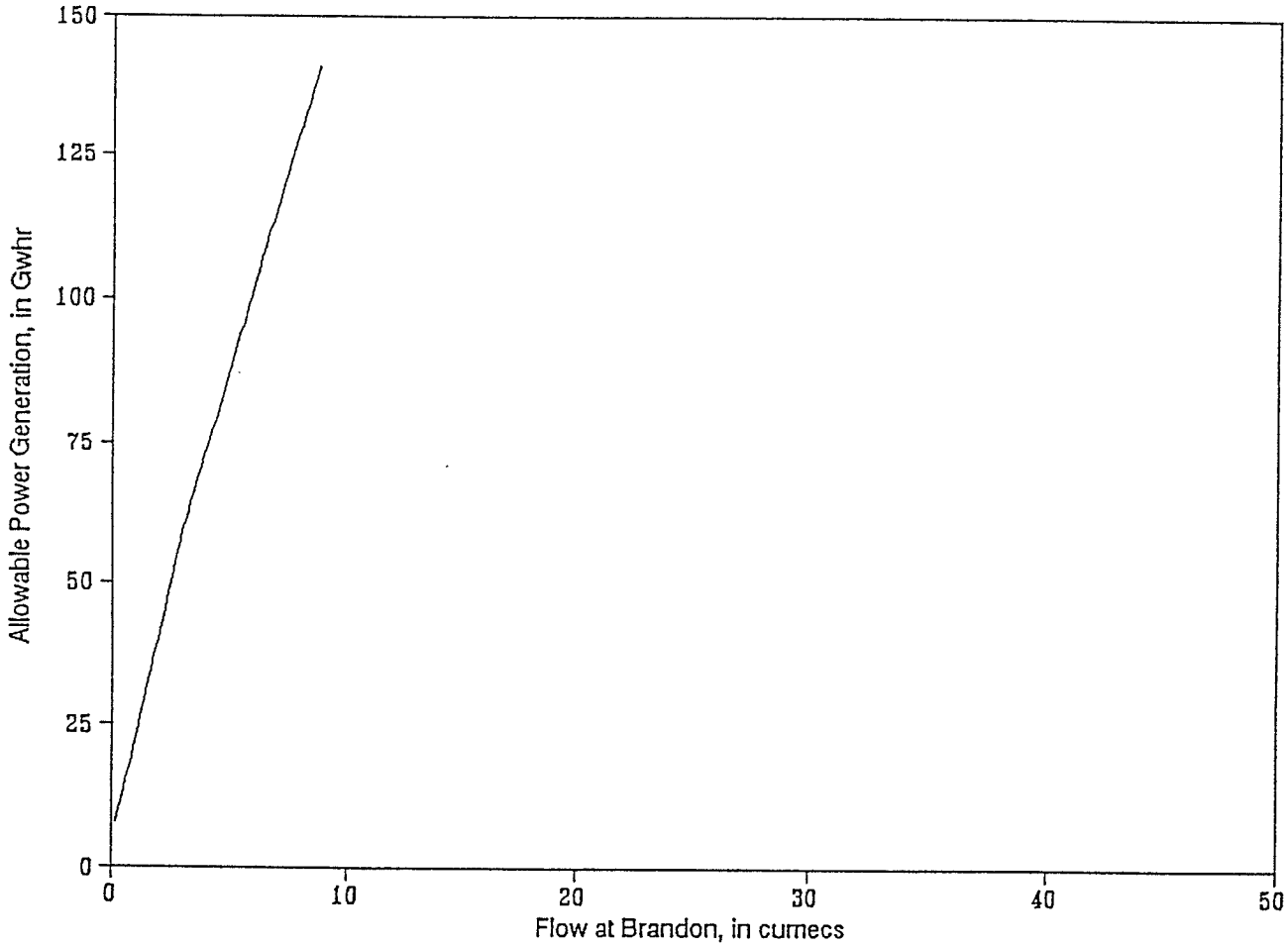


Figure 4.16 Relationship between river flow and allowable power generation for the month of September.

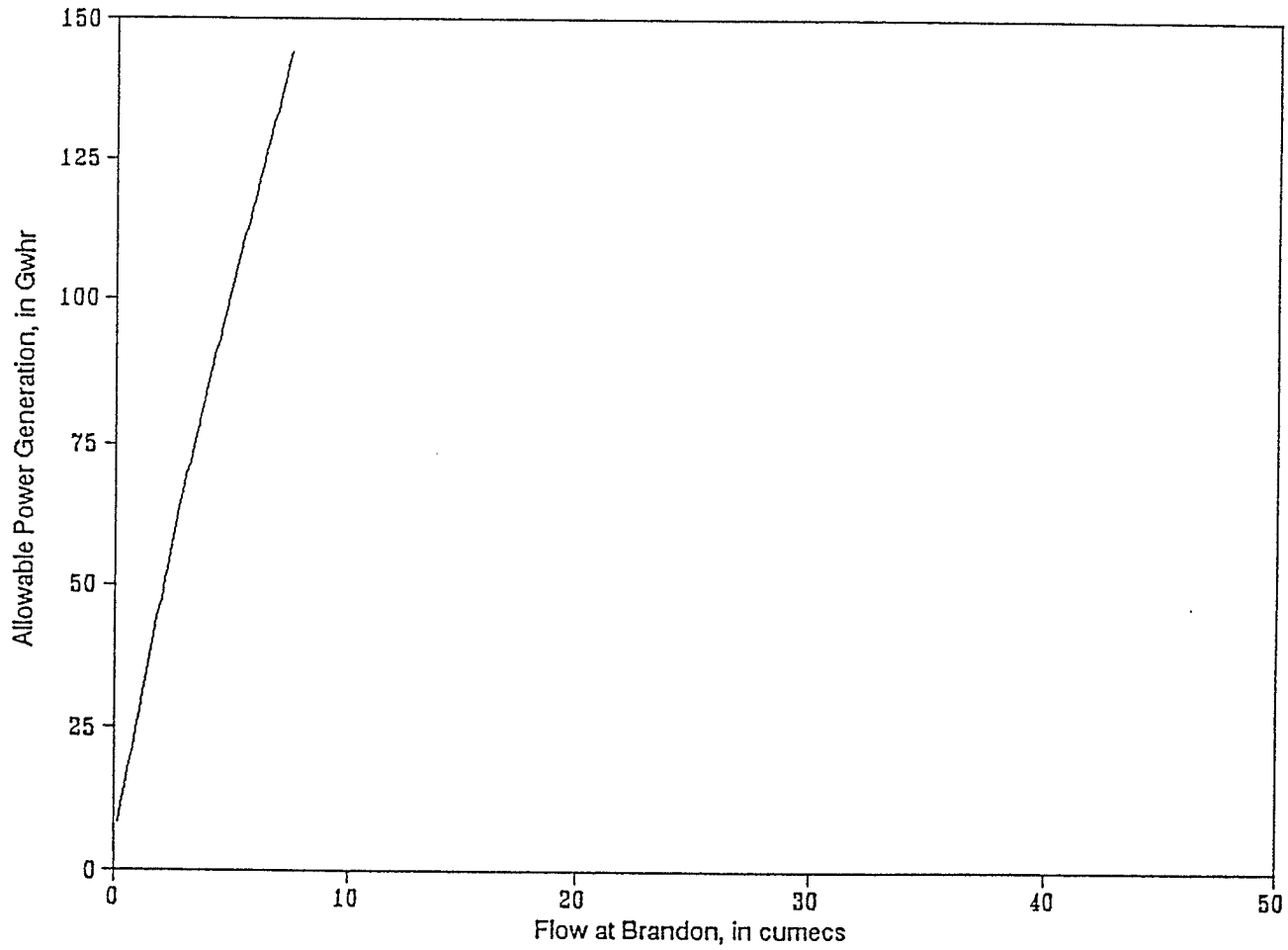


Figure 4.17 Relationship between river flow and allowable power generation for the month of October.

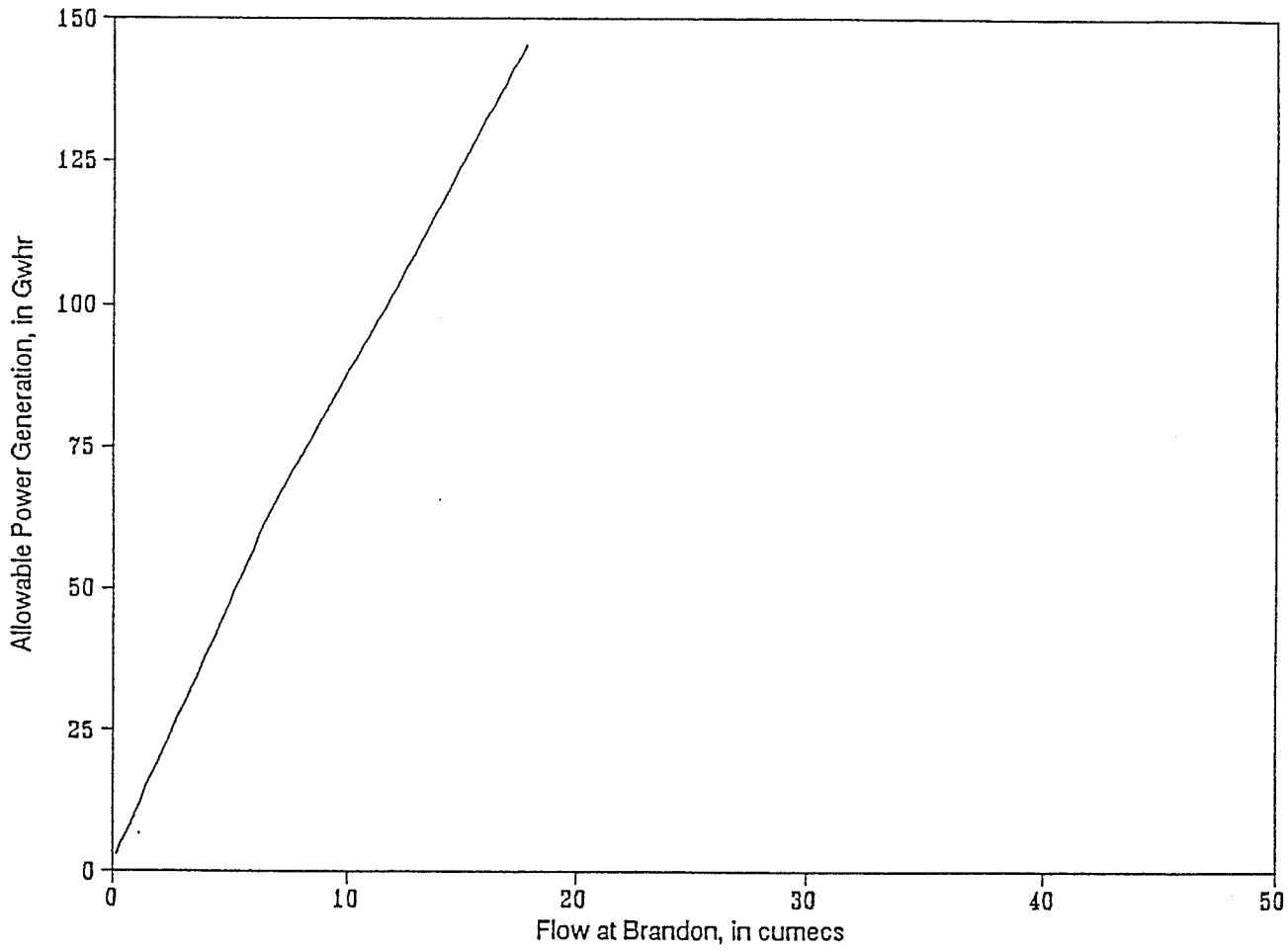


Figure 4.19 Relationship between river flow and allowable power generation for the month of December.

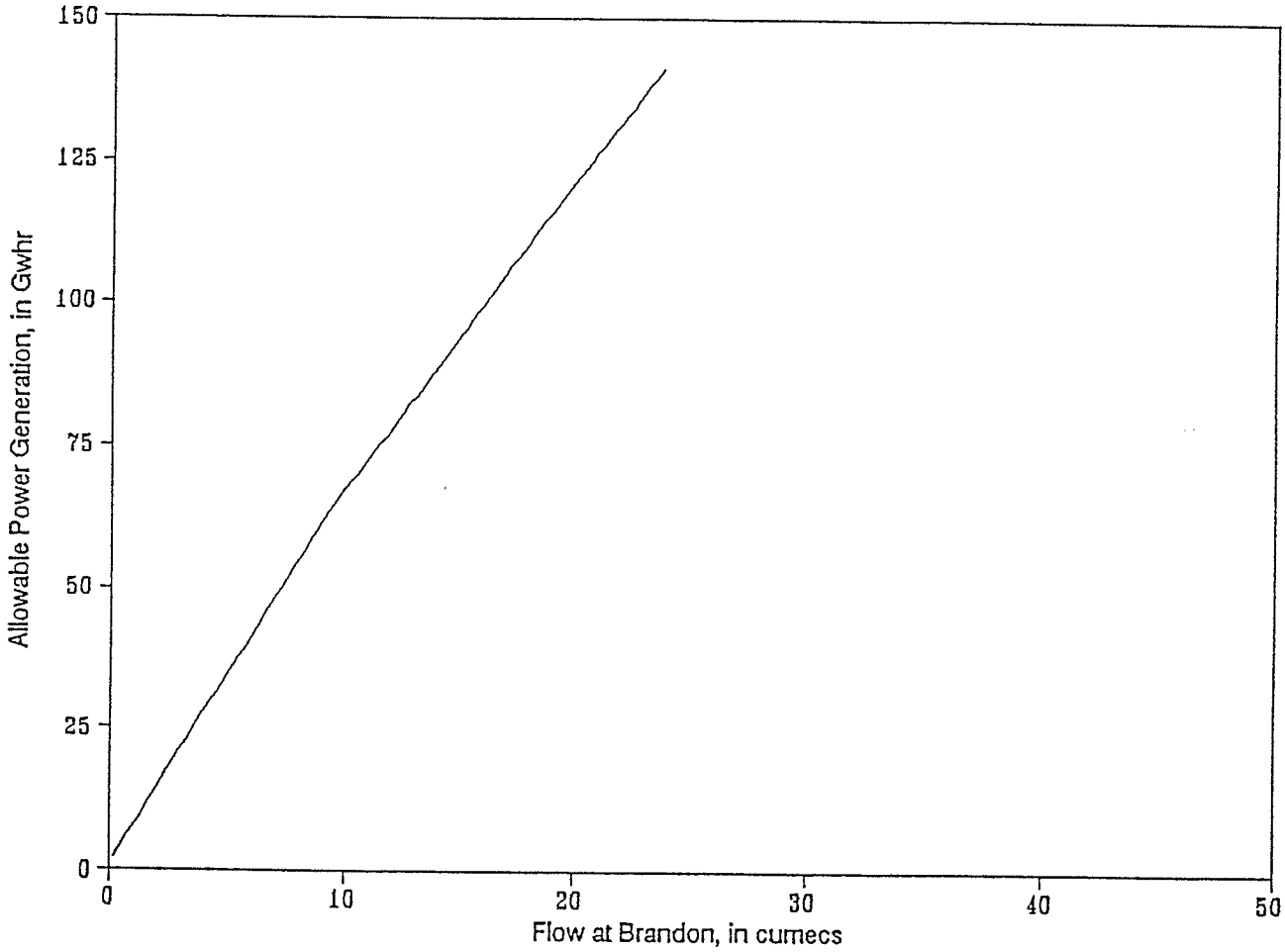


Figure 4.18 Relationship between river flow and allowable power generation for the month of November.

where:

a_i = intercept of the linear equation in month i of year j;

b_i = slope of the linear equation in month i of year j; and

all other variables are described in Section 3.1.

Table 4.5 shows the values of the slope and intercept and the correlation coefficient for this linearized relationship for each month of the year, except May.

Table 4.5 Monthly Values of the Slope and Intercept and the Correlation Coefficient of the Linearized Relationship

Month	slope	intercept	correlation coefficient
January	7.8	8.0	0.9985
February	6.8	7.2	0.9985
March	9.1	7.8	0.9988
April	11.9	6.4	0.9995
May	0.0	0.0	-NA-
June	12.2	5.5	0.9985
July	6.9	3.1	0.9985
August	8.3	5.6	0.9986
September	16.2	14.3	0.9999
October	17.1	17.2	1.0
November	5.2	5.9	0.9974
December	7.5	7.9	0.9985

5. IDENTIFICATION OF AN OPERATING POLICY FOR THE SHELLMOUTH RESERVOIR

The software package used to solve the optimization model is GAMS (BDLMP), copyright of The International Bank for Reconstruction and Development, The World Bank. The results obtained from the optimization model are the monthly storage volumes for each type of year, the sum of the deviations from storage targets, and the sum of the deficits in the generation needs. The optimal storage volume is governed by the requirement that the storage volume be the same in a given month for all years of the same type, the desired and mandatory generation levels, the storage requirements for flood control and recreation, and the sequence of the inflows of the hydrologic scenarios.

5.1 Determining the Weight for the Deviations from the Desired Generation Target

In this research a range of objective function weights, w, for the sum of the desired generation target deviations were investigated (see *Equation* 4.1). A weight of 1 and a weight of 10^6 were used to represent the case when the power generation targets are given lowest priority and highest priority, respectively. The sum of storage deviations that are optimal when weights of 1 and 10^6 are chosen for w denote the feasible range of storage deviations and therefore the maximum possible increase in the sum of the storage deviations. Likewise, this range of weights represents the feasible range of the sum of the generation deficits and therefore the maximum possible decrease in the sum of the generation deficits. For a given weight, w, the percentage increase in the sum of storage deviations is referenced with

respect to the feasible range of the sum of storage deviations. Likewise, the percentage decrease in the sum of generation deficits is referenced with respect to the feasible range for the sum of deficits from the desired generation target. For each scenario of hydrologic input, the weight that yields the largest difference between the percentage decrease in generation deviations and the percentage increase in storage deviations is used to determine the optimal operating policy.

To determine w for each hydrologic scenario the optimization model was solved for increasing values of this weight starting with a weight of 1, using increments of 25. *Appendix* A shows the calculations for determining the values of these weights. The chosen weights for each hydrologic scenario are listed as follows:

Scenario 1 : 1

Scenario 2 : 1

Scenario 3 : 425

Scenario 4 : 5075

Scenarios 1 and 2 yield a value of w equal to 1. The feasible solution space of the LP is highly constrained for these scenarios. For the range of weights from 1 to 10^6, Scenario 1 has only two feasible solutions, and Scenario 2 has only one feasible solution.

5.2 Feasibility of the Optimization Model for the Case Study

When it was specified that the storage volume for the month of April be the same for a similar type of year, no feasible solution for the model given by *Equations* 4.1 - 4.16 could be obtained. This infeasibility was removed by allowing the storage volume in the month of April to take on any value.

5.3 Results of the Optimization Model

The results of the optimization model show that there is a conflict between the goals of storage in the reservoir and desired and mandatory generation levels, although deviations from the target values occur at different times. The deviations in storage targets occur because the reservoir is forced to save water in the spring and summer months (where inflow is the maximum for the year) in order to satisfy the high release requirement for meeting generation targets in the winter months. The other reason for the deviations in storage targets can be attributed to the sequence of inflows. For example, in a scenario in which an average year is followed by a dry year the reservoir would need to store much water in the average year in order to meet the high generation, release, and storage requirements in the forthcoming dry year. Also, for cases in which a dry year is preceded by two consecutive dry years low storage volumes would result in the dry years due to the unavailability of sufficient inflow.

Table 5.1 shows the sum of storage deviations and deficits from the desired generation targets, for each hydrologic scenario. For each of these deviations a lower value represents a better solution. Scenarios 3 and 4 yield better solutions than Scenarios 1 and 2 because the models for these scenarios have a relatively larger feasible solution space in which to make a decision. This relatively larger feasible solution space is due to the less conservative nature of the combination of the wet, average, and dry years offered by Scenarios 3 and 4. Among these two scenarios, Scenario 4 performs best because it begins with a wet year, thus, allowing the reservoir a relatively substantial amount of water initially to achieve the storage and generation goals.

Table 5.1 Sum of Storage Deviations and Desired Generation Deficits for the Four Hydrologic Scenarios

Scenario	Sum of Deviations from Storage Targets, in 10^3 m^3	Sum of Deficits from Desired Generation Targets, in Gwhr
1	1980188.0	586.708
2	2288060.0	620.274
3	1142660.0	253.818
4	1017720.0	204.286

Figure 5.1 shows the storage levels for the four hydrologic scenarios, for a wet, average, and dry year. The X-axis represents the months in the wet, average, and dry year, respectively, where the first month is April. The Y-axis represents the storage operating volume obtained from the solution of the optimization model. Also shown are the range of storage targets for the months of April through August. Since the storage volume for April is not required to be constant for a given type of year this figure shows the mean storage volume of April for each of the three types of years. It can be observed from the figure that the storage volume in the winter months of each year (November through March) is steadily drawn down. This is due to the high release requirement in the winter months for achieving the mandatory and desired generation levels.

Scenarios 1 and 2 have a relatively low storage volume in the spring and summer of the dry years. This observation shows that these policies have a relatively high risk of not meeting the storage targets, satisfying the downstream water requirements, or satisfying the generation needs in winters that follow dry summers. Although Scenarios 3 and 4 perform better in these respects, they require high storage levels during early summer, thus, increasing the risk of evaporation from the reservoir. The optimal storage volume typically decreases in March in order to meet the relatively low target level for early spring, however, Scenario 4 has high storage volumes in April of the dry years. In realistic applications then Scenario 4 may would have a high risk of flooding.

The sensitivity of the model results to variations in the background temperature were examined. Since the winter months have the highest generation needs, the model was evaluated for variations in the background temperatures in these months only (i.e., November through March). The 75 and 90 percentile background temperature values were examined. These results yielded storage values that were

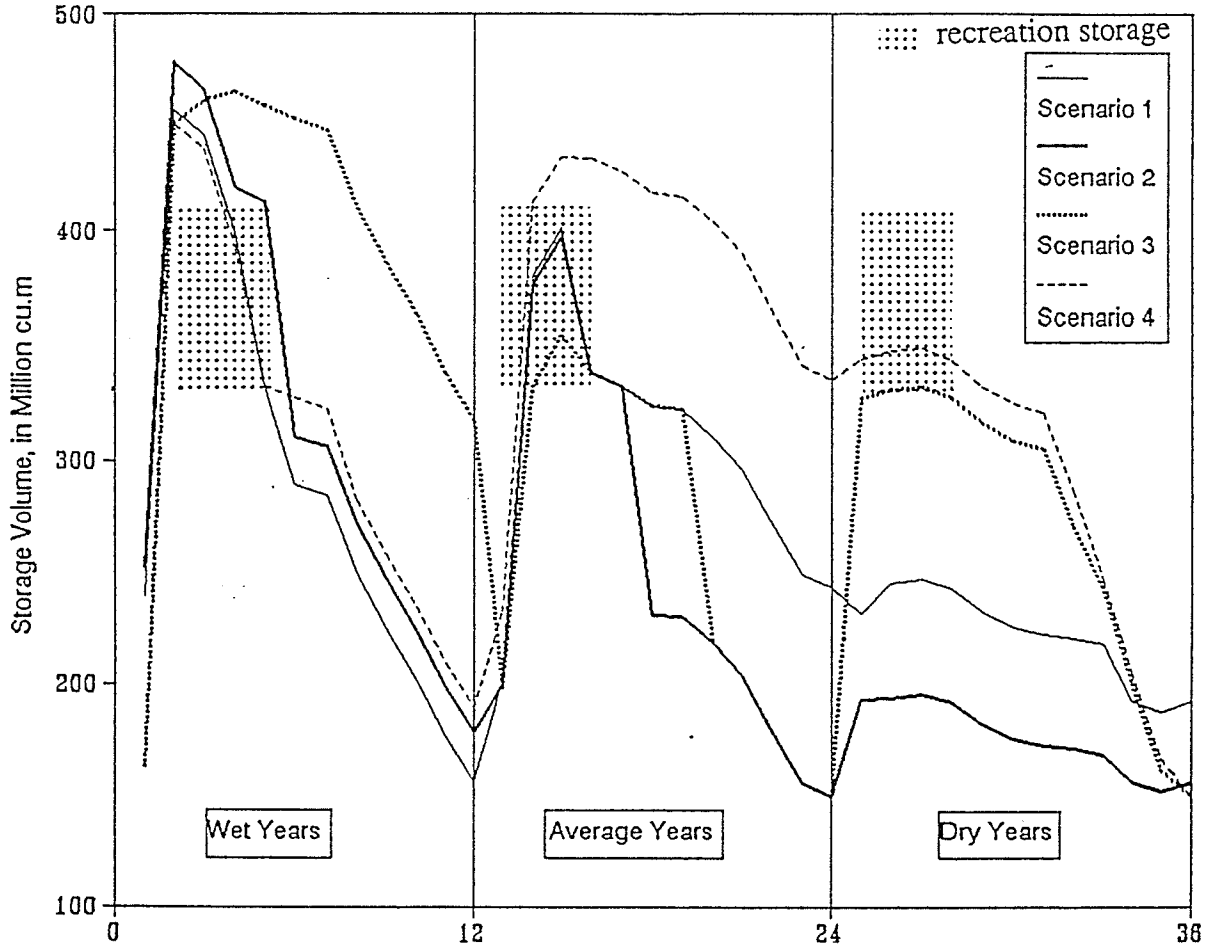


Figure 5.1 Storage operating policies.

essentially the same as those based on the mean background temperatures, although the resultant generation levels decreased.

Figure 5.2 shows the sum of the deficits in meeting the desired and mandatory generation levels for the four hydrologic scenarios. These results are only shown for dry years, since the generation needs are satisfied under all four scenarios, in the wet and average years. The minimum release required to meet the dilution needs of the waste effluent in reach 3, is enough to satisfy the desired generation targets in the months of June to October of the dry years. Scenarios 3 and 4 always satisfy the mandatory level of power generation, and they also have a comparatively lower deficit value in meeting the desired value of power generation. The magnitude of the deficit in meeting the mandatory or desired generation goal is dependent on the amount of release required to satisfy the power generation target and the linear relationship between the river flow and the allowable power generation in that month. In other words, the months which have a relatively lower value of the slope, b, in the linearized relationship tend to have a higher deficit in meeting the desired and mandatory generation levels.

A preliminary observation of the results of the optimization model shows that Scenario 4 is the most attractive policy in terms of recreation storage, water supply, and power generation. However, this particular scenario does not take into account the fact that a similar type of year may occur consecutively, in a realistic situation. Hence, it is essential to evaluate the performance of these policies in a realistic situation. The following sections discuss in detail the simulation model which was used to evaluate the operating policies obtained from the four hydrologic scenarios.

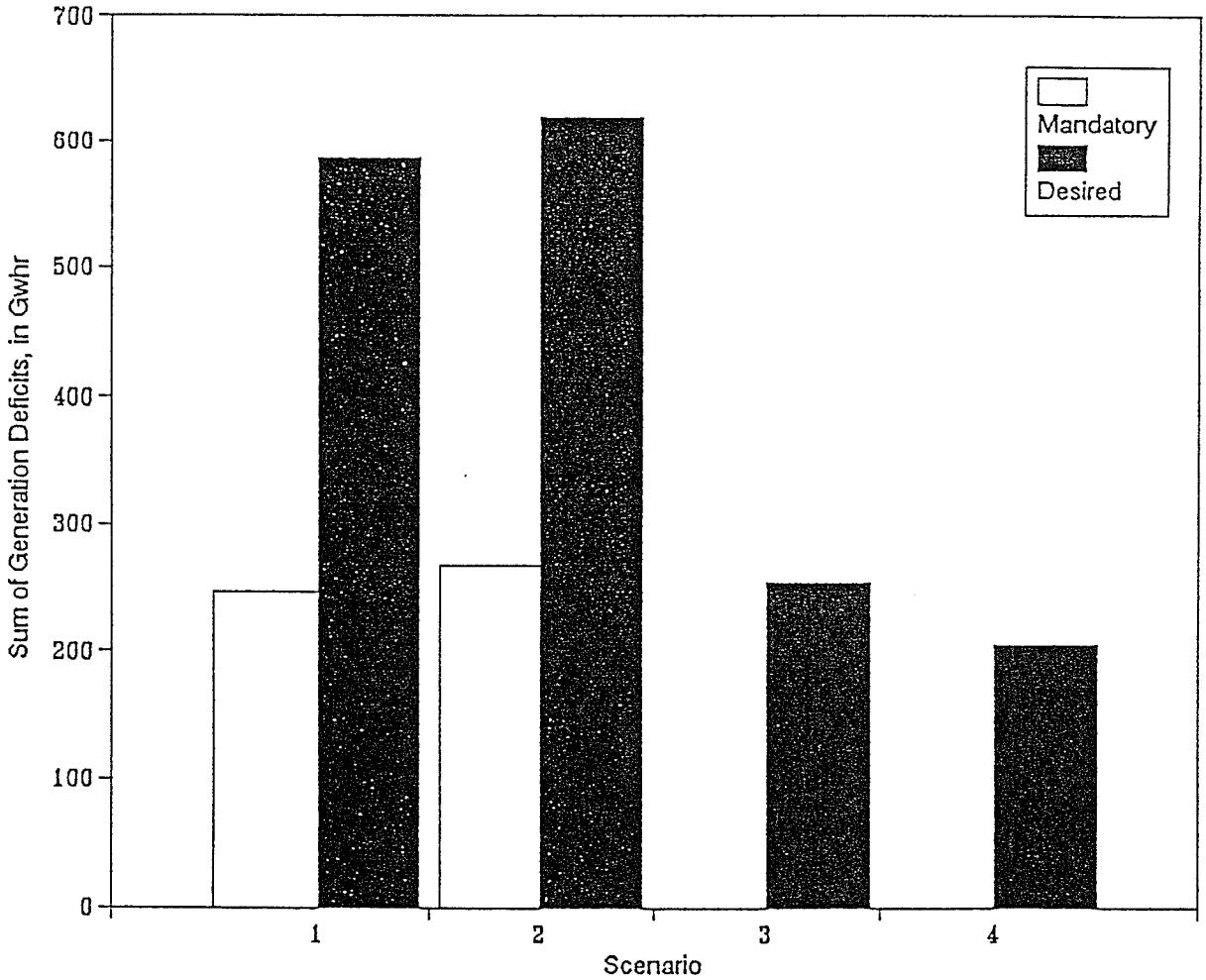


Figure 5.2 Sum of the deficits in the desired and mandatory generation levels for the four hydrologic scenarios.

5.4 The Simulation Model

There are four major reasons to apply a simulation model to this problem. They are: 1) to verify that the optimal storage operating policies work under realistic situations; 2) to investigate more closely, trade-offs among different objectives of the river basin; 3) to evaluate the performance of the storage operating policies based on a set of evaluation criteria (which will described in Section 5.4.3); and 4) to identify a preferred operating policy based on the set of evaluation criteria. The simulation model developed for these purposes is designed for a period of seventeen years, from 1971, the year the Shellmouth Reservoir was constructed to the year 1987. The release rules used for this model are based on an approach developed by *Yang* (1991).

Each year is divided into two time periods, the summer months (May through August) and the non-summer months (September through April). Each of these time periods have different release rules. A monthly time step is used. The input to the simulation model is the yearly forecast of inflow (i.e., predictions of whether it will be a wet, average, or dry year) and the actual recorded inflows for each year of the simulation period. The model is based on the assumption that perfect forecasting has been made for each year of the simulation period. For example, if a certain year was predicted to be wet, then the simulation model assumes that the prediction is correct and applies the storage operating policy obtained from the optimization results for a wet year.

5.4.1 Release Rule for the Non-Summer Months

The basic idea behind the release rule is to try and maintain the monthly storage volume of the operating policy while satisfying all the needs of water supply and power generation. In the non-summer months, if all of these goals cannot be

met, then the storage volume is allowed to change from the optimal operating policy and first priority is given to meeting the municipal and industrial water needs. The second priority is given to meeting the mandatory level of power generation and the third priority is given to meeting the desired level of power generation. At no point in time is the reservoir volume allowed to fall below the dead storage pool level, nor is it allowed to be above the full supply level. The release is strictly constrained to be always less than the maximum outlet capacity of the reservoir. The release rule permits flooding only if it is absolutely unavoidable. *Appendix* B shows the flow chart illustrating the release rules for the non-summer months.

5.4.2 Release Rule for the Summer Months

The summer months have more goals than the non-summer months. Hence, it is necessary to define different release rules for these months. The objectives of the reservoir during the months of April through August are to provide flood protection, recreation in the reservoir, municipal and industrial water supply, and release required to achieve the desired level of power generation. However, the latter use is applicable only during the dry years, as the wet and average years do not have any desired generation requirements in the summer.

In situations where the storage volume of the operating policy lies between the storage targets used in the optimization model (see Table 4.2), then the release is made in order to satisfy all the needs of the reservoir while trying to maintain the storage volume of the operating policy. If it is unable to do so, then the simulation model tries to satisfy all the needs of the reservoir giving last priority to achieving the storage volume of the operating policy. In situations where the storage volume of the operating policy is outside the range of the storage targets, the release decision is taken giving priority in order of flood protection, municipal and industrial water

demands, recreation in the reservoir, irrigation and farm water supplies, mandatory level of power generation, and the desired level of power generation. At no point in time is the reservoir volume allowed to fall below the dead storage pool level, nor is it allowed to be above the full supply level. The release is constrained to be always less than the maximum outlet capacity of the reservoir. The threshold value of flooding is assumed to be 1800 ft^3/sec, and flooding is recorded immediately downstream of the reservoir. *Appendix* B shows the flow chart illustrating the release rules for the summer months.

5.4.3 The Evaluation Criteria

When the reservoir is unable to satisfy any given objective a violation occurs. A continuous period where the reservoir is in violation of meeting a particular objective is termed as a failure state. The simulation model records the magnitude and number of times of violation and the length of the failure states for each of the following reservoir objectives:

municipal and industrial water supply needs, and dilution of municipal and industrial waste effluent;
irrigation and farm water supplies;
flooding;
recreation in the reservoir (in terms of summer storage targets);
mandatory level of power generation; and
desired level of power generation.

Three criteria were used to evaluate the performance of the operating policies with respect to these objectives. These criteria were introduced by *Burn et al.* (1991) and applied in a similar study by *Yang* (1991). They are determined based

on the results of the simulation model. These three criteria are risk, resiliency, and vulnerability.

Risk is a measure of the probability or the frequency of the occurrence of a violation.

$$\text{Risk} = \frac{\text{number of months in which violations occur}}{\text{total number of months}}$$

Resiliency is a measure of the ability of the system to recover from a failure.

$$\text{Resiliency} = \frac{\text{number of months in which violations occur}}{\text{number of failure states}}$$

Vulnerability is a measure of the severity of the violations. It is the sum of the maximum of the violations that occurs in each failure state.

$$\text{Vulnerability} = \sum_{k} \text{maximum violation in failure state } k$$

5.4.4 Results of the Simulation Model

The simulation model results show that the municipal and industrial water needs are satisfied at all times. The mandatory generation targets are also always satisfied in the wet and average years. It should be noted that there are no desired generation targets in the wet and average years. The desired generation targets are always satisfied for the months of June through October. The explicit inclusion of the objective of providing water for thermal generation has the effect of limiting flooding when two or more wet years occur consecutively. This is because the reservoir is emptied partially in the winter (when the generation needs are high) thus allowing more freeboard in the reservoir to accommodate the huge inflow occurring in the following spring. In contrast, the simulation results of *Yang* (1991), which did not include the objective of satisfying the dilution requirements of thermal power generation, showed greater occurrence of flooding.

The simulation results show a conflict between recreation in the reservoir and the release required for thermal power generation. The most crucial months are the winter and early spring months of the dry years, due to the high desired generation requirement and unavailability of sufficient inflow to compensate for recreation storage. These months have a high deficit in the desired generation level.

The simulation model provides insight into conflict in uses of the reservoir that were not obvious from the optimization results. The need for satisfying power generation together with providing water for irrigation and farm water supplies conflicts with the use of providing recreation in the reservoir. This conflict occurs mostly in the dry years where the low inflow is insufficient to raise the water level in the reservoir, and even if the water level is raised up to meet the recreation storage target, it is used up for irrigation in the late spring and summer months.

Risk, resiliency, and vulnerability are calculated for violations in each of the objectives of the reservoir. These values are calculated for the operating policies of each of the four hydrologic scenarios. For the sake of comparison the resulting values of risk, resiliency, and vulnerability are normalized so that they do not exceed a value of unity. The normalized values of risk, resiliency, and vulnerability are shown in Figures 5.3 - 5.5. Lower values of the evaluation criteria indicate a better performance of the given operating policy with respect to the corresponding objective.

Although violations occur in meeting all the objectives, except the municipal and industrial water supply goals, it is difficult to choose the operating policy which has the lowest values of all of the evaluation criteria. Hence, Multiobjective Compromise Programming (MCP) is used to select the most preferred policy.

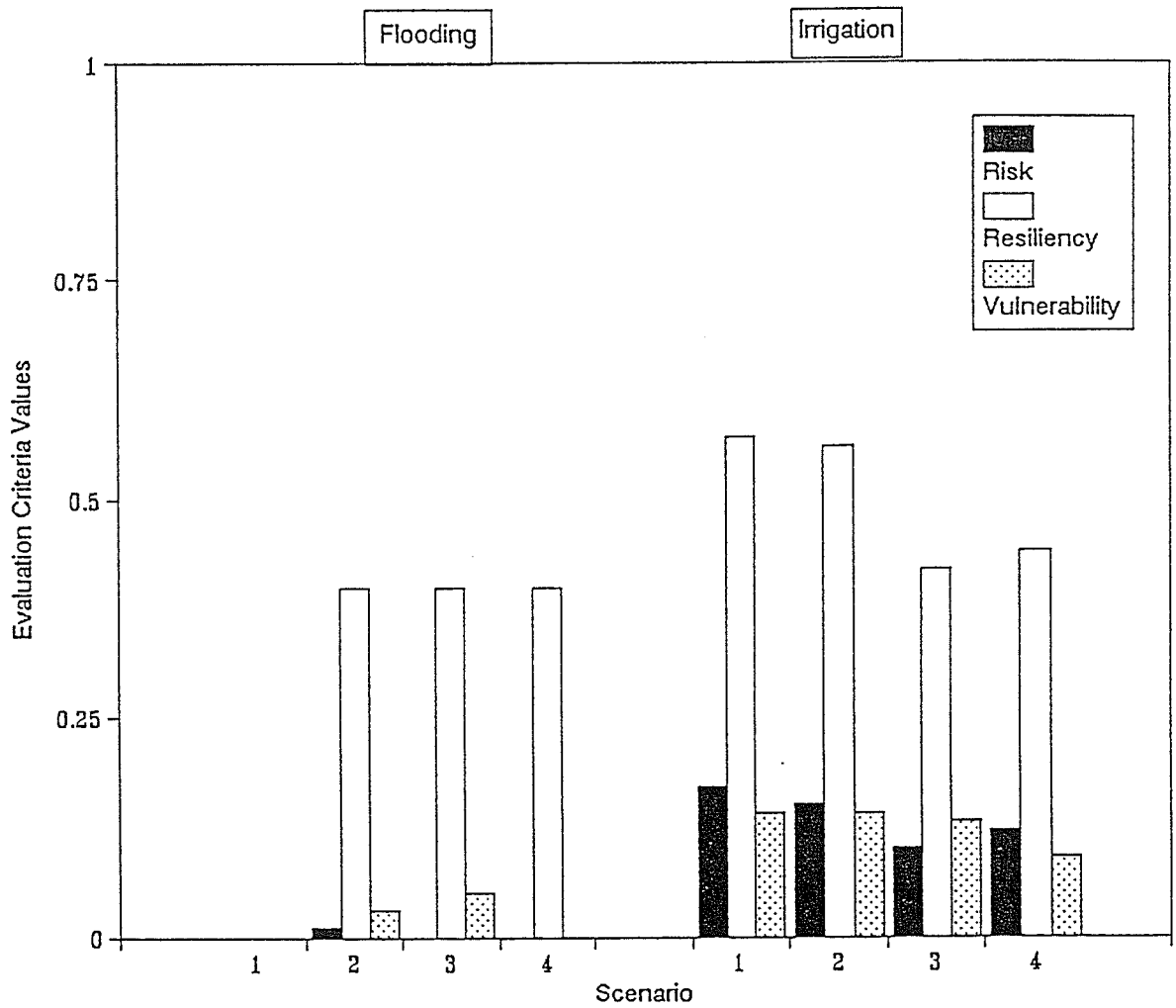


Figure 5.3 Risk, resiliency, and vulnerability recorded for flooding and irrigation.

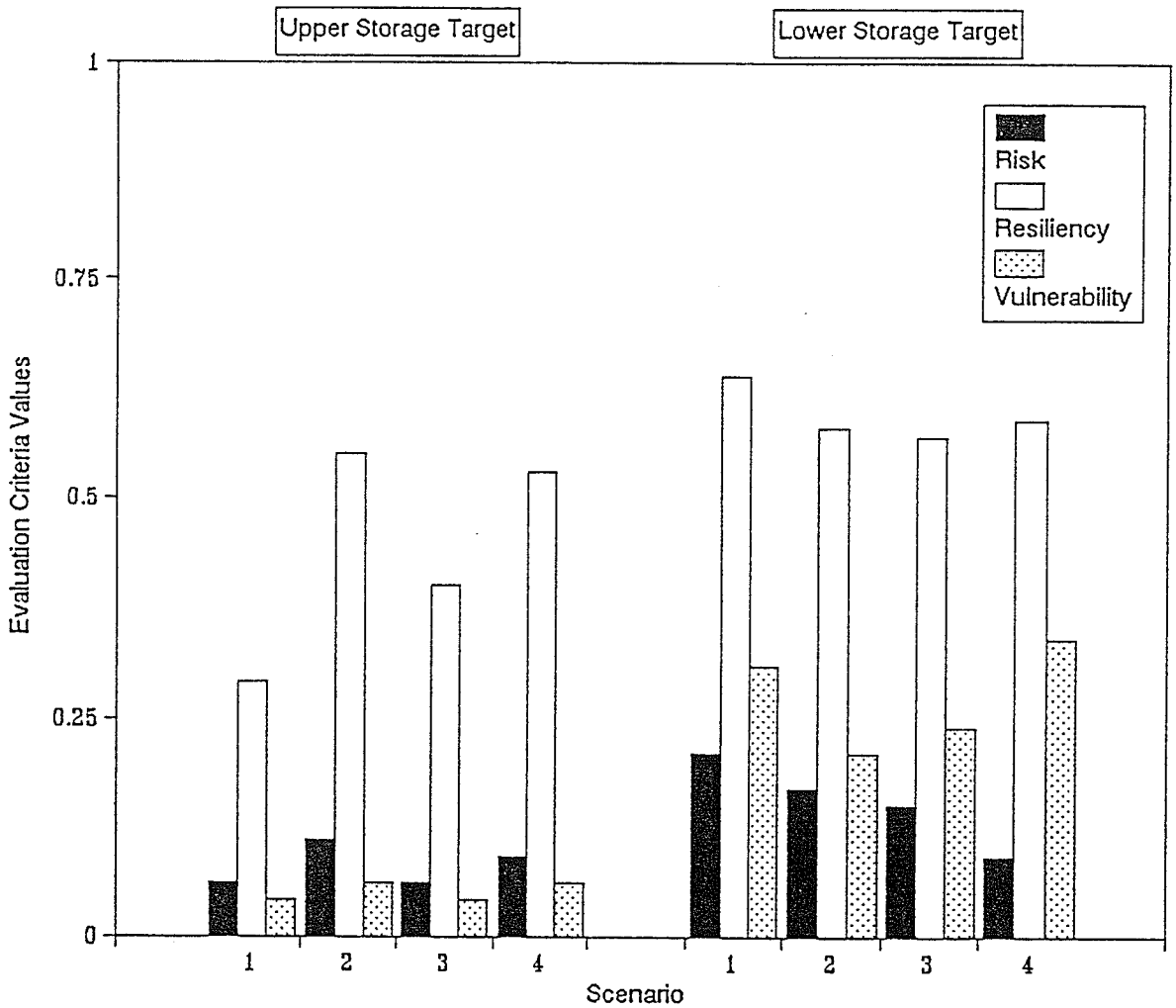


Figure 5.4 Risk, resiliency, and vulnerability recorded for recreation storage.

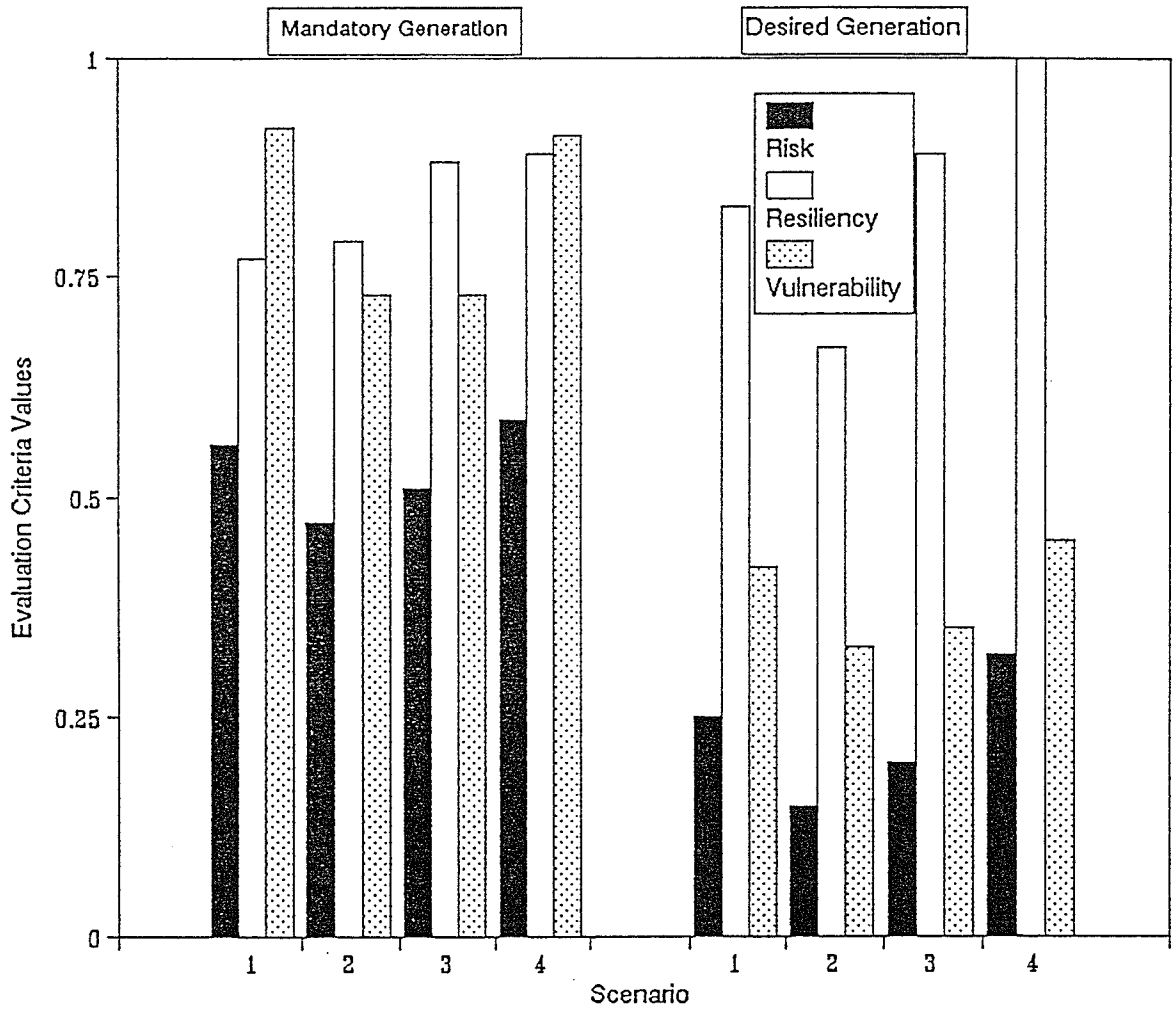


Figure 5.5 Risk, resiliency, and vulnerability recorded for mandatory and desired generation targets.

5.4.5 Selection of an Operating Policy Using Multiobjective Compromise Programming

MCP is a technique which ranks alternative non-inferior multiobjective solutions based on a measure of their distance to an ideal solution. The ideal solution is a solution which has optimal values for all the objectives of the multiobjective model. This solution is practically infeasible, but it serves as a standard for evaluating the alternative non-inferior solutions. The MCP identifies the solution closest to this ideal solution.

The measure of closeness to the ideal solution is defined by the L_s values. The goal of the MCP is to minimize these L_s values which are defined by the following equation:

$$L_s = \sum_{i=1}^{p} \alpha_i^s (Z_i^* - Z_i)^s \qquad (5.1)$$

where:

p	=	number of objectives;
α_i	=	weight or priority assigned to objective i;
Z_i^*	=	value of objective i under the ideal solution;
Z_i	=	value of objective i under the alternative non-inferior solution; and
s	=	a parameter expressing importance of the magnitude of the distance to the ideal solution.

In this work the value of an evaluation criterion is considered to be an objective, and the ideal solution is one in which all of the evaluation criteria are equal to zero. Therefore, Equation 5.1 reduces to:

$$L_s = \sum_{i=1}^{p} \alpha_i^s \; (-Z_i)^s \qquad (5.2)$$

For the MCP evaluation applied in this case study, the weights, α_i , assigned to each of the evaluation criteria for each violation are listed in Table 5.2. These set of weights were chosen by the author since the exact priority among the different uses of the reservoirs could not be determined from the decision makers. A weight of 7 is assumed to assign high priority to a given violation, and a weight of 1 is assumed to assign least priority to that violation. The last set of weights represent a case where no one particular use is more important than the other uses.

The parameter, s is assumed to be in a range of 2 - 5. A value of 1 is not used because the corresponding ranking obtained would not be reasonable and higher values of s were not used in order to avoid an increase in the computational burden. It was also shown that a value higher than 5 would have made no significant difference in the ranking of the operating policies.

Table 5.3 lists the ranking of the optimal storage policies in terms of the MCP objective function values for all four scenarios, for different values of α_i and s. The numbers in the table represent the scenario numbers and the order in which they are written is the ascending order of the MCP objective function values. The most outstanding policy from the MCP evaluation is Scenario 4, since this scenario has a high ranking in most cases. This scenario was also shown to be a good choice from the results of the optimization model (see Section 5.1).

Table 5.2 Weights, α_i, Assigned to the Evaluation Criteria of the Different Objectives (unitless)

Weight Set	FLDG	USTG	LSTG	IRGN	GMAN	GDES
1	7	1	1	1	1	1
2	1	7	1	1	1	1
3	1	1	7	1	1	1
4	1	1	1	7	1	1
5	1	1	1	1	7	1
6	1	1	1	1	1	7
7	1	1	1	1	1	1

FLDG = violation in flooding;

USTG = violation above the upper storage target;

LSTG = violation below the lower storage target;

IRGN = violation in irrigation and farm water supplies;

GMAN = violation in mandatory level of power generation; and

GDES = violation in desired level of power generation.

Table 5.3 Ranking of the Optimal Storage Operating Policies

Reservoir Use Having Highest Priority	$s = 2$	$s = 3$	$s = 4$	$s = 5$
Flooding (Weight Set 1)	1, 2, 4, 3*	1, 2, 4, 3	2, 1, 4, 3	2, 1, 4, 3
Upper Storage Target (Weight Set 2)	4, 2, 1, 3	4, 2, 1, 3	4, 2, 1, 3	4, 2, 1, 3
Lower Storage Target (Weight Set 3)	4, 3, 2, 1	4, 3, 2, 1	4, 3, 2, 1	4, 3, 2, 1
Irrigation (Weight Set 4)	4, 2, 3, 1	4, 2, 3, 1	4, 2, 3, 1	4, 2, 3, 1
Mandatory Generation (Weight Set 5)	3, 4, 2, 1	3, 4, 2, 1	3, 4, 2, 1	3, 4, 2, 1
Desired Generation (Weight Set 6)	3, 4, 1, 2	3, 4, 1, 2	3, 4, 1, 2	3, 4, 1, 2
All Uses Have Equal Priority (Weight Set 7)	4, 1, 2, 3	4, 1, 2, 3	4, 2, 1, 3	4, 2,1, 3

* Scenarios 1, 2, 3, and 4 are listed in the order of the MCP objective function values, i.e., in order of ascending L_s values.

6. A STRATEGY FOR ANALYZING COOLING TOWER OPERATION IN CONJUNCTION WITH RESERVOIR MANAGEMENT

In the process of transforming thermal energy into electrical energy, a great amount of waste heat is produced, which is passed on to the environment. Cooling systems are built in order to mitigate waste heat and cause the least possible impact on the environment. Since cooling towers reduce the requirement for dilution water, they may be beneficial in alleviating the conflicts in the uses of reservoirs which are designed to supply dilution water for heated effluent. This chapter discusses an optimization modelling approach for reservoir management which accounts for the reduction in the heated effluent with dilution and with a cooling tower. The results of this model may be used to select an optimal operating strategy for both cooling towers and reservoirs which are used in conjunction to mitigate waste heat from thermal power plants.

The results from the optimization model discussed in Chapter 5 provide insight into the crucial months of thermal power generation, which conflict with the other uses of the reservoir. For example, for the given case study the results show that the most crucial periods were the winter and early spring months of the dry years (see Figure 5.2). These months have the highest deficits in target generation and also high values of the desired generation level. If a cooling tower were to operate in all of these crucial months, it would definitely reduce the deficits in the desired generation target. But since operation and maintenance costs of a cooling tower are high and are dependent on the time of operation, it is necessary to find an economical operating strategy for the cooling tower. Moreover, the trade-offs between the costs of cooling tower operation and the benefits to the reservoir system need to be ascertained. It may also be necessary to determine the optimal period of operation of

the cooling tower when there is a limit on the available budget for operating such a system. All of the aforementioned reasons make it essential to use an effective modelling approach to obtain an optimal seasonal strategy for the cooling tower in conjunction with reservoir management.

6.1 Model Formulation

The model used is a mixed integer program (MIP) which is a modification of the linear goal programming model described in Chapter 4. MIPs are optimization models in which one or more integer variables exist along with continuous variables. The integer variables in the model presented herein are 0 - 1 variables which indicate whether a cooling tower is not operating or is operating, respectively, for any month of the entire period of the model.

The objective function of the model is a modified version of that presented by *Equation* 3.1 in Section 3.1.1. The deviations from the goals of storage volume, release volume, and the deficits in target generation are minimized. However, in this case the deficits in target generation are divided into those which occur when a cooling tower is operated and those which occur when it is not. The MIP model is formulated as:

$$\text{Minimize } Z = \sum_{j=1}^{m} \sum_{i=1}^{n} (US_i^j + LS_i^j + UR_i^j + LR_i^j) + \sum_{j=1}^{m} \sum_{i=1}^{n} (u_i^j + uc_i^j) \tag{6.1}$$

subject to:

definition of the allowable generation when a cooling tower is not operating:

$$G_i^j - g(T_i^j, Q_i^j, STD_i^j) \leq 0 \qquad \forall\, i = 1, 2,.., n\,, j = 1, 2,.., m \qquad (6.2)$$

definition of the allowable generation when a cooling tower is operating:

$$GC_i^j - gc(T_i^j, Q_i^j, STD_i^j) \leq 0 \qquad \forall\, i = 1, 2,.., n\,, j = 1, 2,.., m \qquad (6.3)$$

deviation from target power generation when a cooling tower is not operating:

$$G_i^j + u_i^j - GDES_i^j\,(1 - X_i^j) \geq 0 \qquad \forall\, i = 1, 2,.., n\,, j = 1, 2,.., m \qquad (6.4)$$

deviation from target power generation when a cooling tower is operating:

$$GC_i^j + uc_i^j - GDES_i^j\,(X_i^j) \geq 0 \qquad \forall\, i = 1, 2,.., n\,, j = 1, 2,.., m \qquad (6.5)$$

limit on the number of months of operation of a cooling tower:

$$\sum_{j=1}^{m} \sum_{i=1}^{n} X_i^j - N \leq 0 \qquad (6.6)$$

and Equations 3.2 - 3.9 described in Chapter 3.

where :

uc_i^j = deficit in target generation when a cooling tower is operating in time period i of year j, in Gwhr;

GC_i^j = generation which occurs when a cooling tower is operated in time period i of year j, in Gwhr;

$gc(T_i^j, Q_i^j, STD_i^j)$ = relationship defining the allowable generation as a function of river flow when a cooling tower is operating in time period i of year j;

X_i^j = 0 - 1 integer variable which denotes whether a cooling tower is or is not operating. If $X_i^j = 0$ the cooling tower is not operating in time period i of year j, if $X_i^j = 1$, it is;

N = limit on the number of time periods of cooling tower operation for the entire time period of the model; and

all other variables are as defined in Section 3.1.

Equations 6.2 and 6.3 define the allowable generation without and with a cooling tower operating in time period i and year j, respectively. *Equations* 6.4 and 6.5 define the deficits in target generation without and with a cooling tower operating, respectively. When X_i^j is zero, then a cooling tower is not in operation and uc_i^j is driven to zero. When X_i^j is one, then a cooling tower is in operation and u_i^j is driven to zero. *Equation* 6.6 limits the number of time periods of cooling tower operation for a given year.

6.2 Relationship Between River Flow and Allowable Generation When a Cooling Tower Operates

A direct cooling system transfers the waste heat to the cooling water which is discharged as thermal effluent into the river or receiving water body. In a cooling tower the thermal effluent is circulated through a tower shaped heat exchanger, where all or part of the waste heat is transferred to the ambient air. The transfer of heat may take place with or without direct exposure of the thermal effluent to the cooling air. The former case may have a faster rate of heat exchange but results in a consumptive use of water (i.e., the water lost in the heat exchange process). This thesis deals with the latter case in which it is assumed that the water required for cooling tower operation is negligible.

If the cooling tower is operated for an entire facility, the function which represents the allowable power generation, $gc(T_i^j, Q_i^j, STD_i^j)$, is unlimited below

the sustainable capacity of that facility, and so is GC_i^j. However if only a portion of a power facility is cooled by the cooling tower a modified version of *Equation* 3.17 will need to be applied. Let the portion of the power facility cooled by the cooling tower be Y, in Gwhr. Then *Equation* 3.17 described in Section 3.2 may be rewritten, taking into account the fact that no river flow is required to cool the portion of the generation (Y), that makes use of the cooling tower. The modified version of *Equation* 3.17 is:

$$GC = \frac{\gamma\, Q\, \mathrm{CF}\left[(Tx - Tb)\exp\left(\frac{K_r X}{V}\right)\right]}{R_g} + Y \qquad (6.7)$$

where:

GC = allowable generation with a cooling tower; and

all other variables are as defined in Section 3.2 of Chapter 3.

Equation 6.1 is typically non-linear, but may be approximated as linear.

6.3 Solution of the Mixed Integer Program

The MIP can be solved using the Branch and Bound technique. The introduction of integer variables increases the computational time. However, the increase in computational time can be reduced by keeping the number of integer variables as small as possible. The optimization model described in Chapter 3 may be used to gain information regarding the crucial months of thermal power generation, so that the potential periods of cooling tower operation may be identified. This process may help reduce the number of integer variables. For example, the results for the case study (see Chapter 5) showed that no conflicts exist when water is

released for thermal power generation during the wet years. Hence, X_i^j may be set equal to zero for all i in the wet years.

7. APPLICATION OF THE MIXED INTEGER PROGRAMMING MODEL TO THE CASE STUDY

This chapter describes the application of the MIP model discussed in Chapter 6 to the Shellmouth Reservoir and the thermal power plant at Brandon. A cooling tower is considered for handling a portion of the waste heat generated from the thermal power plant. Since, the cooling tower reduces the water need for dilution of the heated effluent, it is hoped that the operation of a cooling tower would reduce the conflict between the reservoir uses of storage recreation and thermal power generation.

7.1 Model Formulation

The objective function is to minimize the sum of the deviations above and below the upper and lower storage targets, respectively, and the deficits in mandatory and desired generation levels in the months in which a cooling tower is and is not operating. The targets defining storage recreation occur only in the first five months (April through August) of the hydrologic year of the model. The mandatory generation requirements occur only in the five winter months (November through March) of the hydrologic year of the model. Desired generation targets are present only in the dry years and occur throughout the year. The model is formulated as:

$$\text{Minimize } Z = \sum_{j=1}^{9} \sum_{i=1}^{5} (US_i^j + LS_i^j) + C_w \sum_{j=1}^{9} \sum_{i=8}^{12} (D_i^j + DC_i^j)$$

$$+ \sum_{j \,\varepsilon\, L} \sum_{i=1}^{12} (u_i^j + uc_i^j) \qquad (7.1)$$

subject to:

definition of the deviation from the target level of mandatory power generation when a cooling tower is not operating:

$$G_i^j + D_i^j - GMAN_i\ (1 - X_i^j) \geq 0 \qquad \forall\ i = 1, 2, \ldots, 12,\ j = 1, 2, \ldots, 9 \qquad (7.2)$$

definition of the deviation from the target level of mandatory power generation when a cooling tower is operating:

$$GC_i^j + DC_i^j - GMAN_i\ (X_i^j) \geq 0 \qquad \forall\ i = 1, 2, \ldots, 12,\ j = 1, 2, \ldots, 9 \qquad (7.3)$$

definition of the deviation from the target level of desired power generation when a cooling tower is not operating:

$$G_i^j + u_i^j - GDES_i\ (1 - X_i^j) \geq 0 \qquad \forall\ i = 1, 2, \ldots, 12,\ j\ \varepsilon\ L \qquad (7.4)$$

definition of the deviation from the target level of desired power generation when a cooling tower is operating:

$$GC_i^j + uc_i^j - GDES_i\ (X_i^j) \geq 0 \qquad \forall\ i = 1, 2, \ldots, 12,\ j\ \varepsilon\ L \qquad (7.5)$$

and *Equations* 6.2, 6.3, and 6.6 described in Chapter 6 and *Equations* 4.2 - 4.12 described in Chapter 4.

Also, in order to obtain a general management strategy, the storage volume is constrained to be the same in the same month of the same type of year and if a cooling tower operates in a given month in a certain type of year it operates for that month in all similar years. For example, if a cooling tower operates in November of one dry year, it operates in the month of November of all dry years.

where:

DC_i^j = deviation below the mandatory value of power generation in month i of year j when the cooling tower is operating, in Gwhr;

uc_i^j = deviation below the desired value of power generation in month i of year j when the cooling tower is operating, in Gwhr;

GC_i^j = generation in month i of year j when the cooling tower is operating, in Gwhr; and

all other variables are as described in Section 6.1.

The objective function as described by *Equation* 7.1 is nearly similar to the *Equation* 4.1 described in Chapter 4. Here the deficits in mandatory and desired generation targets are modified in order to account for the months in which a cooling tower is not and is operating, respectively. *Equation* 7.1 does not include the weight, w, which was present in *Equation* 4.1 of the GP optimization model. This weight is excluded to reduce since the value of N in *Equation* 6.6 which limits periods of operation of the cooling tower tend to overshadow any trade-offs between the storage and release requirements. X_i^j is a 0 - 1 integer variable denoting if the cooling tower is not or is operating in month i and year j, respectively. When it is zero the deficits in mandatory and desired generation in *Equations* 7.3 and 7.5 are driven to zero. The following section describes the procedure for obtaining the linear relationship between allowable power generation and river flow when a cooling tower is operating, as described by *Equation* 6.3 in Chapter 6.

7.2 Reducing the Size of the Mixed Integer Programming Model

Usually the solution procedure of an MIP is very time consuming. However, the computational time can be minimized by keeping the number of integer variables as small as possible. The information obtained from the optimization results discussed in Chapter 5 were used in this analysis to reduce the number of integer variables.

The results of the optimization model and the simulation discussed in Chapter 5 have shown that there is no difficulty in meeting the generation goals during the wet years and during the months of June to October in the dry years. However, a cooling tower may be required in the five winter months from November to March in the average years, and in the seven winter and early spring months from November to May in the dry years. Recall the constraint specifying that the cooling tower operates in the same month of a similar type of year. Given this constraint and the observations from the optimization model, the number of integer variables may be reduced to 36, where 15 integer variables represent the possible months of cooling tower operation in the three average years and 21 integer variables represent the possible months of cooling tower operation in the three dry years.

7.3 Linearization of the Relationship Between River Flow and Allowable Generation with a Cooling Tower

The thermal generating station at Brandon consists of five generating units of which the fifth is the largest and most efficient. Manitoba Hydro is considering building a cooling tower for this unit. It is assumed that the cooling tower is capable of handling all of the waste heat generated by Generating Unit 5. It is also assumed

that the amount of water lost in the heat exchange process of the cooling tower is negligible. The value of Y in *Equation* 6.7 for this case study is denoted by the monthly capacity of Generating Unit 5, in Gwhr. That is:

$$Y = 2.112 \text{ x (number of days in the month)} \tag{7.6}$$

The relationship between allowable power generation and river flow when a cooling tower is operating is plotted for the months of November through April (i.e., the crucial months of power generation) in Figures 7.1 - 7.6. These plots were developed using *Equation* 6.7 and the three-step method described in Section 4.5. Linear relationships for these plots are determined and have the general form:

$$gc\ (T_i, Q_i^j, STD_i) = ac_i + bc_i\ (Q_i^j) \tag{7.7}$$

where:

ac_i = intercept of the linearized relationship;

bc_i = slope of the linearized relationship; and

all other variables are described in Section 3.1.

Equation 6.7 described in Section 6.2 is not applicable to the month of May, which has a higher background temperature than the stream temperature standard. Hence, no generation is possible in May without a cooling tower. With the cooling tower, an allowable generation equal to the capacity of Generating Unit 5 is possible. Hence the relationship between allowable power generation and river flow for the month of May is as follows:

$$gc\ (T_{(May)}, Q_{(May)}^j, STD_{(May)}) = 65.47 \text{ Gwhr} \tag{7.8}$$

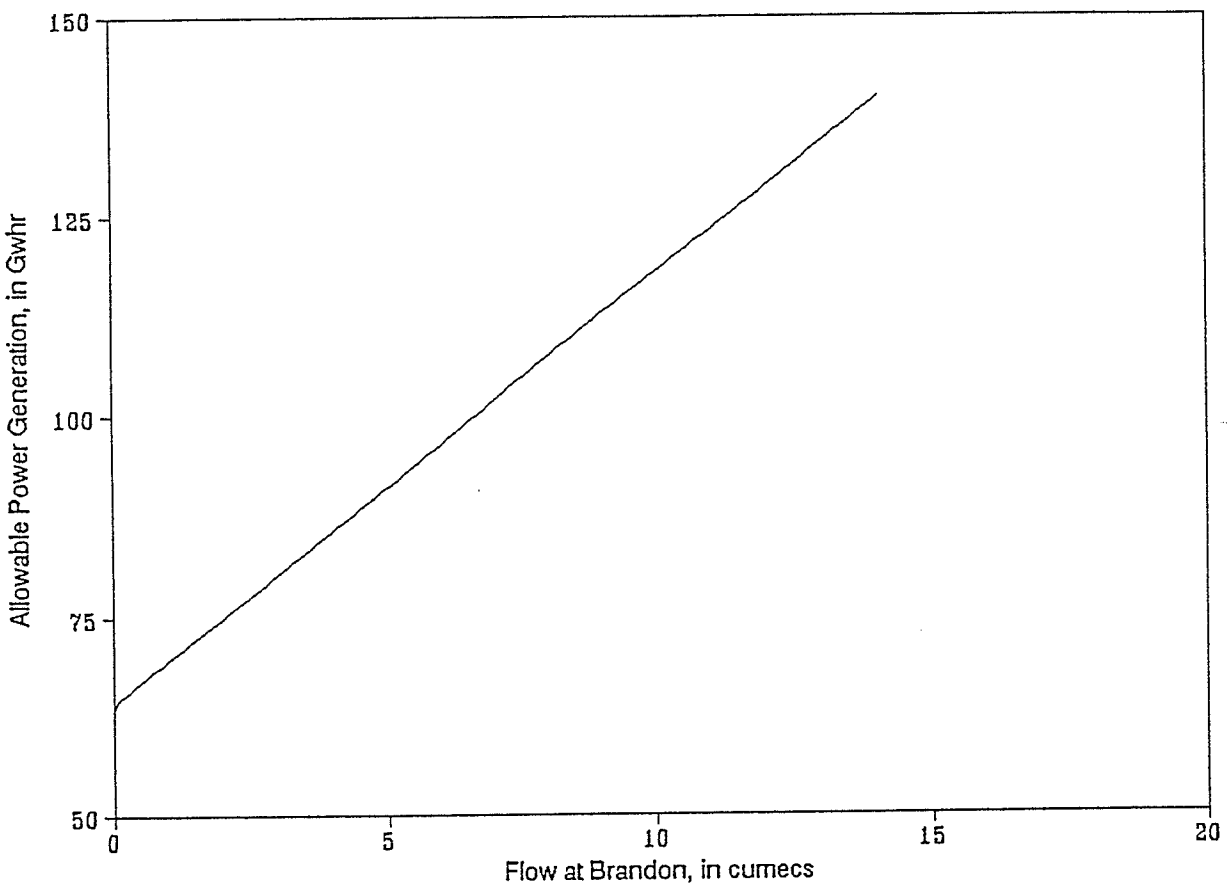


Figure 7.1 Relationship between river flow and allowable power generation with a cooling tower operating for the month of November.

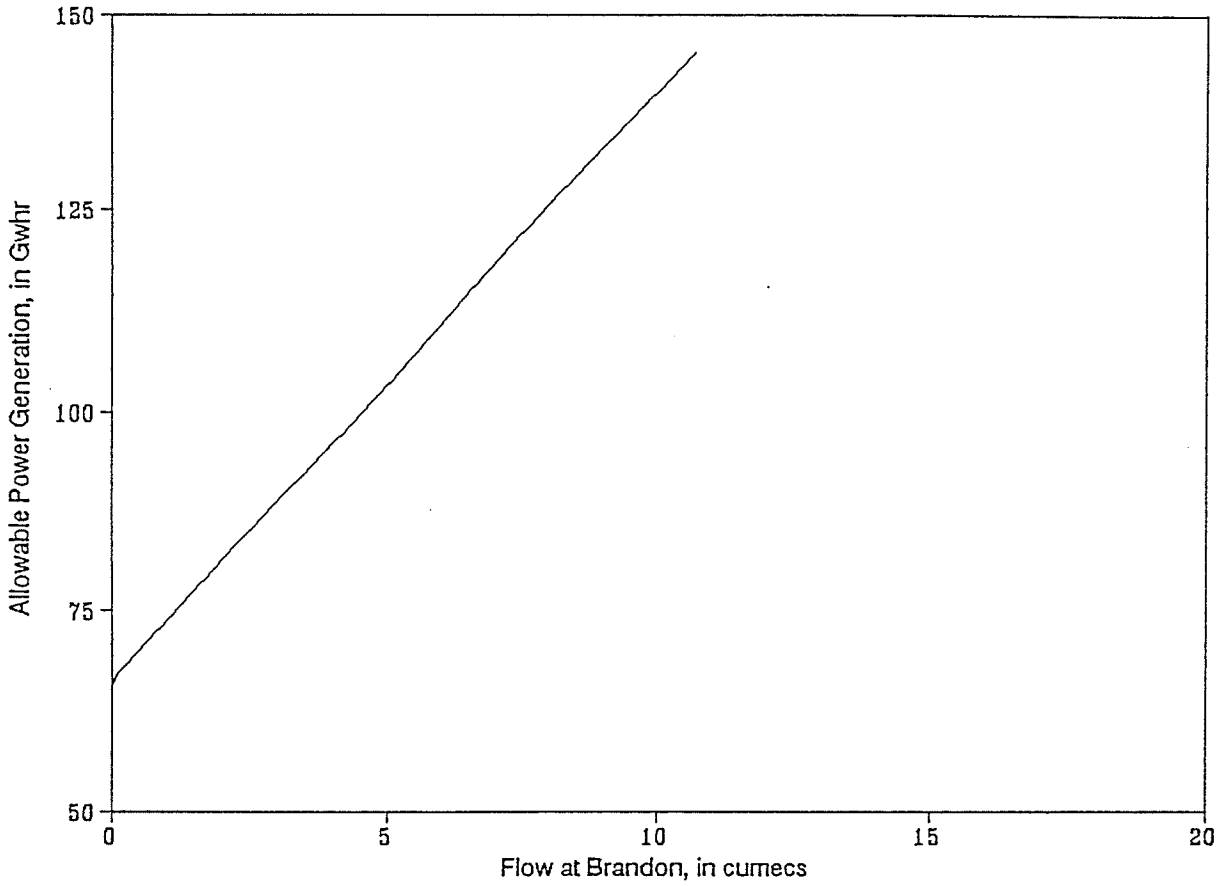


Figure 7.2 Relationship between river flow and allowable power generation with a cooling tower operating for the month of December.

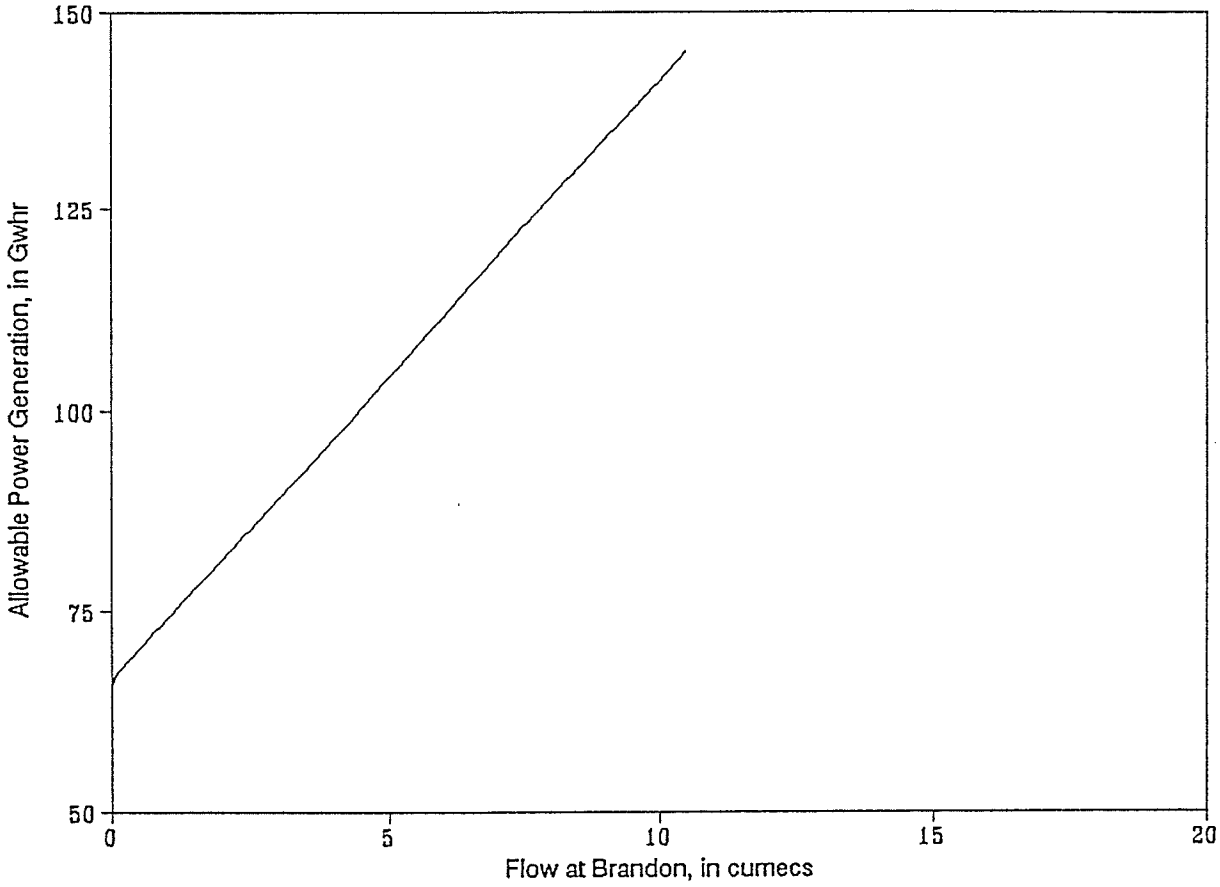


Figure 7.3 Relationship between river flow and allowable power generation with a cooling tower operating for the month of January.

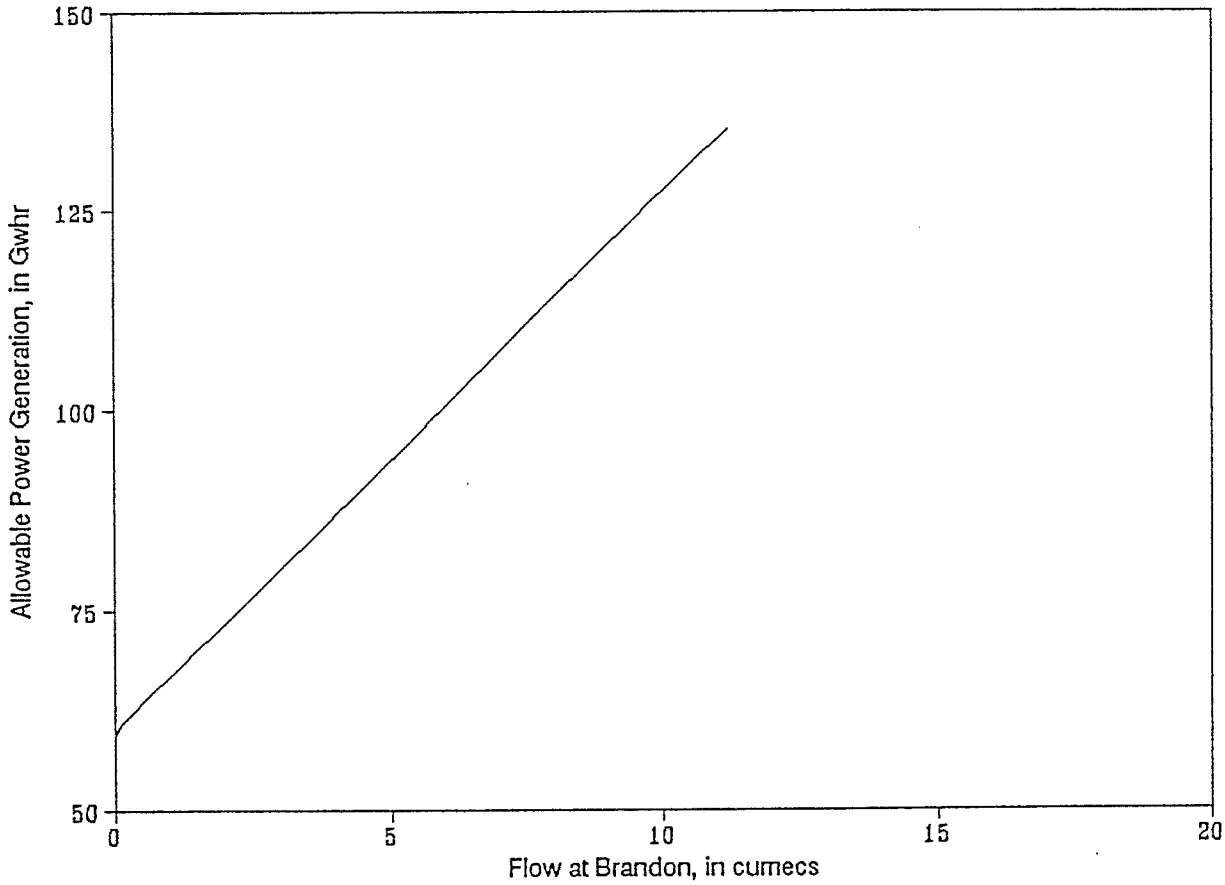


Figure 7.4 Relationship between river flow and allowable power generation with a cooling tower operating for the month of February.

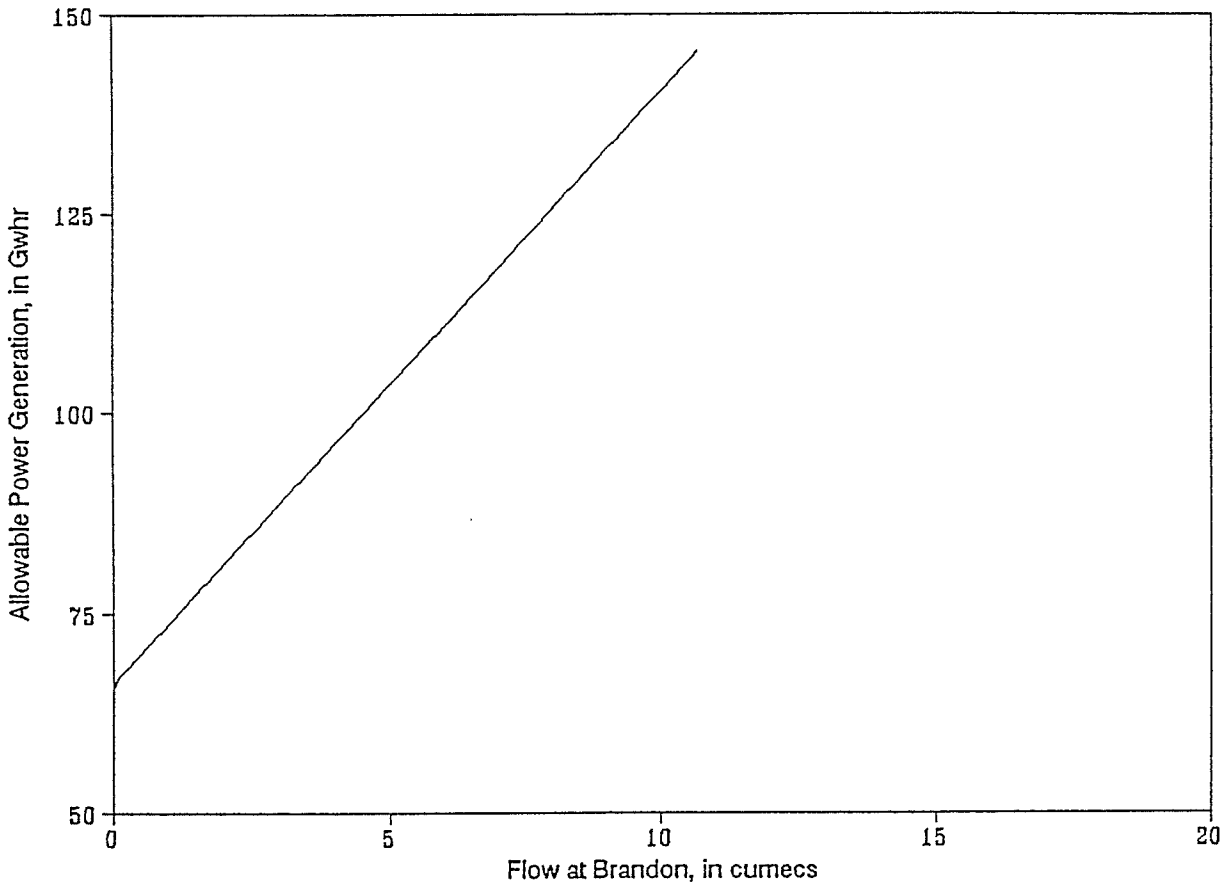


Figure 7.5 Relationship between river flow and allowable power generation with a cooling tower operating for the month of March.

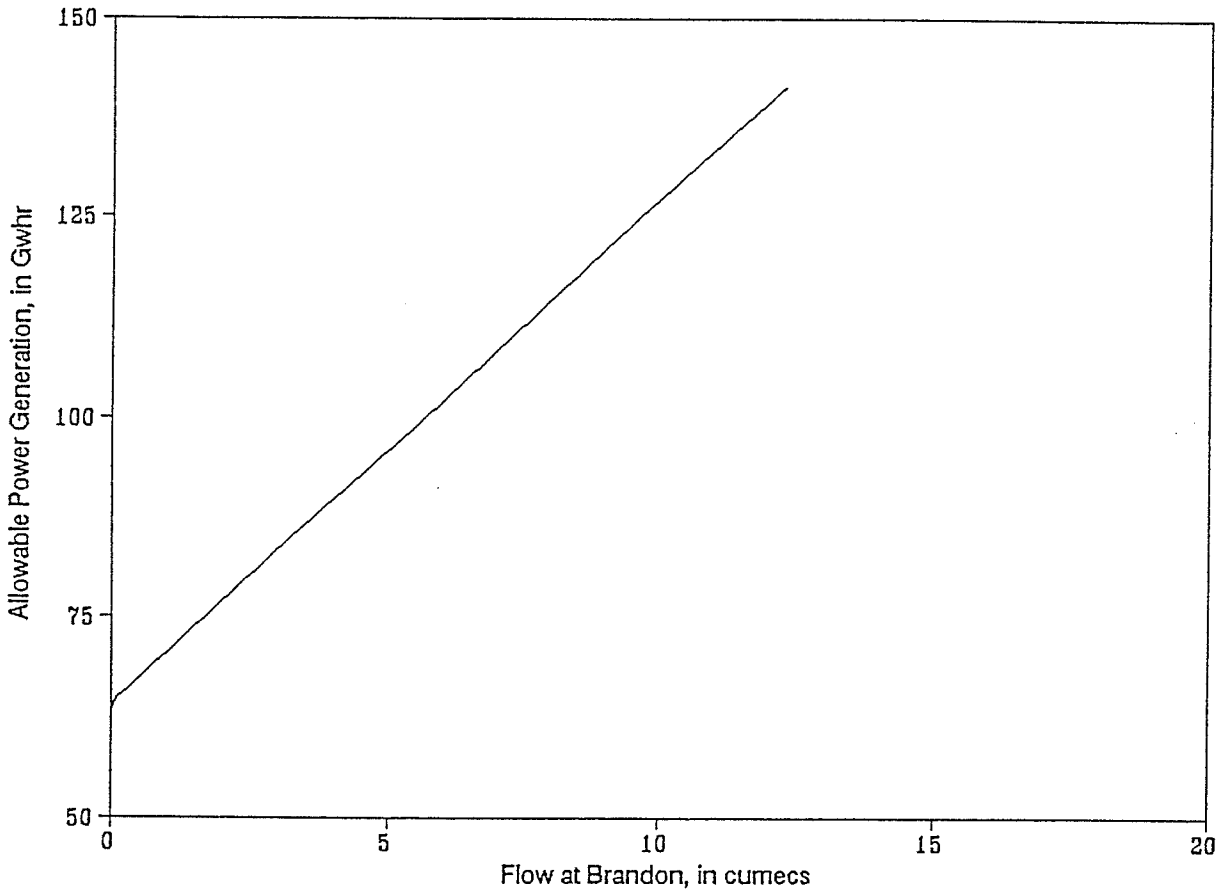


Figure 7.6 Relationship between river flow and allowable power generation with a cooling tower operating for the month of April.

7.4 Results of the Mixed Integer Program

Hydrologic Scenarios 1 and 2 are not considered as the results of the optimization and simulation models showed these scenarios to be highly conservative and unrealistic. Hence, the model is solved only for Scenarios 3 and 4.

The MIP was solved using the Branch and Bound technique, using the software package GAMS (BDLMP) to solve the relaxed MIP at each branching node. As discussed in Section 7.2, the months in which cooling towers could be operated were from November to March in the average years and November to May in the dry years. The limit on the total number of months of cooling tower operation, N, was varied from 0 to 18 for hydrologic Scenario 3, and from 0 to 21 for hydrologic Scenario 4. A further increase in the value of N did not reduce the reservoir storage or power generation deviations for either scenario.

Figure 7.7 shows the sum of storage deviations and the sum of the deficits in desired generation, for a given number of months of cooling tower operation for Scenario 3. Table 7.1 lists the months of cooling tower operation for values of N from 0 to 18. As shown in the table, the cooling tower is only operated in the dry years. The hydrologic scenario consists of a dry, average, and wet year occurring sequentially. It was found that a cooling tower was unnecessary for the average years since they are always followed by wet years. During the average years the water in the reservoir is used to satisfy the generation needs, since the reservoir faces high inflows in the following wet years. An increase in the number of months of cooling tower operation above zero does not reduce the storage deviations any further (see Figure 7.7). However, it greatly reduces the deficits in desired generation levels. Maximum benefits for this system are attained at a point where the value of N is 18. A further increase in the N value does not reduce the sum of the desired

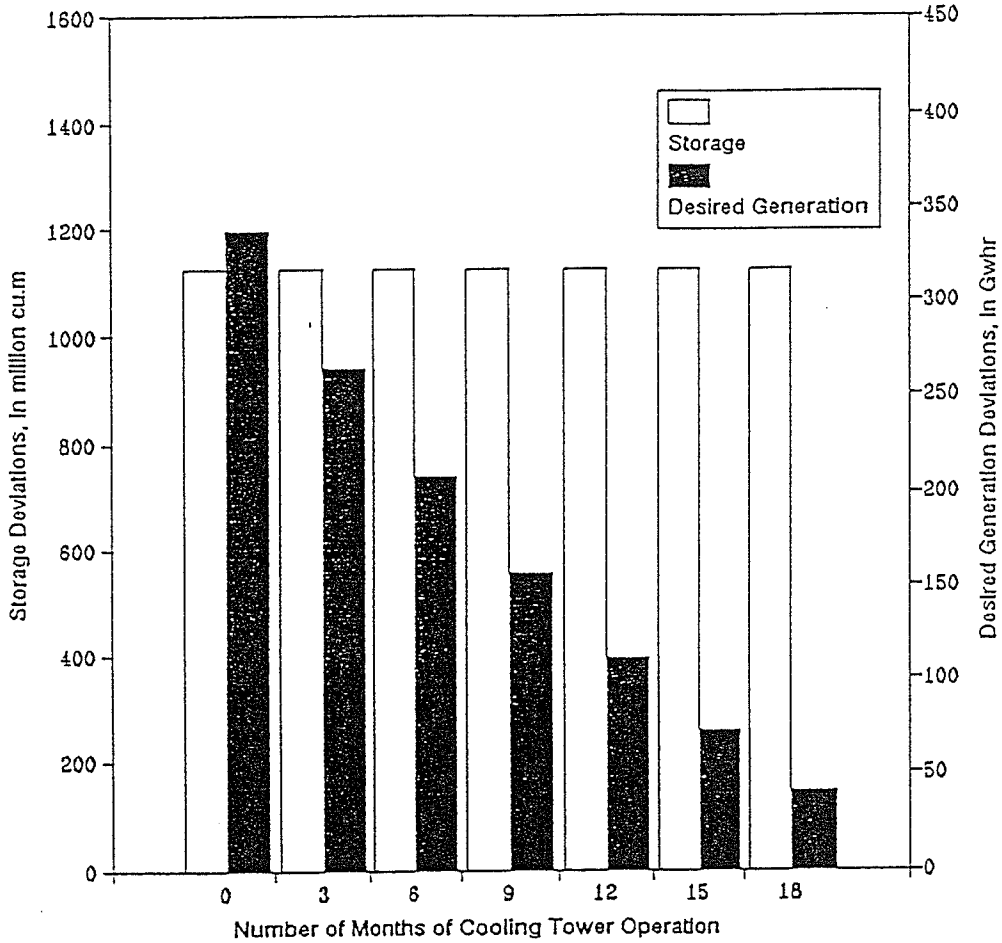


Figure 7.7 Number of months of cooling tower operation, sum of the deviations recorded from storage targets, and sum of the deficits in desired generation for Scenario 3.

Table 7.1 Months of Cooling Tower Operation for Scenario 3

Number of Months of Cooling Tower Operation, *N*	Type of Year	Months of Cooling Tower Operation
0	NA	NA
3	dry	Nov.*
6	dry	Nov., Mar.
9	dry	Nov., Mar., Apr.
12	dry	Nov., Dec., Mar., Apr.
15	dry	Nov., Dec., Mar., Apr., May
18	dry	Nov., Dec., Jan., Mar., Apr., May

NA - Not Applicable

* Operates in November of all 3 dry years.

generation deficits.

The factors which affect the selected months of cooling tower operation in the dry years are the relationship between river flow and allowable generation, the magnitude of tributary inflow, and the desired generation level. For example, when N is equal to 3, the month of November, which has the most restrictive linear relationship between river flow and allowable generation in the winter months , is selected. The relatively high amount of release required to satisfy the generation need for November is reduced by the cooling tower, and this water is stored in the reservoir and utilized for achieving the generation needs in the other months. Although April has a high desired generation target and a more restrictive allowable generation relationship than November, it is selected only when N is increased to 9, since April also has a high tributary inflow.

Figure 7.8 shows the sum of storage deviations and the sum of the deficits in desired generation, for Scenario 4. Table 7.2 lists the months of cooling tower operation for a given value of N from 0 to 21. The solution of the MIP shows that, unlike hydrologic Scenario 3, a cooling tower is necessary for both the average and the dry years in Scenario 4. Scenario 4 consists of a wet year followed by an average year followed by a dry year. Hence, the water saved in the reservoir by using a cooling tower in the average years, can be utilized in the following dry years. The average year has storage target deviations caused by the mandatory generation goals. Hence, it is beneficial to operate a cooling tower in the average years, as it decreases the deviations from storage recreation targets by reducing the release required to meet these generation needs. Maximum benefits for this system are attained at a point where the value of N is 21.

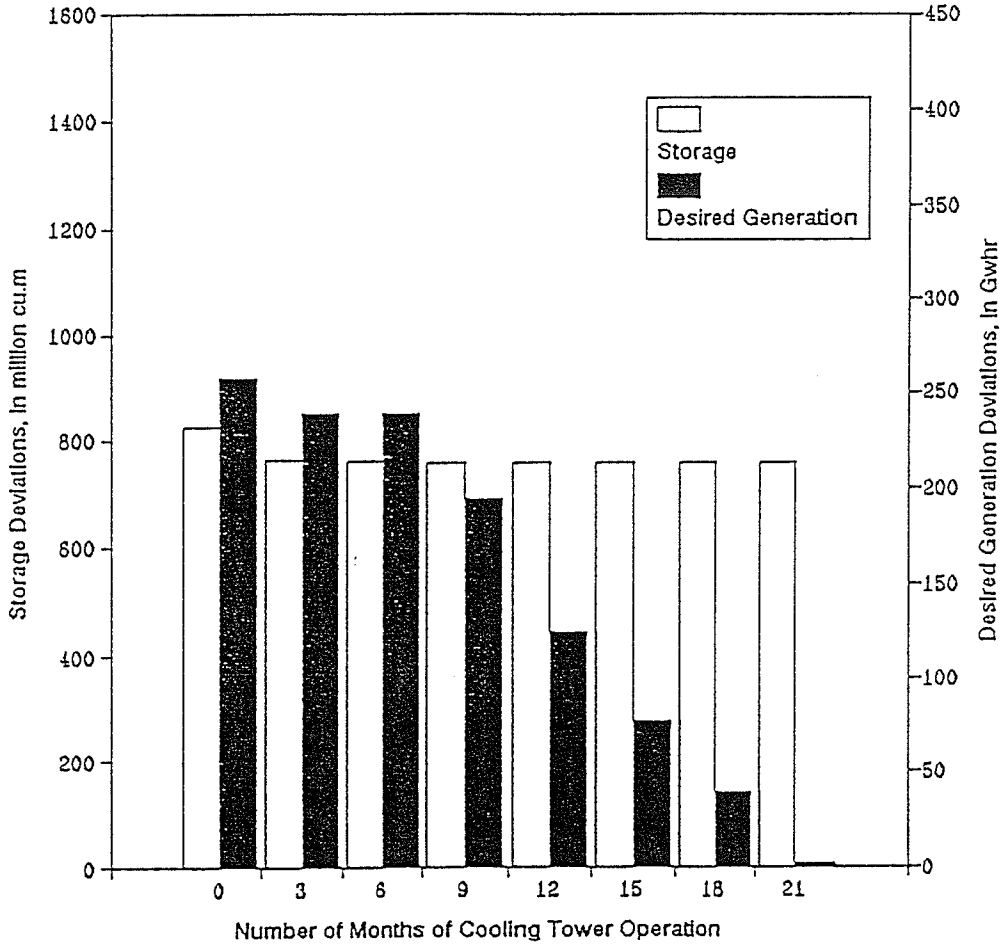


Figure 7.8 Number of months of cooling tower operation, sum of the deviations recorded from storage targets, and sum of the deficits in desired generation for Scenario 4.

Table 7.2 Months of Cooling Tower Operation for Scenario 4

Number of Months of Cooling Tower Operation, *N*	Type of Year	Months of Cooling Tower Operation
0	NA	NA
3	average	Jan.*
6	average	Nov., Mar.
9	average	Nov., Jan., Mar.
12	average dry	Nov., Jan., Mar. Nov.
15	average dry	Nov., Jan., Mar. Nov., Apr.
18	average dry	Nov., Jan., Mar. Nov., Apr., May
21	average dry	Nov., Jan., Mar. Nov., Dec., Apr., May

NA - Not Applicable

* Operates in January of all 3 average years.

The first nine months of cooling tower operation are selected in the average years, and the sum of deviations from storage targets decrease for these solutions. However, increasing the value of N above 3 causes no further decrease in the sum of storage deviations. Since the feasible solution space of the MIP is limited only in the sum of the deficits in desired generation levels are reduced. As N is increased beyond 9, the selected months of cooling tower operation are determined by the relative restrictiveness of the allowable generation relationship, the tributary inflows, and the desired generation level. For example, the month of January is selected first although it has a relatively mild sloping allowable generation relationship, because it has very low tributary inflow. The next additional month of cooling tower operation is the month of April since it has the most restrictive allowable generation relationship.

Appendix C lists the reservoir management policy for hydrologic Scenarios 3 and 4 for the different values of N. The reservoir management policy is in terms of the storage volume for wet, average, and dry years. The validity of the performance of the storage operating policies obtained from the MIP model was checked by a simulation model which is discussed in the following Section.

7.4.1 The Simulation Model

The months in which a cooling tower operates require a relatively smaller amount of water release, when compared to a situation when a cooling tower does not operate. The simulation model used for evaluating the results of the optimization model described in Chapter 5 is slightly modified to incorporate the change in the release requirement depending on the operating strategy (i.e., months of operation) of the cooling tower. However, the release rules remain the same. This simulation

model is used only to verify the results of the MIP and not to select an optimal strategy.

The results of the simulation showed that an increase in the number of months of cooling tower operation caused a decrease in storage target deviations, a decrease in mandatory and desired generation deficits, and an increase in the ability to meet the irrigation water supply. However, there was a slight increase in the magnitude of flooding in the same months as that recorded by the simulation model described in Chapter 5.

8. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

8.1 Conclusions

This thesis develops a GP model for obtaining a management policy for a multipurpose reservoir that accounts for the generation needs of a downstream thermal generating station. The model is illustrated with a case study based on the Shellmouth Reservoir and Dam and the thermal generating station at Brandon. A simulation model and multiobjective compromise programming technique is used to evaluate the optimization model results and to select a preferred management policy for the case study.

Four management policies are obtained for the case study based on four hydrologic scenarios which are used as input to the goal programming model. The evaluation procedure showed that hydrologic Scenario 4 performed the best since it offered the most flexible input to the optimization model. Part of the reason for the selection of Scenario 4, however, may be attributed to the priorities assigned by the author to the various uses of the reservoir. Hence, the selection of the most preferred policy may vary depending upon the priority of the various uses of the reservoir. Hydrologic Scenarios 1 and 2 proved to be highly conservative and unrealistic for the case study of this thesis. However, it cannot be concluded that these scenarios are unrealistic for all potential case studies.

The latter part of the thesis identifies seasonal operating strategies for a cooling tower which is managed in conjunction with a regulated reservoir. No attempt is made to select a single preferred management strategy for the cooling tower

of the case study, since more information regarding the cost of operation at different times would be necessary to perform such an assessment.

The results of the mixed integer programming model for cooling tower operation shows that trade-offs exist between the number of months of cooling tower operation and the corresponding benefits in recreation storage, and generation needs. This is confirmed by the simulation model. These results would provide a decision maker with information regarding the potential benefits of different operating strategies for a cooling tower.

The effective use of optimization techniques in obtaining management policies for multipurpose reservoirs while considering thermal generation needs, and in investigating alternate cooling systems, is demonstrated in the thesis. This research may be considered as among the first studies in water resources that have used optimization techniques to explicitly account for thermal generation in reservoir management.

8.2 Recommendations for Future Work

No information regarding the economic costs of operating the reservoir or cooling tower or the economic value of the recreation storage targets are available at this time. The availability of cost data, especially for the MIP model would improve selection of the operating strategy for the cooling tower. This would assist the decision maker in selecting a single operating strategy from the trade-offs presented between the number of months of cooling tower operation and the benefits of recreation and power generation.

The development and incorporation of the relationship between river flow and allowable generation is an important contribution of this thesis. Preliminary investigations have shown that this relationship may also be modified to relate river flow to potential temperature standard violation given a constraint which strictly satisfies all generation needs. The typical objective of this optimization model would be the minimization of the violation in temperature standard. Such a model could be used to give a decision maker information regarding the degree of temperature standard violation under the condition that all uses of the river have high priority.

The results of the case study have shown that the objective of providing water for thermal generating needs conflicts with the recreation needs of the reservoir. Since the conflict among the various reservoir uses may increase as growth or changes in the river basin occur, it may also be necessary to investigate more efficient management of the reservoir in such cases. The modelling approach explained in this thesis would be valuable in structuring a new model that would identify efficient management policies that incorporate growth and changes in the river basin.

The approach developed in this thesis may be used to construct optimization models that determine the capacity and the type of cooling facility for a new thermal generating station. It may also be used in some cases to locate the ideal site for building a thermal power plant (for example, a power plant may be located at a site which has the highest magnitude of river flow). Furthermore, with significant modification, these models may be used to determine the maximum instantaneous generation possible at any time in the year. The information obtained in such cases may be more helpful in operating a thermal generating station that has random generation needs at any given time in the year.

The optimal management policies obtained from the optimization models may be attributed in part to the method used in this research to incorporate stochasticity. The performance of the goal programming model and the mixed integer programming model should be studied when different methods of incorporating stochasticity are considered such as Chance Constrained Programming or Reliability Programming.

Some detailed modifications of the existing models may be necessary for a realistic application to this and other case studies. The assumption of complete mixing at the point of thermal emission in the river could result in a poor prediction of the downstream temperature in streams having a low velocity of flow. More complex temperature models may need to be investigated in slow moving waterways to incorporate the behavior of the thermal plume formed from the thermal effluent.

In cold climates such as that of the case study, the reservoir would usually be ice capped in the winter months. A large release of water in the winter months in order to satisfy power generation would result in the breaking up of the ice layer on the reservoir and cause difficulty in the operation and maintenance of the reservoir. Future optimization models must try to incorporate this issue in their formulation.

Finally the simulation model obtains results for flooding in a monthly time period, while testing the performance of the optimal operating policies. It does not provide the time and the corresponding magnitude of flooding at a specific day in the month. A daily simulation model which is structured to obtain daily flooding information may provide more insight into the performance of the operating policies obtained from the optimization models and may need to be examined.

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Appendix A

Determining the Weight, w in the Objective Function of the GP Model for the Case Study

Scenario 1

Trial	Range of w	percentage increase in sum of storage deviations, C	percentage decrease in sum of generation deficits, B	Difference Between Columns 3 and 4
1	1^* - 400	0	0	0
2	425 - 10^6	100	100	0

Scenario 2

Trial	Range of w	percentage increase in sum of storage deviations, C	percentage decrease in sum of generation deficits, B	Difference Between Columns 3 and 4
1	1^* - 10^6	0 or 100	0 or 100	0

Scenario 3

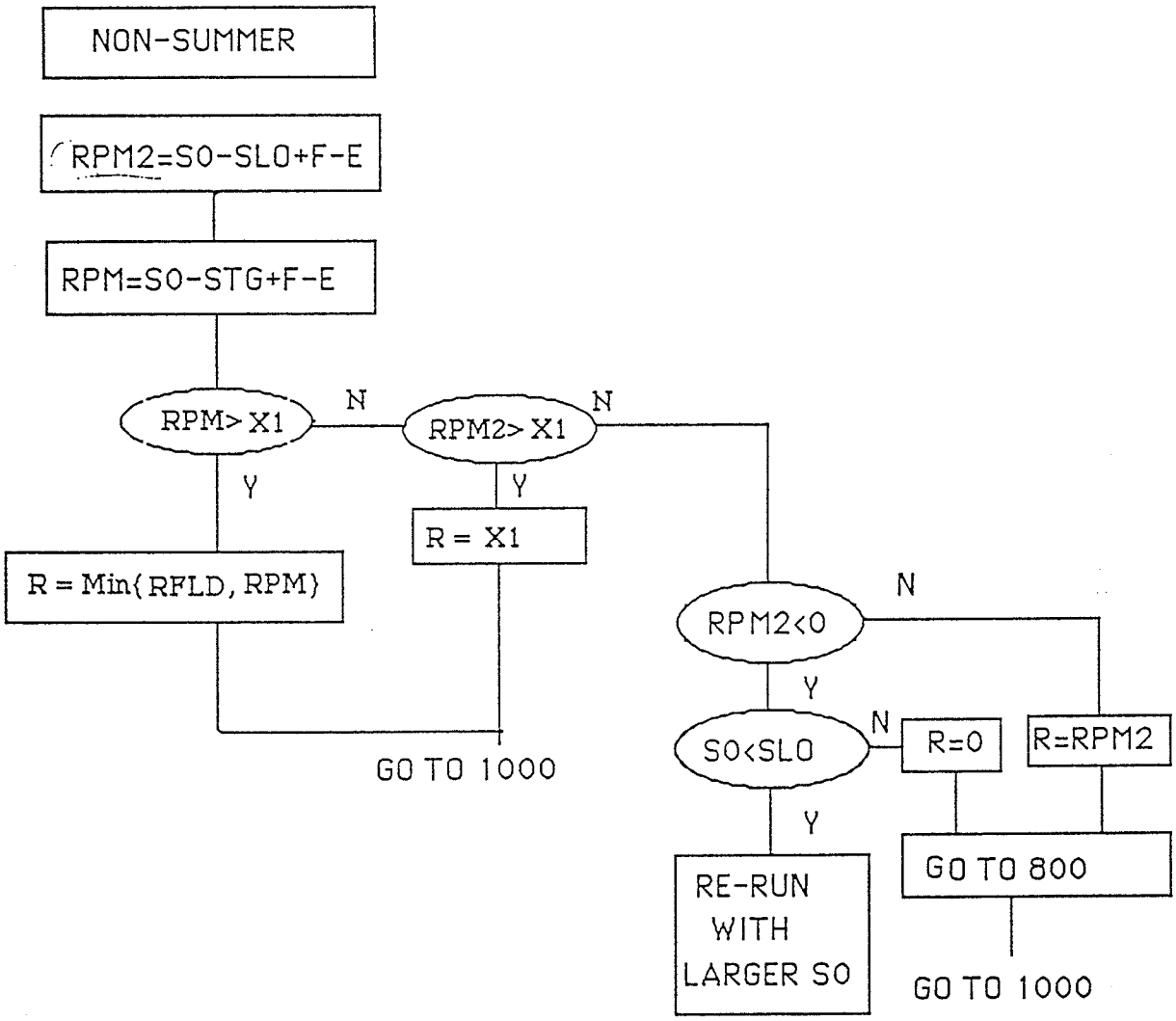
Trial	Range of w	percentage increase in sum of storage deviations, C	percentage decrease in sum of generation deficits, B	Difference Between Columns 3 and 4
1	1 - 150	0	0	0
2	175 - 400	10.61	53.9	42.48
3	425^* - 1250	16.16	70.46	54.3
4	1275 - 2000	20.01	73.46	53.45
5	3000	43.5	83.49	39.99
6	3500 - 10^6	100	100	0

Scenario 4

Trial	Range of *w*	percentage increase in sum of storage deviations, C	percentage decrease in sum of generation deficits, B	Difference Between Columns 3 and 4
1	1 - 100	0	0	0
2	500 - 1000	0.06	2.49	2.43
3	5000 - 5050	20.44	31.85	11.41
4	5075* - 6325	22.02	33.59	11.57
5	6350 - 6500	86.33	89.64	3.31
6	7000 - 10000	97.66	98.84	1.18
7	10^6	100	100	0

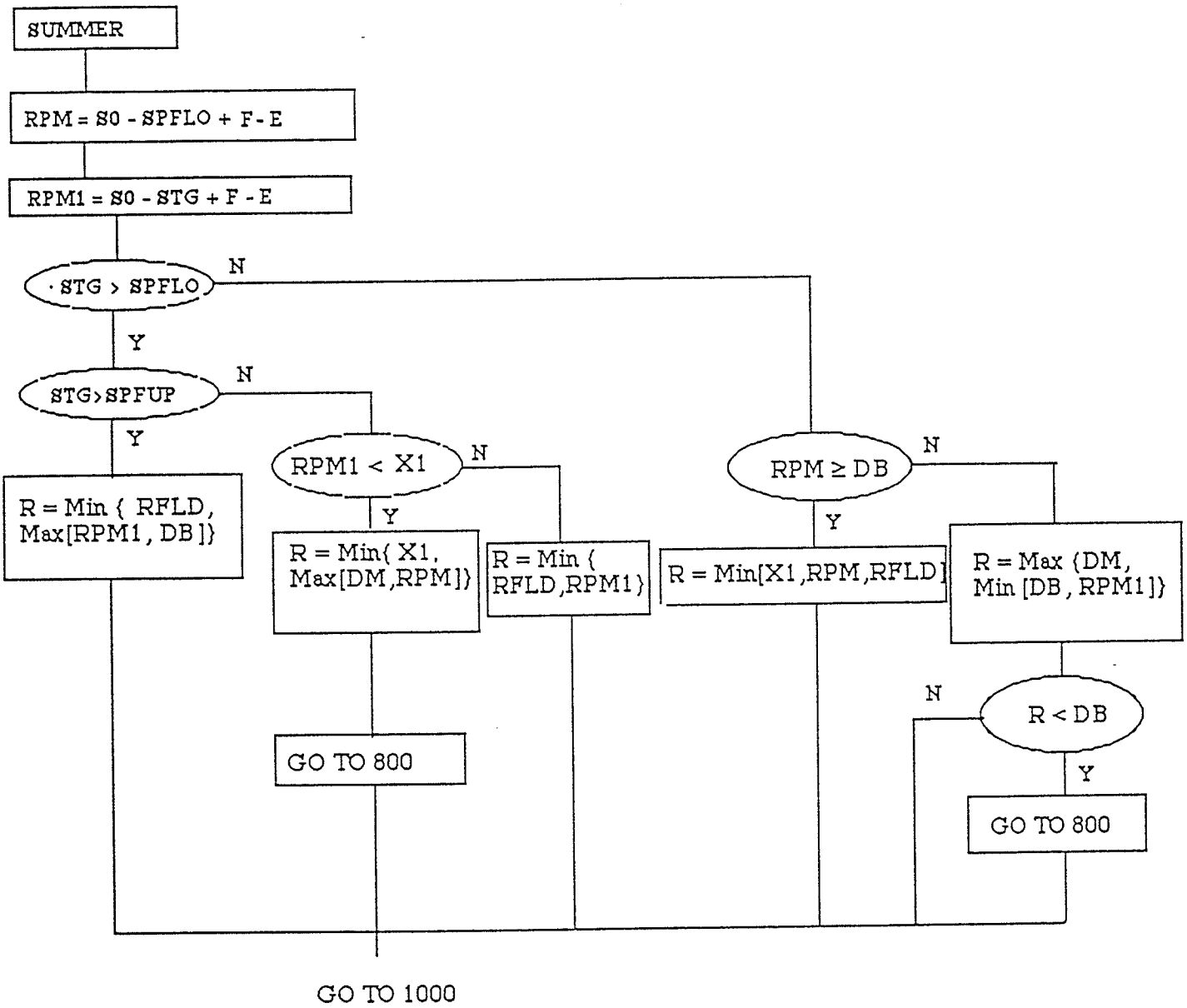
Appendix B

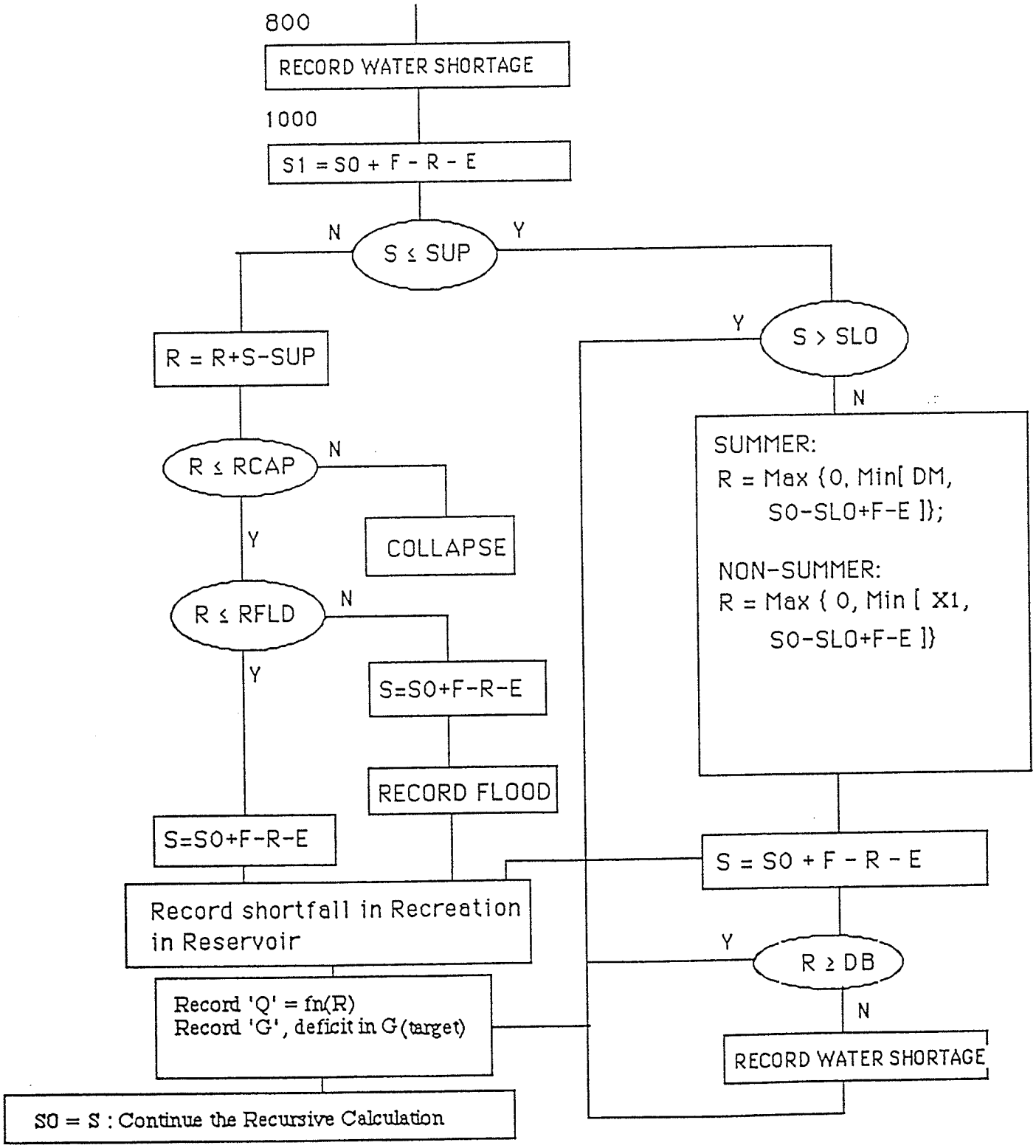
Flow Chart Describing the Simulation for Evaluating the Performance of the Operating Policies Obtained From the GP Model



800: RECORD WATER SUPPLY SHORTAGE.

1000: CALCULATE S1=SO+F-E-R


SUMMER
RPM = S0 - SPFLO + F - E
RPM1 = S0 - STG + F - E
STG > SPFLO
N
Y
STG>SPFUP
N
Y
R = Min { RFLD, Max[RPM1, DB]}
RPM1 < X1
N
Y
R = Min{ X1, Max[DM,RPM]}
R = Min { RFLD,RPM1}
GO TO 800
RPM ≥ DB
N
Y
R = Min[X1,RPM,RFLD]
R = Max {DM, Min [DB, RPM1]}
R < DB
N
Y
GO TO 800
GO TO 1000


800
RECORD WATER SHORTAGE
1000
S1 = S0 + F - R - E
N
S ≤ SUP
Y
R = R+S-SUP
R ≤ RCAP
N
COLLAPSE
Y
R ≤ RFLD
N
S=S0+F-R-E
RECORD FLOOD
Y
S=S0+F-R-E
Record shortfall in Recreation in Reservoir
Record 'Q' = fn(R)
Record 'G', deficit in G(target)
S0 = S : Continue the Recursive Calculation
Y
S > SLO
N
SUMMER:
R = Max {0, Min[DM, S0-SLO+F-E]};
NON-SUMMER:
R = Max { 0, Min [X1, S0-SLO+F-E]}
S = S0 + F - R - E
Y
R ≥ DB
N
RECORD WATER SHORTAGE

Notation for the Flow Chart

SLO	=	dead pool level of the Shellmouth Reservoir;
STG	=	storage operating policy obtained from the GP model;
X1	=	maximum of the release required to satisfy the desired generation level or the release required to satisfy the dilution needs of Winnipeg;
RFLD	=	flooding threshold value downstream of the Shellmouth Reservoir;
R	=	release decision;
SPFLO	=	lower storage target;
SPFUP	=	upper storage target;
DB	=	release required to satisfy all irrigation, municipal, and industrial needs;
DM	=	release required to satisfy all municipal, and industrial needs;
SUP	=	upper physical limit of the storage volume of the Shellmouth Reservoir;
F	=	inflow into the Shellmouth Reservoir;
E	=	evaporation from the Shellmouth Reservoir;
S1	=	ending storage in the month; and
RCAP	=	capacity of the outlet of the Shellmouth Reservoir.

Appendix C

Storage Operating Policies Obtained from the MIP Model

Scenario 3

This scenario has only one storage operating policy, irrespective of the number of months of cooling tower operation, *N*.

	Storage Operating Policy, 10^6 m^3		
Month	Wet	Average	Dry
April	197.2	200.0	305.29
May	449.08	333.05	309.44
June	437.21	337.99	310.88
July	441.31	338.23	305.77
August	435.4	333.05	295.1
September	429.01	229.95	287.48
October	424.02	229.39	283.85
November	388.43	218.05	273.21
December	363.8	203.64	240.61
January	340.36	180.06	200.0
February	315.52	155.71	168.72
March	295.43	150.0	156.44

Scenario 4

Number of Months of Cooling Tower Operation, $N = 3$

	Storage Operating Policy, 10^6 m^3		
Month	Wet	Average	Dry
April	197.62	200.0	333.16
May	449.08	380.11	337.19
June	437.21	401.32	338.44
July	392.84	400.92	333.05
August	387.53	395.04	322.06
September	288.5	386.15	314.15
October	284.4	384.48	310.35
November	249.16	372.99	275.13
December	224.64	358.51	240.63
January	201.24	353.72	200.0
February	176.43	329.25	162.27
March	156.44	323.4	150.0

Scenario 4

Number of Months of Cooling Tower Operation, $N = 6$

Month	Storage Operating Policy, 10^6 m^3		
	Wet	Average	Dry
April	197.62	200.0	333.16
May	449.08	377.22	337.19
June	437.21	398.47	338.44
July	392.84	398.09	333.05
August	387.53	392.25	322.06
September	288.5	383.38	314.15
October	284.4	381.74	310.35
November	249.16	384.88	275.13
December	224.64	370.39	240.63
January	201.24	346.72	200.0
February	176.43	322.25	162.27
March	156.44	323.4	150.0

Scenario 4

Number of Months of Cooling Tower Operation, N = 9, 12, 15, 18, and 21

	Storage Operating Policy, 10^6 m^3		
Month	Wet	Average	Dry
April	197.62	200.0	333.16
May	449.08	376.27	337.19
June	437.21	397.53	338.44
July	392.84	397.16	333.05
August	387.53	391.33	322.06
September	288.5	382.47	314.15
October	284.4	380.83	310.35
November	249.16	393.98	275.13
December	224.64	369.49	240.63
January	201.24	364.69	200.0
February	176.43	340.21	162.27
March	156.44	341.35	150.0