Working Paper

An Interactive Multi-Criteria Decision Model for Reservoir Management: the Shellmouth Reservoir Case

Per J. Agrell
Barbara J. Lence
Antonie Stam

WP-95-090
September 1995

IIASA
International Institute for Applied Systems Analysis ◻ A-2361 Laxenburg ◻ Austria
Telephone: +43 2236 807 ◻ Fax: +43 2236 71313 ◻ E-Mail: info@iiasa.ac.at

An Interactive Multi-Criteria Decision Model for Reservoir Management: the Shellmouth Reservoir Case

Per J. Agrell
Barbara J. Lence
Antonie Stam

WP-95-090
September 1995

IIASA International Institute for Applied Systems Analysis □ A-2361 Laxenburg □ Austria
Telephone: +43 2236 807 □ Fax: +43 2236 71313 □ E-Mail: info@iiasa.ac.at

An Interactive Multi-Criteria Decision Model for Reservoir Management: the Shellmouth Reservoir Case

PER J. AGRELL
DEPARTMENT OF PRODUCTION ECONOMICS,
LINKÖPING INSTITUTE OF TECHNOLOGY,
S-581 83 LINKÖPING, SWEDEN.

BARBARA J. LENCE
INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS,
A-2361 LAXENBURG, AUSTRIA
AND
DEPARTMENT OF CIVIL ENGINEERING,
UNIVERSITY OF MANITOBA,
WINNIPEG, MANITOBA R3T 2N2, CANADA.

ANTONIE STAM
DEPARTMENT OF MANAGEMENT,
TERRY COLLEGE OF BUSINESS,
UNIVERSITY OF GEORGIA
ATHENS, GEORGIA 30602, USA.

September 5, 1995

FOREWORD

Initiated as an inter-disciplinary Young Scientist Summer Program (YSSP) collaboration between the Water Resources (WAT) and Methodology of Decision Analysis (MDA) Projects, the research leading to this Working Paper in many way illustrates the mutual benefit stemming from applying state-of-the-art decision analysis methodologies to the complex problems that real life offers. Especially in reservoir management, involving large monetary and ecological investments and being of high industrial, agricultural and societal interest, the necessity of reviewing, analysing and communicating policies for release, storage and flood protection is apparent. This work is a dedicated attempt to introduce a method, the Interactive Weighted Tchebycheff Procedure, which previously has not been used in water resources management. By extending and adapting a reservoir management model, developed for the application of a reservoir with downstream thermoelectric power plants, a suitable platform for an illustration is provided. Using a real life case study, the Shellmouth Reservoir in Manitoba, Canada, the multi criteria decision support framework is demonstrated by means of an expert decision maker. The application has given rich inspiration for future co-operation between the two projects and also valuable insights in methodological research topics of general interest.

An Interactive Multi-Criteria Decision Model for Reservoir Management: the Shellmouth Reservoir Case

ABSTRACT

Reservoir management is inherently multi-criterial, since any release decision involves implicit trade-offs between various conflicting objectives. The release decision reflects concerns such as flood protection, hydroelectric power generation, dilution of downstream wastewater and heat effluents, downstream municipal, agricultural and industrial water supply, environmental standards and recreational needs. This paper presents a framework for analysing trade-offs between several decision criteria, and includes the management of heated effluents from downstream thermoelectric power generation in an optimisation model for reservoir management. The model is formulated and analysed in an interactive multi-criteria decision making (MCDM) modelling framework. Rather than providing specific target levels or *ad hoc* constants in a Goal Programming framework, as proposed elsewhere, our multi-criteria framework suggests a systematic way of evaluating trade-offs by progressive preference assessment. The MCDM model, based on a Tchebycheff metric and a contracted cone approach, is learning-oriented and permits a natural exploration of the decision space while maintaining non-dominated decisions. A detailed case study of the Shellmouth Reservoir in Manitoba, Canada, serves as an illustration of the model.

Keywords: Reservoir Management, Multi-Criteria Decision Making, Systems Analysis, Operations Research, Multi-Objective Linear Programming, Interactive Weighted Tchebycheff Procedure, Thermoelectric Power Generation.

Introduction

Reservoir operation is a complex and challenging decision problem, not only because of the presence of multiple conflicting objectives, but also due to seasonal and stochastic variations in the water demand and supply. The seasonal aspect of reservoir operation is not restricted to system inputs and outputs, since the evaluation criteria themselves are often closely related to seasonal activities and events. For example, when a release decision is made in January to meet the demand for hydroelectric power generation, the trade-off against recreational demands may be different from a prospective release in July, when fishery and tourism are at their peaks. An added objective exists related to the need to minimise violations in the allowable in stream temperature levels, when the reservoir is used to mitigate the effects of waste heat effluents from downstream thermoelectric power generation plants. In such cases, the amount of water released from the reservoir implicitly determines the maximum attainable power generation that would meet allowable temperature levels. Hence, the release decision must also take into consideration current and expected reservoir inflows, ambient stream temperature, ecological requirements for sustainability of the fish populations and biological requirements for acceptable water quality.

While the release decision may be planned in advance, it is in effect a real-time decision due to inaccuracy in forecasting. Any viable decision support provided for reservoir management must fulfil high standards of model validation and comprehensibility, and still be of limited conceptual and operational complexity. Moreover, the need for communication and negotiation between the agents concerned calls for a formulation with a minimum of technical constants and *a priori* constraints that are fixed. Trade-offs between criteria should be acknowledged and different scenarios tested without the direct involvement of operations analysts by means of tuning weights and technical constants, since the framework should preferably be interactive in order to facilitate experimentation by the actual decision maker(s). Yet, the reservoir management framework needs to be powerful enough to encompass the true decision context and contain a natural, flexible user dialogue to facilitate learning.

The organisation of the paper is to give an overview over previous research in the area, to present the mathematical dam management model, to discuss and motivate our choice of decision criteria, to introduce the Interactive Tchebycheff Procedure as an MCDM framework, to present the application of the model to the Shellmouth Reservoir in Manitoba, Canada and to report the results from the interactive decision process when applying the methodology to the numerical data.

Reservoir Management and Multi-Criteria Decision Analysis

Owing to its adaptability to quantitative modelling, its distinctive multi-criteria character and its importance in public policy, the water resource management area is well-documented in the MCDM literature. Another incentive to undertake formal planning and analysis is that the investments and long-term consequences of water resource decisions are often large. For an early review of optimisation models applied to multipurpose reservoirs, see Yeh (1985). Giles and Wunderlich (1981) use Dynamic Programming (DP) to solve an operational model with five criteria. Szöllosi-Nagy (1982) formulates a three-stage optimisation schedule for a reservoir design problem, involving 29 Hungarian reservoirs. The first stage is interactive and uses a strict lexicographic ordering of the criteria, the second stage involves a medium range LP planning problem and the third stage is an optimal control model. The model acknowledges the different planning needs in reservoir management, but the results show a considerable lack of stability.

A number of Goal Programming (GP) formulations for the reservoir management problem have been presented, e.g., Yang *et al.* (1992), Yang *et al.* (1993), Can and Houck (1984), Datta and Burges (1984) and Goulter and Castensson (1988), the latter with a mixed integer GP extension. Gilbert (1985) reports a dam management problem involving multiple criteria. Two models are presented, for short- and long-range planning, the latter using DP. The short-range model is based on simulation and is primarily used for evaluating long-range scenarios. Gilbert's multi-criteria framework involves a lexicographic ordering within a GP setting. As a complement to deterministic approaches, Changchit and Terrel (1989) suggest a chance constrained GP model for a series of reservoirs. Their GP approach, however, is not very suitable for interactive use, and does not facilitate a rigorous trade-off analysis. The *a priori* goal levels and arbitrary weights, possibly combined with a lexicographic ordering of the goals, make the method inflexible and quite sensitive to the influence of the analyst.

Some early references of non-GP MCDM reservoir management models are Cohon and Marks (1973), Monarchi *et al.* (1973), Haimes and Hall (1974) and Haimes *et al.* (1975). In the management of wastes in a river basin, Sobel (1971) uses a global optimisation approach, applying the Tchebycheff[1] minimax norm to evaluate waste discharge policies.

Haimes *et al.* (1975) study a problem with two reservoirs and a hydroelectric power plant. In their model, three criteria are formulated: to maximise power generation, to minimise expected operating cost and to maximise water storage. The non-linear programming model formulated is solved using the Surrogate Worth Trade-off (SWT) Technique. Another SWT example given in Haimes *et al.* (1975) involves a single reservoir with downstream water demand and with decision criteria to minimise quadratic treatment costs for downstream waste discharges, to maximise storage levels, and to minimise the resulting level of pollutants in the river. Gandolfi and Salewicz (1991) and Ríos Insua and Salewicz (1993) propose multi-criteria formulations for managing the Lake Kariba reservoir in Zambia. Recently, Georgakakos (1993) presented a trade-off analysis for the operation of a reservoir in the presence of a downstream hydroelectric power plant. Aiming at the operational level of the reservoir, close to real time, Georgakakos applies optimal control to determine the optimal trajectory of the storage trace. The underlying bi-criterion model comprises of compliance to energy generation targets and reservoir level targets.

One of the few interactive (non-SWT) approaches to a water management problem is that of El Magnouni and Treichel (1994). The authors apply the interactive method by Jacquet-Lagrèze *et al.* (1987) to a linearised groundwater problem. A sampled representation of the efficient set is used to create an additive, piece-wise linear, global utility function, which is then employed to solve the model. Berkemer *et al.* (1993) and Makowski *et al.* (1995) apply the Interactive Reference Point method (Wierzbicki, 1980) to a water treatment plan for the Nitra River system in Slovakia. The main trade-offs in their model are between three waste treatment cost criteria and three water quality criteria.

The reservoir management model for which the MCDM framework is applied in this case study is a medium range planning model (i.e., monthly, quarterly), which is deterministic and provides an objective basis for operational planning and resolution of conflicting objectives. The stochastic aspects of the problem are investigated with simulation experiments on the solutions selected. By enriching the model to include water quality objectives for instream temperature, but not constraining these to arbitrary levels, we arrive at an attractive framework for decision support.

[1] Alternative spellings (in English) are Chebishev, Chebyshev or Chebichef.

The MCDM Reservoir Management

Our multi-criteria decision making framework for dam management improves upon the model by Lence *et al.* (1992) for operational use by avoiding the problem of requiring *ad hoc* constants and the summation of incommensurable quantities. Furthermore, it generalises the previous model by allowing for multiple thermoelectric power plants, and by relaxing some restrictive assumptions in Lence *et al.* (1992) and Yulianti and Lence (1993). In this section, we describe the reservoir and give the mathematical model of its operation.

Notation

Suppose that 1) the planning period is n years, and let each year be sub-divided into m discrete planning periods (e.g., weeks or months), 2) there are K river reaches, $k = 1, ..., K$, downstream from the reservoir, 3) thermoelectric power plants are located in a subset of the river reaches $K_T \subseteq \{1, ..., K\}$, and 4) hydrologic forecasts for evaporation, inflows, temperatures exist for the entire horizon. Typically, planning models are determined using historical hydrologic and atmospheric conditions and assuming that these would be similar to future conditions. For a dam management problem, either the release or the storage level is selected as the decision variable, depending on the context and model formulation. In the context of our MCDM model, several important criteria are readily defined in terms of storage levels. The operating policy, the release, is then a direct consequence of the derived storage plan.

When determining a release policy, one must decide whether the design storage level in the reservoir should be constant for each period throughout the planning period, or completely flexible, changing for each consecutive period and year. The former logically implies that the dam manager is ignorant of the type of hydrologic year to follow perfectly, with a rather restrictive hypothetical policy as a result. The latter assumes that the dam manager not only can forecast the hydrologic type of year to follow, but also the sequence in which the years occur. Needless to say, such assumptions would probably not be fulfilled in a realistic setting. We have chosen the compromise suggested in Yang (1991), *inter alia,* to create three types of annual hydrologic conditions, wet, average and dry years, from historical data and then optimise the storage for each type of year over the planning period horizon. The resulting policy can be applied successfully under the plausible condition that the decision maker can roughly categorise the upcoming year in terms of the three types. Thus, the decision vector consists of periodic storage levels to be determined for each storage period $i = 2, ..., m$, S_i^W during wet years, S_i^A during average years and S_i^D during dry years. To provide for continuity, the first period of each year, regardless of type, is excluded from the storage policy. In reality, as well as in the model, the initial conditions for each year will vary depending on the type of the preceding year.

The notation used in our model is summarised in Tables 1-3. Decision variables are to be determined by the model, whereas auxiliary variables are derived implicitly from the decision variables. The use of the latter is to increase the readability and interpretation of the model and results. Parameters are scalars set prior to the optimisation.

Tables 1-3 about here

Assumptions

Following a conservative policy, we assume that the tributary inflow into a river reach is available only at the end point of the reach and that the total demand for the reach is withdrawn at the very beginning of the reach. The net of incoming upstream transit release, tributary inflow and reach demand is called net demand if it is a negative volume and transit release if it is a positive volume. In the case of a transit release, the surplus contributes to the inflow to the succeeding reach. Figure 2 illustrates schematically the relationship between tributary inflows, demand and transit releases. Note that a downstream excess in water supply cannot compensate for an upstream shortfall. All water consumption, except cooling of the thermoelectric plants is assumed to be drawn from the river, whereas the entire volume used in the cooling process is assumed to pass through the plant via a once-through cooling process and be available downstream of the plant. Without loss of generality, we assume that each reach has at most one thermoelectric power plant, located at the beginning of the reach. If more than one plant is located in a single geographical river reach, the reach may be partitioned accordingly. In the unlikely event that two or more plants exist at the same location, so that no partitioning of the reach is possible, these plants are aggregated into a single plant.

Figure 1 About here

Relationships between Power Generation, Temperature Violation and Discharge

A crucial issue in modelling of the interaction between the discharge of thermoelectric power plants and the environment is the relationship between the waste heat emission and the downstream temperature. The average emission temperature (in °C) for the thermoelectric power plant in reach k during period i of year j, $T^k_{e,ij}$, is given by

$$T^k_{e,ij} = \frac{G^k_{ij} H^k_R}{Q^k_{e,ij}\gamma \cdot 10^{18}} + T^k_{u,ij}, \qquad i = 1,\ldots,m;\; j = 1,\ldots,n;\; k \in K_T, \tag{1}$$

where G^k_{ij} is the power (in GWh) generated at the thermoelectric power plant in river reach k during period i of year j, when once-through cooling is used; $Q^k_{e,ij}$ is the discharge (in 10^6 m^3) that is withdrawn from the river and is used to cool the thermoelectric power plant in river reach k, during period i of year j; $T^k_{u,ij}$ is the average temperature (in °C) immediately upstream of the point of emission in reach k during period i of year j; γ is the specific weight of water (in g/cm^3) and H^k_R is the heat rejected per unit power generation (in kcal/GWh) for the thermoelectric power plant in reach k. Define the water temperature d meter downstream of the point of emission by $T^k_{ij}(d)$. Assuming that the effluent is mixed proportionally with the stream discharge, the temperature immediately downstream of the point of emission, $T^k_{ij}(0)$, is given by

$$T^k_{ij}(0) = \frac{T^k_{u,ij}\left(Q^k_{ij} - Q^k_{e,ij}\right) + T^k_{e,ij} Q^k_{e,ij}}{Q^k_{ij}}, \quad i = 1,\ldots,m;\; j = 1,\ldots,n;\; k \in K_T \tag{2}$$

,

where Q^k_{ij} is the total water volume (in 10^6 m^3) available for cooling the thermoelectric power plant in river reach k during period i of year j and all other variables are defined above. Note that the water quantity used for diluting the discharge effluent from the power plant is $Q^k_{ij} - Q^k_{e,ij}$, which has a temperature of $T^k_{u,ij}$. $T^k_{ij}(d)$ is determined by the one-dimensional first order temperature decay model:

$$T^k_{ij}(d) = \left(T^k_{ij}(0) - T^k_{u,ij}\right) e^{\left(\frac{K^k_{r,ij}}{v^k_{ij}}\right)d} + T^k_{u,ij}, \qquad i = 1,\ldots,m;\; j = 1,\ldots,n;\; k \in K_T, \tag{3}$$

where the heat exchange coefficient (in $days^{-1}$) for river reach k during period i of year j, $K^k_{r,ij}$, is a function of the average river depth, wind speed, dew point temperature and specific density of water in reach k, and v^k_{ij} is the average stream velocity (in m/day) for the length of the river between the point of emission and the monitoring point, d meters downstream of the thermoelectric plant in reach k, during period i of year j. The velocity v^k_{ij} is actually a function of Q^k_{ij}. Thus, if the temperature standard (in °C) for the power plant in reach k, period i, equals $\hat{T}_i^k$, the temperature violation (in °C), $\Delta^k_{ij}(d)$, at a location d m downstream of the power plant in reach k, is given by

$$\Delta^k_{ij}(d) = T^k_{ij}(d) - \hat{T}_i^k, \quad i = 1,\ldots,m;\ j = 1,\ldots,n;\ k \in K_T. \tag{4}$$

Lence *et al.* (1992) use (1) - (3) to derive a condition for the total allowable power generation for a given river reach k during period i of year j, G^k_{ij}, as a function of the stream discharge,

$$G^k_{ij} = \frac{Q^k_{ij}\gamma 10^{18}\left(\hat{T}_i^k - T^k_{u,ij}\right) e^{\left(\frac{K^k_{r,ij}}{v^k_{ij}}\right)d}}{H^k_R}, \quad i = 1,\ldots,m;\ j = 1,\ldots,n;\ k \in K_T \tag{5}$$

After assessing velocities for a given flow, average monthly dew point temperatures, average monthly temperature standards and background stream temperatures, the relationship between river flow and allowable power generation can be linearised to (6),

$$G^k_{ij} = a^k_i + b^k_i Q^k_{ij}, \qquad i = 1,\ldots,m;\ j = 1,\ldots,n;\ k \in K_T, \tag{6}$$

where a^k_i and b^k_i are the intercept and the slope of the function, respectively. For the Shellmouth Reservoir problem, the coefficients are given in Lence *et al.* (1993). Latheef (1991) shows that the fit of the linearisation is very good for the Shellmouth case. In Lence *et al.* (1992), (6) is used as a constraint, given a standard temperature, in effect implying an upper limit on the temperature violation, $\Delta^k_{ij}(d)$. Yulianti and Lence (1993) employ an inverse formulation of the temperature deviation problem, and use (5) to estimate $\Delta^k_{ij}(d)$, given that the (single) power plant always meets its power production targets.

Formulation of Criteria

The criteria chosen for our model are to reflect the concerns of the decision maker in a quantifiable relationship to the decision variables. Reservoir managers traditionally operate such systems with certain targets and ranges for storage levels and release rates. Some of these, such as the physical limits on water storage, are easily treated as constraints, since their violation would yield an infeasible storage policy. However, others, e.g., the release rate upper target for downstream flooding, can be violated under some circumstances. Other implicit consequences of the storage decision, e.g., allowable power generation, are traditionally included as constraints, although they may well be viewed as valid decision criteria. When applicable, we have attempted to use the existing knowledge and expertise expressed in terms of policy targets within an MCDM framework, without resorting to either hard constraints or a pure GP formulation.

The need for the decision maker to simultaneously consider the entire storage plan represents an interesting challenge in terms of presenting the results of the interactive analysis. The result in terms of criterion values from the model, however detailed, must be accompanied with graphs and, in the later stages, simulation studies in order to assess and evaluate the robustness of the proposed plan. In our application, the main objective trade-off result from an increase or decrease of the storage level. Whereas an increase in the storage level (up to a certain target) is beneficial from a recreational viewpoint and for safeguarding against expected or unexpected drought, a decrease in storage (i.e., an increased release) would enable higher power generation, meet downstream flood control, dilution and downstream water demand.

Our formulation differs from hydroelectric power plant models in that hydroelectric power plants are located at the dam site and their operations are highly interdependent with dam operations, whereas thermoelectric power plants may be located downstream of the dam, and are operated independently of the dam. Moreover, the timing of the power generation cycle of thermoelectric and hydroelectric plants differs substantially. Hydroelectric power generation is minimal during dry years, due to insufficient water flow, and maximal during wet years. In contrast, reservoirs with thermoelectric plants are expected to alleviate the power deficit during drought periods, but are not as essential during wet years. Reservoir releases for cooling thermoelectric power plants are thus required more often in dry years. Unfortunately, agricultural, recreational and municipal needs are not completely correlated with power generation, and the resulting conflict between these demands and storage targets must be resolved. In our Multi-Criteria Decision Support (MCDS) framework, criteria are proposed for addressing the following issues: flood protection, dam safety, water demand, power supply, recreation and environmental impact. Next, we introduce these criteria in detail:

Flood protection

With historical data available, experienced dam managers are able to establish the channel capacity, $\hat{R}$ (in 10^6 m^3). The channel capacity serves as a safety threshold, and a release rate beyond $\hat{R}$ would be undesirable, causing downstream flooding. Although a violation of this threshold can have serious consequences, under certain conditions slight violations may be acceptable, so that we include the threshold violation as a flood protection criterion to be minimised, rather than as a "hard" constraint. Denote the release during period i of year j by R_{ij}. Since large violations can be disastrous and should be avoided at any time, we minimise the maximum threshold violation $R_{ij} - \hat{R}$ over all i, j:

$$\text{minimise } y_1 = \max_{i,j} \left\{ R_{ij} - \hat{R}, 0 \right\}. \tag{7}$$

A heuristic method of safeguarding against flooding is to use storage targets in critical spring months, when large inflows of water can be expected. The recreational criteria presented below provide this opportunity in our model, where flooding targets can be included along with other storage level targets.

Dam safety

The concerns of dam operation are primarily related to dam safety and operational stability. The structural safety of the dam is assured by "hard" constraints on the physical upper and lower reservoir levels. However, operational stability cannot be reflected by constraints, since this should always be judged in relation to the feasible range under current hydrological conditions. Following Yang *et al.* (1993), we interpret stability as a measure of change in release. Large variations in consecutive releases, which are frequently recommended by unconstrained LP-models, are undesirable with respect to environmental and river engineering considerations. Downstream navigation would suffer especially from a high variability in the release rate. Thus, defining a release change ΔR_{ij} as

$$\Delta R_{ij} = \begin{cases} R_{ij} - R_{i-1,j}, & i = 2,\ldots,m, j = 1,\ldots,n, \\ R_{1j} - R_{n,j-1}, & j = 2,\ldots,n, \\ 0, & i = 1,\ j = 1. \end{cases} \tag{8}$$

The dam safety criterion for operational stability is formulated as a minimisation of the sum of release changes,

$$\text{minimise } y_2 = \sum_{i=1}^{m}\sum_{j=1}^{n} \Delta R_{ij} \ . \tag{9}$$

The criterion in (9) serves to smooth the release pattern over time. An initially formulated min-max criterion was discarded, because the decision maker judged the associated storage patterns over time inferior to those associated with (9).

Water supply to municipalities and agriculture and dilution of industrial and municipal effluents

The water demand for various non-energy related usage is fairly well-documented. As the ability to supply consumers with water is an important criterion, we include the fraction of unsatisfied demand as a performance measure, minimising the maximum water deficit,

$$\text{minimise } y_3 = \max_{i,j}\left\{1 - R_{ij}\left\{\sum_{k=1}^{K} F_{ij}^{k}\right\}^{-1}, 0\right\}, \tag{10}$$

where F_{ij}^{k} is the total net water requirement in river reach k, during period i of year j. Obviously, if all demand is satisfied at all time, $y_3 = 0$. If there exists unsatisfied water demand, the criterion in (10) ensures that the shortfall will be spread over several periods, rather than occurring in one single period.

Power generation

The deviation of the power production at thermoelectric plant in reach k during period i of year j, from its desired production target, $\hat{G}_{ij}^{k}$ (in GWh), is of interest to management. An alternative formulation, with gross energy production as a measure of performance, is less effective, since thermoelectric plants are utilised primarily under specific circumstances, i.e., as a backup power for peak load. Also, since power is to be produced at the very instant of its consumption, the gross energy production measure would be hard to interpret within the decision making context. For each thermoelectric power plant in reach $k \in K_T$ under separate ownership[2], we minimise the largest deviation from $\hat{G}_{ij}^{k}$, $\hat{G}_{ij}^{k} - G_{ij}^{k}$,

$$\text{minimise } y_4^{k} = \max_{i,j}\left\{\hat{G}_{ij}^{k} - G_{ij}^{k}, 0\right\}, \qquad k \in K_T . \tag{11}$$

The generation of energy by means of thermoelectric plants requires that water be released from the reservoir. Thus, the release decision implicitly constrains output of the thermoelectric power plants.

The set of criteria in (11) is likely to be in direct conflict with recreational interests, especially during dry years, when on the one hand the thermoelectric power plants have to supplement hydroelectric power plants, but on the other hand the reservoir is needed for fishery and boating during the summer. Next, criteria reflecting recreational needs are introduced.

Recreation

Often, as in the Shellmouth Reservoir, the dam serves an important, even dominant role in the economic life of its surrounding area during the spring and summer seasons. Fishery, recreation

[2] Multiple thermoelectric power plants under the same ownership, if any, should be aggregated.

and tourism in the dam area require a sufficient storage level. Upper and lower target levels SU_i, and SL_i (in 10^6 m^3) are established for this purpose, from experience and engineering design, i.e., the design depth of docks. We define the (annual) average (y_6, y_8) and maximum deviation (y_5, y_7) from the storage level targets as criteria. Also, navigation at the reservoir may be impaired if the storage level varies significantly during the summer, even within the desired bounds. Thus, we propose to minimise the sum of deviations from the midpoints between SU_i and SL_i as an additional stability criterion, y_9. The rationale for selecting three types of criteria, rather than one, is that they highlight different aspects of the problem. Whereas small-sized violations may be justified on the basis of power generation or water supply arguments, a sequence of violations would be harmful to the local economy. On the other hand, an average deviation within a reasonable range may very well hide a single disastrous violation. In the Shellmouth Reservoir, y_9 does not include the targets for April, since this target is intended solely to prevent flooding.

$$\text{minimise } y_5 = \max_{i,j}\left\{S_{ij} - SU_i, 0\right\}, \tag{12}$$

$$\text{minimise } y_6 = \frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n}\max\left\{S_{ij} - SU_i, 0\right\}, \tag{13}$$

$$\text{minimise } y_7 = \max_{i,j}\left\{SL_i - S_{ij}, 0\right\}, \tag{14}$$

$$\text{minimise } y_8 = \frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n}\max\left\{SL_i - S_{ij}, 0\right\}, \tag{15}$$

$$\text{minimise } y_9 = \sum_{i=1}^{m}\sum_{j=1}^{n}\left|S_{ij} - \tfrac{1}{2}(SU_i + SL_i)\right|. \tag{16}$$

To some extent, the recreation criteria are in conflict with the power generation and water supply criteria. When high emphasis is given to recreation, the optimal storage level remains higher in the late spring and early summer. During dry years, the conflict becomes overt as the power generation criterion calls for early releases to meet the targets. The reservoir level stability criterion, y_9, may be in conflict with the operational stability criterion, y_2. Whereas operational stability benefits from a stable release rate, which under varying inflow and evaporation conditions may imply a highly variable storage level, the reservoir stability criterion has the opposite effect.

Environmental impact

Due to the non-linearity of the relationship between temperature violation and power generated for a given release rate, the minimisation of temperature deviation cannot be included as a criterion without constraining power generation (Yulianti and Lence, 1993). While temperature violation is of high ecological importance, it involves trade-offs that are not well-defined. Power production, on the other hand, is of immediate economic and societal concern. Hence, power generation is in our model included as a set of criteria ($\left\{y_4^k\right\}$, $k \in K_T$), and subsequently the environmental impact is limited to a "hard" constraint on river temperature. Nevertheless, our formulation is easily modified to include temperature violation as a criterion if power generation is considered as a constraint.

The Constraint Set

In this section, we introduce the constraints of the model. The relation between the decision variables for wet, average and dry years, and the storage level is given by

$$S_{ij} = \begin{cases} S_i^W, & i = 2,\ldots,m;\ j \in J_W, \\ S_i^A, & i = 2,\ldots,m;\ j \in J_A, \\ S_i^D, & i = 2,\ldots,m;\ j \in J_D. \end{cases} \tag{17}$$

Note that the first period of each type of year is excluded from the generic storage policies, to allow for flexible initial conditions. The within-year and between-year storage continuity equations are provided in (18) and (19), respectively,

$$S_{ij} - S_{i-1,j} + R_{ij} = I_{ij} - V_{ij}, \qquad i = 2,\ldots,m;\ j = 1,\ldots,n, \tag{18}$$

$$S_{1j} - S_{m,j-1} + R_{ij} = I_{1j} - V_{1j}, \quad j = 2,\ldots,n, \tag{19}$$

where I_{ij} and V_{ij} are the inflow and evaporation, respectively, in the reservoir, during period i of year j. Furthermore, the model enforces restoration of the initial storage level through (20),

$$S_{11} = S_{mn}. \tag{20}$$

The limits on release based on ecological and flood control requirements are given by

$$R_{\min} \le R_{ij} \le R_{\max}, \qquad i = 1,\ldots,m;\ j = 1,\ldots,n. \tag{21}$$

Due to the elevation of the dam outlet, the storage level has a lower bound of $S_{\min}$, which is the dead pool volume. The structural upper storage limit to prevent dam collapse is given by $S_{\max}$,

$$S_{\min} \le S_{ij} \le S_{\max}, \qquad i = 1,\ldots,m;\ j = 1,\ldots,n. \tag{22}$$

Following the assumptions regarding tributary inflow and transit of excess release, the transit release and net water requirement for downstream reaches are given by (23) and (24) respectively,

$$TR_{ij}^k = \max\left\{TR_{ij}^{k-1} + TI_{ij}^{k-1} - D_{ij}^k, 0\right\}, \quad i = 1,\ldots,m;\ j = 1,\ldots,n;\ k = 2,\ldots,K \tag{23}$$

$$F_{ij}^k = \max\left\{D_{ij}^k - TR_{ij}^{k-1} - TI_{ij}^{k-1}, 0\right\},\ i = 1,\ldots,m;\ j = 1,\ldots,n;\ k = 2,\ldots,K, \tag{24}$$

where D_{ij} and TI_{ij}^k are the total water demand in and total tributary inflow to river reach k, respectively, during period i of year j. Conditions (23) and (24) are adjusted somewhat for the first reach, since in our model the first reach enjoys no tributary inflows and the release from the reservoir substitutes for the transit release, for long-term continuity of the system.

$$TR_{ij}^{1} = \max\left\{R_{ij} - D_{ij}^{1}, 0\right\}, \quad i = 1,\ldots,m;\ j = 1,\ldots,n, \tag{25}$$

$$F_{ij}^{1} = \max\left\{D_{ij}^{1} - R_{ij}, 0\right\}, \quad i = 1,\ldots,m;\ j = 1,\ldots,n. \tag{26}$$

The magnitude of the discharge at the site of each thermoelectric power plant, on reach k, is obtained as,

$$Q_{ij}^{k} = TR_{ij}^{k-1} \qquad i = 1,\ldots,m;\ j = 1,\ldots,n;\ k > 1;\ k \in K_T. \tag{27}$$

If a thermoelectric power plant is located in the first reach, the equivalent of condition (27) is consequently,

$$Q_{ij}^{1} = R_{ij} \qquad i = 1,\ldots,m;\ j = 1,\ldots,n;\ \left\{1\right\} \in K_T. \tag{28}$$

The maximum attainable power generation is given as a function of the discharge, using (6), as in,

$$G_{ij}^{k} \le a_i^{k} + b_i^{k} Q_{ij}^{k}, \qquad i = 1,\ldots,m;\ j = 1,\ldots,n;\ k \in K_T, \tag{29}$$

and non-negativity applies to all variables, i.e.,

$$S_{ij}, R_{ij}, F_{ij}^{k} \ge 0, \qquad i = 1,\ldots,m;\ j = 1,\ldots,n;\ k = 1,\ldots,K, \tag{30}$$

$$TR_{ij}^{k} \ge 0, \qquad i = 1,\ldots,m;\ j = 1,\ldots,n;\ k = 1,\ldots,K, \tag{31}$$

$$G_{ij}^{k}, Q_{ij}^{k} \ge 0, \qquad i = 1,\ldots,m;\ j = 1,\ldots,n;\ k \in K_T, \tag{32}$$

$$S_i^{W}, S_i^{A}, S_i^{D} \ge 0, \qquad i = 1,\ldots,m \tag{33}$$

Multi-Criteria Methodology

We next introduce definitions and notation related to MCDM, and summarise the interactive multi-objective linear programming (interactive MOLP) method used in our paper, the Interactive Weighted Tchebycheff Procedure (IWTP).

Multi-Criteria Definitions and Notation

A MOLP problem, minimising q criteria functions, can be written as

$$\begin{aligned} &\min \left\{y_1\right\} \\ &\quad \vdots \\ &\min \left\{y_q\right\} \\ &\text{subject to } \mathbf{x} \in X, \end{aligned} \tag{34}$$

or equivalently as

$$\min \{\mathbf{y}\}$$

$$\text{subject to } \mathbf{x} \in X , \tag{35}$$

where the y_i are criterion functions, $\mathbf{y} \in Y \subseteq \Re^q$, Y is the criterion (outcome) space, $\mathbf{x}$ is any vector of decision variables, and X is the feasible region in decision space.

A criterion vector $\mathbf{y}'$ is nondominated, if and only if there does not exist another $\mathbf{y} \in Y$ such that $y_i \leq y'_i$ for all i and $y_i < y'_i$ for at least one i. Two reference vectors of particular interest, both in terms of providing the decision maker with a benchmark during the interactive trade-off analysis, and for the operation of the MOLP method itself, are the ideal (utopia) vector $\mathbf{y}^*$ and the nadir vector $\mathbf{y}_*$. The ideal vector is easily determined as $\mathbf{y}^* = \left(y_1^*, \ldots, y_q^*\right)$, where y_i^* is the selfish solution for criterion i, obtained by the single-objective optimisation of y_i, i.e.,

$$y_i^* = \min_{\mathbf{x} \in X} \{ y_i \} . \tag{36}$$

The nadir vector is an approximate upper bound of the nondominated set, i.e., the worst criterion values to be encountered for any nondominated solution. Except for problems of small dimensions, the true nadir vector is difficult to determine, but an estimate can be determined by collecting the maximum row values in the payoff table for the problem (Isermann and Steuer, 1988; Korhonen, Salo and Steuer, 1994).

The $\mathbf{y}^*$ and $\mathbf{y}_*$ vectors are used in the decision analysis, to indicate the relevant ranges of solutions that can be expected during the interactive process of determining the most preferred solution. In the usual case, where some of the criteria are conflicting, the ideal vector cannot be achieved, requiring a compromise solution. Of course, if there is no conflict between the criteria, the ideal vector is the optimal solution, and there is no need for a multi-criteria analysis. Typically, the nadir vector is strictly dominated.

Multi-Criteria Solution Procedure

Researchers have developed a variety of MOLP solution procedures (see, e.g., Evans, 1984; Shin and Ravindran, 1991; Gardiner and Steuer, 1994). We chose the Interactive Weighted Tchebycheff Procedure (IWTP) of Steuer and Choo (1983), due to its desirable mathematical and decision-support related properties. The IWTP is attractive computationally, since it can be implemented using existing commercial optimisation software, since it is guaranteed to provide the decision maker with nondominated solutions at all times, and since it is user-interactive and provides flexible decision-support for multi-criteria programming problems.

The IWTP does not require the decision maker to determine *a priori* relative importance weights for the criteria. Instead, the IWTP is based on the progressive articulation of preferences. At each iteration of the interactive decision process, the decision maker is asked to select the most preferred solution from a sample of nondominated solutions. Upon the next iteration, the IWTP then generates a new sample from the nondominated set for evaluation by the decision maker, in the neighbourhood of the most preferred solution(s) of the previous iteration. An advantage of this approach is that the IWTP does not assume any particular form of value function. In fact, as long as the decision criteria are monotonous, the IWTP even works if the decision maker's preference structure cannot be described by a functional form. The method does not require the decision maker to converge to a final solution at pre-determined rate, and a previously discarded solution can be reconsidered at any time, thus facilitating learning about the problem. The decision maker can also guide the solution process at any time by inserting bounds on the criteria. A comparative experimental study of interactive MOLP methods by Buchanan and Daellenbach (1987) found the IWTP to be favoured over several competing methods, from the user's viewpoint.

Mathematically, any multi-criteria problem needs to be scalarised to form an unambiguous mathematical program to be solved by standard algorithms. The structure of the scalarising function, $s(y, \omega)$, where y is the criterion vector and ω is an associated set of weights and technical parameters, determines the quality of the solution. The IWTP uses an augmented Tchebycheff scalarising function[3] to assure that only nondominated solutions are obtained by problem (37),

$$\min s\left(y, \{\lambda, \varepsilon\}\right) = \|\mathbf{w}\|_\infty^\lambda + \varepsilon \mathbf{1}^T \mathbf{w}$$

$$\text{subject to} \qquad w_i = \frac{y_i - y_i^{**}}{y_{i*} - y_i^{**}}, \qquad i = 1, \ldots, q,$$

$$\mathbf{x} \in X. \tag{37}$$

where $\varepsilon > 0$ is a sufficiently small scalar, $\mathbf{w}^T = (w_1,\ldots,w_q)$ is the scaled criterion vector and $\lambda^T = (\lambda_1,\ldots,\lambda_q)$ is a normalised weight vector such that

$$\sum_{i=1}^{q} \lambda_i = 1 \text{ and } \lambda_i \geq 0, \; i = 1, \ldots, q. \tag{38}$$

Instead of y_i^*, we use

$$y_i^{**} = y_i^* - \delta_i \tag{39}$$

where $\delta_i > 0$ is a small but computationally significant scalar to assure that $\mathbf{y}^*$ is a strict lower bound to the non-dominated space. The first term of $s(.)$ in (37) represents the weighted Tchebycheff metric, whereas the second term guarantees that each solution is non-dominated by extremising all criteria, (cf. Wierzbicki, 1986).

Upon the first iteration, a large number N of λ-vectors is randomly generated, half of them from the uniform distribution, the other half from the Weibull distribution. The N λ-vectors are filtered to obtain the $2P$ most widely dispersed ones, according to the Tchebycheff distance measure. These λ-vectors are then used to solve $2P$ MOLP problems of the form in (37), where each criterion is scaled according to its range over the nondominated set, as estimated from the payoff table. The resulting $2P$ nondominated solutions are filtered to the P most dispersed criterion vectors. When presented with the sample, the decision maker selects one as the most preferred, say $\mathbf{y}^1$, and the λ-vector, λ^1, associated with $\mathbf{y}^1$ is used to reduce the sample space of λ-vectors in the next iteration. The rate of reduction, r, can be modified at any point of the decision process. In general, let the most preferred solution and corresponding λ-vector at iteration h be denoted by $\mathbf{y}^h$ and λ^h, respectively. Then, the sample space of λ-vectors at iteration h, is defined by

[3] Some notation is introduced. If $\mathbf{a} \in \Re^q$ is a vector and $\mathbf{w} \in \Re^q$ the corresponding non-negative weight vector then the weighted p-norm is defined as,

$$\|\mathbf{a}\|_p^{\mathbf{w}} = \left[\sum_{i=1}^{q} w_i (a_i)^p\right]^{1/p},$$

and the weighted Tchebycheff norm is the special case when $p = \infty$,

$$\|\mathbf{a}\|_\infty^{\mathbf{w}} = \max_{i=1,\ldots,q} \left\{w_i |a_i|\right\}$$

$$
\left[l_i^{h+1}, u_i^{h+1}\right] = \begin{cases} \left[0, r^h\right] & \text{iff } \lambda_i^h - \frac{1}{2} r^h \leq 0, \\ \left[1 - r^h, 1\right] & \text{iff } \lambda_i^h + \frac{1}{2} r^h \geq 1, \\ \left[\lambda_i^h - \frac{1}{2} r^h, \lambda_i^h + \frac{1}{2} r^h\right] & \text{otherwise,} \end{cases} \tag{40}
$$

where l_i^{h+1} and u_i^{h+1} are the lower and upper bound of λ_i^{h+1}, respectively, and r^h denotes r raised to the power of h. If the decision maker guides the convergence by imposing bounds on the criterion values, a modified payoff table is constructed, and the criteria are rescaled. The IWTP continues to contract the space of λ-vectors, until the decision maker locates a satisfactory (satisficing) final solution, or no further contraction is possible.

The Shellmouth Reservoir

This paper demonstrates the application of an MCDM model for addressing an existing water management problem, the Shellmouth Reservoir and Dam. Since the erection of the dam in 1969-71, the Shellmouth Reservoir in Southwest Manitoba, Canada, has been used to regulate flows in the Assiniboine River. The reservoir is approximately 1.3 km wide and 56 km long and has a flood area of 61.5 km^2. Originally intended for flood protection, the reservoir presently must satisfy a number of additional requirements (Yang, 1991), including municipal water supply for the cities of Brandon and Portage La Prairie, Manitoba, irrigation and agricultural water supply for downstream farmers on the Assiniboine River, dilution of the waste effluents from Brandon, Portage La Prairie and Winnipeg, dilution of the heated effluents from Manitoba Hydro's thermoelectric generating plant in Brandon, dilution of industrial waste effluents from facilities on the Assiniboine River, maintenance of sport fisheries in the Shellmouth reservoir and the Assiniboine River, industrial water supply for facilities on the Assiniboine River, and recreation. A detailed physical description of the reservoir, the hydrological conditions of the system, reservoir storage targets, power generation targets, channel capacity, power generation linearisation coefficients, monthly inflows to the reservoir, monthly evaporation, monthly tributary inflows and monthly water demands are given in Yang *et al.* (1992) and Lence *et al.* (1992). The geographic location of the vicinity of the dam is shown in Fig. 2.

Figure 2. About here

Previous Research on the Shellmouth Reservoir

Yang (1991) and Yang *et al.* (1992) formulate linear goal programming (LGP) models for the optimal monthly operating policies for the dam, under five hydrological scenarios. The goals in these models are to minimise undesirable deviations from target levels for the storage level and release rate for downstream water supply. In Yang (1991) a downstream thermoelectric power plant poses itself as the primary water consumer, although its demand is considered constant. Yang *et al.* (1993) later improve on the operational quality of Yang's (1991) LGP model by including a third goal of minimising changes in release so as to induce a smoother release pattern. Latheef (1991) and Lence *et al.* (1992) extend the scope of the formulation by explicitly including the release requirements of downstream thermoelectric power generation. Latheef (1991) and Lence *et al.* (1992) use a linearisation of the relationship between allowable power generation and required release for a given temperature standard, assuming once-through cooling, and formulate the management problem as a LGP model which limits deviations from power generation targets, subject to strict "hard" water quality constraints for instream temperature levels. However, one implication of including allowable temperature(s) as "hard" constraints is that in the optimal solutions each constraint level is either at its upper or lower bound, leading to extreme solutions. In practice, where trade-offs between power generation, water storage and water temperature are essential, the release decision may be made in a more flexible manner. Yulianti and Lence (1993) subsequently transform the model using a minimax approach, in which the sums of maximal deviations for storage levels, power generation targets and temperature deviations are minimised simultaneously. From a decision theoretical standpoint, the disadvantage of the minimax model is that the decision maker has little control over the type of solution obtained, and that the approach depends upon *ad hoc* constants with potentially adverse implications when summing criteria with different orders of magnitude.

Illustration

In the Shellmouth Reservoir, we chose a planning period of nine years, and the planning scenario investigated consists of three cycles of a wet, an average and a dry year. The use of discrete scenarios for planning is supported by Georgakakos (1993), who uses three scenarios for an operational level, continuous time model. Gilbert (1985) also utilises scenarios to evaluate proposed plans. The three-cycle planning scenario used here is examined by Lence *et al.* (1992), along with other scenarios, and may be considered as a relatively difficult hydrologic scenario. The storage, release and power generation targets for the problem obtained from Lence *et al.* (1992) are given in Table 5. The monthly planning period corresponds to operational practice at the reservoir. A weekly operating policy would be unnecessarily detailed, while periods longer than a month would hide some challenging variations in inflows and demand. We solve the underlying model with 1150 constraints and 800 variables using GAMS (Brooke *et al.*, 1988). The MCDM shell is coded in Visual Basic under MS Excel (1995), in order to facilitate decision maker experimentation and the graphical presentation while comparing different alternatives. All calculations were carried out on a PC 486/DX2, 66 MHz, and the time needed to solve each sub-problem (37) without any pre-processing averaged 45 seconds. The decision maker, experienced in dam reservoir modelling, is familiar with the reservoir and the preferences of the dam management. The size of the presentation set in IWTP, *P*, is set to seven vectors, a number in the psychologically feasible range according to Miller (1956).

Table 5 about here

Initially, the ideal vector $\mathbf{y}^*$, the nadir vector $\mathbf{y}_*$ determined from the initial pay-off table in Table 6 and the selfish solutions 1-1 to 1-9 are discussed with the decision maker. From the table, it is evident that there is a conflict between the release rate criterion y_1, recreational criteria (y_5, y_7, y_8) and power generation y_4. Also, the reservoir stability criterion y_9 varies widely between solutions. As expected, a maximal fulfilment of the power generation targets, as in vector 1-4, implies a penalty in terms of maximum and average under-achievements of lower storage targets in dry years. Furthermore, the conflict between the dam stability criterion, y_2, and the reservoir stability criterion, y_9, is apparent in table 6 from solutions 1-2 and 1-9. It is expected that a reservoir policy minimising release change would result in a highly varying storage trace, given the variations in inflow. The maximum storage violation criteria, y_5 and y_7, are primarily concerned with deviations from the flood protection target in April, which is very restrictive and penalises any deviation form the desired value. Thus, the average storage target criteria, y_6 and y_8, play an important role to indicate whether violations occur also during the summer.

Table 6 about here

The first iteration is prepared by the algorithm generating 400 random λ–vectors, equally split between the Weibull and uniform distributions. From the pool of λ–vectors, the 14 most dispersed vectors are filtered and the 14 associated mathematical programs (37) are formulated and solved. Table 7 contains the seven most dispersed solutions of those. Notice that all presented vectors in iteration are different from the selfish solutions in table 6, although they are the result of a filtering process. One desirable property of the IWTP is the ability to easily generate not only non-dominated extreme points, but also points in the interior of the non-dominated frontier. All vectors in the sample are presented in numerical form and with a graph of their associated storage traces and any other information the decision maker requests.

Table 7 about here

The technique utilised is a basically a two-phase process of elimination of unacceptable extremes and pairwise comparisons of the reduced subset. In principle, the decision maker prioritises the criteria in order of their importance as dam requirements. Thus, the highest priority of the dam manager is to prevent flooding (criterion 1). Next, the non-energy water demand fulfilment (criterion 3) is considered, thereafter the recreational criteria (criteria 5-9). Power generation (criterion 4) is finally employed to select a most preferred solution from a screened sample. The dam stability criterion 2 is indicative of the robustness of the solution and considered in pairwise comparisons.

Vector 2-6, although offering a low flooding violation is immediately discarded due to unacceptable criterion values for criteria 8 and 9. Next, vector 2-7 is discarded when the graph is studied, the high values for criteria 5 and 9 correspond to over-achievements in wet years and large under-achievements in dry years. Vector 2-4 does not show any violations of the upper storage target, but a consistent under-achievement, which makes it unattractive. The similarities between vectors 2-1 and 2-3 encourage a pairwise comparison. Both vectors show a competitive achievements in criteria related to violation of the lower storage target, but when compared to vector 2-2, the trade-off in terms of violations of the upper storage target and power generation does not convince the decision maker. Thus, vectors 2-1 and 2-3 are preferentially dominated by vector 2-2. Vector 2-5 show a very smooth storage trace, at the cost of almost all other criteria, which the decision maker considers unacceptable. However, the payoff-table and the sample have brought the decision maker to realise that high flooding is not a prerequisite for acceptable levels of other criteria. Thus, the decision in the first iteration is to select 2-2 as the most preferred vector and to pursue the desired reduction in criterion value 1 by inserting a constraint of 5% in the next iteration.

After assessing the updated pay-off table for the second iteration in Table 8, the procedure proceeds as in the first iteration, with the difference that all generated λ-vectors are slightly contracted around λ^{2-2} according to (40). The interesting characteristic to note in Table 8 is that the reduction by half of the flooding criterion did not worsen the most important criteria (water demand, recreation and power) to the a high extent. The minimal under-achievement of the lower storage target (y_7) increased from 34% to 37% and the reservoir stability criterion (y_9) rose from 779 to 867, the other recreational criteria remained at their initial level.

Table 8 about here

All criterion vectors in iteration 2, given in Table 9, display acceptable criterion values for flooding, thus the decision maker screens the solutions visually by means of the storage traces. As indicated by the high criterion values for criterion 9, vectors 4-3, 4-6 and 4-7 are immediately discarded by the decision maker after the screening. Vector 4-1 is further preferentially dominated by vector 4-2, since the latter offers superior flooding, recreation and flood protection. Vector 4-4 is similar to vector 2-5 and is eliminated after comparison with either vectors 4-2 or 2-2.

Table 9 about here

Now, the decision maker faces the choice between vectors 4-5 and 2-2, which are similar, and vector 4-2. Vector 4-2 exhibits no planned violation of the upper storage targets and has lower deficit in power generation. Thus, the decision maker prefers vector 4-2 and decides to impose bound on the reservoir stability criterion, y_9 , not to exceed the value for the chosen vector, i.e., 1 800 (10^6 m^3). This measure is a result of the observation by the decision maker that the reservoir stability criterion is a good indicator whether a specific storage trace is feasible. Since the limit is feasible, the procedure readily accepts the new bound after rescaling of all criteria. Iteration 3 proceeds updated pay-off table for iteration 3 is given as Table 10. The inserted bound is mainly affecting the ideal values for the release stability criterion, y_2, and the maximum violation of the lower storage target, y_7.

Table 10 about here

The sample in iteration 3, given as Table 11, displays an interesting spread of solutions, now with increased quality and subsequently higher difficulty in choosing the most preferred. The initial screening in the third iteration results in no reduction in the number of acceptable vectors, since the imposed limit has forced the operating policy to reasonably satisfy the recreational targets. However, four of the presented vectors, namely 6-4, 6-5, 6-6 and 6-7 show some common traits. Compared to the vector with the lowest flooding, 6-5, the others offer little in return, considering the fact that the graph associated with 6-5 is excellent from a recreational viewpoint. An additional vector, 6-2, is eliminated on the argument that the comparative improvement to 6-5 in power generation deficit is insufficient to compensate for the low performance in flood protection and recreation. However, the final comparison is more difficult and the aggregate criteria are not exhaustive for the final evaluation Thus, the decision maker requests additional information regarding the criterion vectors, namely the exact occurrence of possible flooding events, demand deficits and power generation deficits, presented in Table 12.

Table 11 about here

Table 12 about here

In the final round in addition to the remaining three vectors from iteration 3, the preferred vectors from the previous two iterations are considered for reference. Note that all solutions satisfy the municipal and agricultural water demand, effectively reducing the set of criteria for evaluation. Another interesting remark can be made regarding the deficit in power generation., comparing vectors 2-2 and 6-5. Although solution 2-2 shows a substantially lower maximum deficit in power generation, 68 GWh, than the corresponding value for solution 6-5, 95 GWh, the actual performance is worse, with 10 deficits occurring in nine years summing up to a total of 472 GWh, almost double the amounts for 6-5. The times of the deficits also differ. Whereas vector 2-2 favours compliance to storage targets and holds back release in the late summer months during dry years, vectors 6-5 emphases the stability criteria and tries to maintain a stable release, which leads to violations of the peak demand in January and February during dry years. In the phase of pairwise comparisons, vector 6-5 is compared to 6-3. The former shows worse criterion values on flooding and mean and maximum power generation deficit, in exchange for improvements in recreation. All graphs of storage levels are however similar, indicating that the recreational and operational stability targets to some extent are satisfied. Subsequently, 6-5 is preferentially dominated, as is 2-2 with an analogous line of reasoning. Briefly, the trade-off in comparison between vectors 4-2 and 6-1 is a smoother storage trace and some months of summer recreation in dry years against a 10% violation of the upper storage target and one instance fewer failures to satisfy power generation and 4 GWh higher mean deficit in power generation during the nine year period. Since the violation of the upper storage target is undesirable during wet years and the average violation of the lower storage target is roughly the same, vector 4-2 is preferred. The final comparison between vectors 4-2 and 6-3 is to the advantage of the latter. As evident in Fig. 3, the two storage policies are similar for the first (wet) year, but 6-3 is preferable during average (year 2) and dry (year 3) years. Moreover, policy 6-3 shows higher stability, closer adherence to the lower bounds and better performance in power generation with respect to failure frequency, mean and total deficit. The two annual deficits for policy 6-3 occur in November and December, whereas policy 4-2 shows a more erratic pattern in Fig. 4. The decision maker has acquired sufficient knowledge on the non-dominated set to exit the procedure.

For the purposes of this presentation, the sensitivity analysis is omitted, although the advantages of using IWTP to conduct preferential robustness tests are clearly demonstrated in the numerical example. The emphasis in the current example is however not to present a superior operating policy, *per se*, but to demonstrate the versatility and usefulness of IWTP in the application. Although the finally preferred solution, as in the Shellmouth Reservoir case, may very well be characterised by traditional properties, such as no flooding, the decision maker arrives at the solution through a different mode of thinking than before. The strength of IWTP, the exposition of non-dominated sample, forces the decision maker to articulate trade-off preferences and prevents early bias to certain types of solutions.

Figure 3. about here.

Figure 4. about here.

Conclusion

After twenty years of research, reservoir management is still a fruitful area to apply the interactive MCDM methodology, both in terms of supporting the decision maker in the decision process and of gaining insights into the properties of a given mathematical model. Reservoir management is characterised by multiple decision criteria, stochastic, real-time decision-making and economic, environmental and societal impacts. The decision problem poses many challenges to the decision maker and the analyst, in structuring, preparing and presenting information concerning the consequences of a proposed operating policy from different viewpoints.

We have extended a reservoir management model to include multiple thermoelectric power plants and to encompass nine decision criteria in an interactive MCDM framework. The criteria reflect a carefully chosen subset of the many important and conflicting interests that influence the operation of the dam, such as flooding, operational stability, municipal and agricultural water demand, power generation and recreational interests. Although the decision model is deterministic, the stochastic nature of the problem is acknowledged through the utilisation of simulation. Also, to increase the applicability of the obtained policy, the outcome is optimised for each of three generic hydrologic types, wet, average and dry years. The interactive MCDM framework is based on the IWTP (Steuer and Choo, 1983) to guarantee non-dominated solutions through-out the decision process and to provide the decision maker with a powerful and flexible interaction, in the absence of *a priori* weights, restricting preference assumptions and hypothetical preference assessment.

The model, implemented using standard commercial optimisation software and spreadsheets, is used to solve a real case, the Shellmouth Reservoir, Manitoba. The dam manager as decision maker investigates the properties of the model through a three-iteration exercise. In the process, different solutions are presented and evaluated in each iteration, before the contraction of the search space is sufficiently narrowed. Bounds on decision criteria are implemented in the second and third iteration in order to focus on the preferred sub-space of the non-dominated set.

The work high-lights a number of interesting topics for further research. One example is the formulation of smoothing and stability criteria for dam management problems, in order to increase the fit between good dam management engineering practice and the results of our model. An alternative could be to include the frequency and mean magnitude of violations of storage, release and power generation targets, as illustrated in the final iteration in the numerical example. Another approach would be to address the environmental concerns by solving the problem using temperature violation as a criterion for a given power generation level. The generality and applicability of the approach to other hydrologic scenarios, to other reservoir problems and to hydroelectric power generation problems are also under investigation. Methodologically, a challenge may be to capture the preferences of the decision maker and utilising them in the filtering process of the method, in order to display solutions of higher perceived quality to the decision maker and thus improve the time-efficiency of the approach. Research aimed at combining simulation and multi-criteria optimisation for complex systems, such as Agrell and Wikner (1994), may also prove useful in the context of reservoir management.

Acknowledgement

The research in this study was carried out in part when the authors were at the International Institute for Applied Systems Analysis, Laxenburg, Austria. Besides the kind support from the institute, involving the Water Resources Management and Methodology of Decision Analysis projects, grants from the Swedish Research Foundation (FRN) and the Natural Sciences and Engineering Research Council of Canada (award no. OGP00416343) supported the work during the summer of 1995, and provided funds for data collection, respectively. The third author was supported in part by a Terry/Selig Summer Research Fellowship from the University of Georgia.

References

Agrell, P. J. and J. Wikner, *A Multicriteria Framework for Dynamic Systems.* Working Paper WP-218, Department of Production Economics, Linköping Institute of Technology, Linköping, Sweden, 1994.

Berkemer, R., M. Makowski and D. Watkins, *A Prototype of a Decision Support System for River Basin Water Quality Management in Central and Eastern Europe.* Working Paper WP-93-049, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1993.

Brooke, A., D. Kendrick and A. Meeraus. *GAMS: A User's Guide*. Scientific Press, Redwood City, CA, U.S.A., 1988.

Buchanan, J. T. and H. G. Daellenbach, A Comparative Evaluation of Interactive Solution Methods for Multiple Objective Decision Models. *European Journal of Operational Research* 29(3), 1987, 353-359.

Can, E. K. and M. H. Houck, Real Time Reservoir Operations by Goal Programming. *ASCE Journal of Water Resources Planning and Management* 110(3), 1984, 297-309.

Chanchit, C. and M. P. Terrell, CCGP Model for Multiobjective Reservoir-Systems. *ASCE Journal of Water Resources Planning and Management* 115(9), 1989, 658-670.

Cohon, J. L. and D. H. Marks, Multiobjective Screening Models and Water Resource Investment. *Water Resources Research* 9(4), 1973, 826-836.

Datta, B. and S. J. Burges, Short-Term Single Multipurpose Reservoir Operation: Importance of Loss Functions and Forecast Errors. *Water Resources Research* 20(9), 1984, 1167-1176.

El Magnouni, S. and W. Treichel, A Multicriterion Approach to Groundwater Management. *Water Resources Research* 30(6), 1994, 1881-1895.

Evans, G. W., An Overview of Techniques for Solving Multiobjective Mathematical Programs. *Management Science* 30(11), 1984, 1268-1282.

Gandolfi, C. and K. A. Salewicz, Water Resources Managment in the Zambesi Valley: Analysis of the Lake Kariba Operation. In *Hydrology for the Management of Large Rivers*, F. H. M. Van de Ven, D. Gutknecht and K. A. Salewicz (Eds.), IAHS Publication No. 201, 1991, 13-25.

Gardiner, L. K. and R. E. Steuer, Unified Interactive Multiple Objective Programming. *European Journal of Operational Research* 74(3), 1994, 391-406.

Georgakakos, A. P., Operational Trade-Offs in Reservoir Control. *Water Resources Research* 29(11), 1993, 3801-3819.

Gilbert, K. C., Management Science in Reservoir Operation. In *Applications of Management Science*, R. L. Schultz (Ed.) 4, 1985, 107-130.

Giles, J. E. and W. O. Wunderlich, Weekly Multipurpose Planning Model for TVA Reservoir System. *ASCE Journal of Water Resources Planning and Management* 107(2), 1981, 495-511.

Goulter, I. C. and R. Castensson, Multi-Objective Analysis of Boating and Fishlife in Lake Sommen, Sweden. *Water Resources Development* 4(3), 1988, 191-198.

Haimes, Y. Y. and W. Hall, Multiobjectives in Water Resource Systems Analysis: The Surrogate Worth Trade-Off Method. *Water Resources Research* 10, 1974, 615-624.

Haimes, Y. Y., W. A. Hall and W. A. Freedman, *Multiobjective Opimization in Water Resources Systems*. Elsevier, Amsterdam, the Netherlands, 1975.

Isermann, H. and R. E. Steuer, Computational Experience Concerning Payoff Tables and Minimum Criterion Values over the Efficient Set. *European Journal of Operational Research* 33(1), 1988, 91-97.

Jacquet-Lagrèze, E., R. Meziani and R. Slowinski, MOLP with an Interactive Assessment of a Piecewise Linear Utility Function. *European Journal of Operational Research* 31(3), 1987, 350-357.

Korhonen, P., S. Salo and R. E. Steuer, *A Heuristic for Estimating Nadir Criterion Values in Multiple Objective Linear Programming*. Working Paper, Helsinki School of Economics, Helsinki, Finland, 1994.

Latheef, M. I., *Application of Optimization Techniques for Reservoir Management in Conjunction with Thermoelectric Power Generation.* M.S. Thesis, University of Manitoba, Winnipeg, Manitoba, Canada, 1991.

Lence, B. J., M. I. Latheef and D. H. Burn, Reservoir Management and Thermoelectric Power Generation. *ASCE Journal of Water Resources Planning and Management* **118**(4), 1992, 388-405.

Makowski, M., L. Somlyódy and D. Watkins, *Multiple Criteria Analysis for Regional Water Quality Management: The Nitra River Case.* Working Paper WP 95-022, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1995.

Microsoft Excel 5.0, User's Guide, Microsoft Co., New York, U.S.A., 1995.

Miller, G., The Magical Number Seven Plus Minus Two: Some Limits on Our Capacity for Processing Information. *Psychological Review* 3(2), 1956, 81-97.

Monarchi, D. E., C. C. Kiesel and L. Duckstein, Interactive Multiobjective Programming in Water Resources: A Case Study. *Water Resources Research* 9, 1973, 837-850.

Ríos Insua, D. and K. A. Salewicz, *The Operation of Lake Kariba: A Bayesian Analysis.* Discussion Paper 93-14, ISDS, Duke University, Durham, NC, U.S.A., 1993.

Shin, W. S. and A. Ravindran, Interactive Multiple Objective Optimization: Survey I - Continuous Case. *Computers & Operations Research* **18**(1), 1991, 97-114.

Sobel, M. J., Chebishev Optimal Waste Discharges. *Operations Research* **19**, 1971, 308-322.

Steuer, R. E. and E. U. Choo, An Interactive Weighted Tchebycheff Procedure for Multiple Objective Programming. *Mathematical Programming* **26**(1), 1983, 326-344.

Steuer, R. E., *Multiple Criteria Optimization : Theory, Computation, and Application.* Wiley, New York, U.S.A., 1986.

Szöllosi-Nagy, A., On the Short-Term Control of Multiobjective Reservoir Systems: A Case Study of the Kapos Basin, Hungary. In *The Operation of Multiple Reservoir Systems*, Z. Kaczmarek and J. Kindler (Eds.), CP-82-S3, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1982.

Wierzbicki, A. P., The Use of Reference Objectives in Multiobjective Optimization. In *Multiple Criteria Decision Making*, G. Fandel and T. Gal (Eds.), Springer, Berlin, Germany, 1980, 468-486.

Wierzbicki, A. P., On the Completeness and Constructiveness of Parametric Characterizations to Vector Optimization Problems. *OR-Spektrum* **8**, 1986, 73-87.

Yang, Y., *Identification of an Optimal Operating Policy for a Multipurpose Reservoir.* M.S. Thesis, University of Manitoba, Winnipeg, Manitoba, Canada, 1991.

Yang, Y., S. K. Bhatt and D. H. Burn, Reservoir Operating Policies Considering Release Change. *Civil Engineering Systems* **10**, 1993, 77-86.

Yang, Y., D. H. Burn and B. J. Lence, Development of a Framework for the Selection of a Reservoir Operating Policy. *Canadian Journal of Civil Engineering* **19**, 1992, 865-874.

Yeh, W. W-G., Reservoir Management and Operations Models: A State of the Art Review. *Water Resources Research* **21**(12), 1985, 1797-1818.

Yulianti and B. J. Lence, Reservoir Management and Thermoelectric Power Generation. In *Proceedings of 1993 Specialty Conference, ASCE Water Resources Planning and Management Division*, Seattle, Washington, U.S.A., 1993, 846-849.

Table 1. Notation: Indices and Sets

Indices and Sets	
$i \in \{1, ..., m\}$	Index of periods in a specific year
$j \in \{1, ..., n\}$	Index of years
$J_W \subseteq \{1, ..., n\}$	Set of all wet years
$J_A \subseteq \{1, ..., n\}$	Set of all average years
$J_D \subseteq \{1, ..., n\}$	Set of all dry years
$k \in \{1, ..., K\}$	Index of all river reaches
$K_T \subseteq \{1, ..., K\}$	Set of those river reaches with thermoelectric power plants

Table 2. Notation: Variables.

Decision Variables	
S_i^W	Reservoir storage level at the end of period i of a wet year (in 10^6 m^3)
S_i^A	Reservoir storage level at the end of period i of an average year (in 10^6 m^3)
S_i^D	Reservoir storage level at the end of period i of a dry year (in 10^6 m^3)
Auxiliary Variables	
F_{ij}^k	Total net water requirement in river reach k, during period i of year j (in 10^6 m^3)
G_{ij}^k	Power generated at the thermoelectric power plant in river reach k when once-through cooling is used, during period i of year j (in GWh)
Q_{ij}^k	Discharge available for the cooling of th thermoelectric power plant in river reach k, during period i of year j (in 10^6 m^3)
R_{ij}	Water volume released during period i of year j (in 10^6 m^3)
S_{ij}	Reservoir storage level at the end of period i of year j (in 10^6 m^3)
TR_{ij}^k	Total transit water release from river reach k during period i of year j (in 10^6 m^3)

Table 3. Notation: Parameters.

a_i^k	Intercept term of the linearised relation between river flow and power generated at the thermoelectric power plant in reach k, for period i (in GWh)
b_i^k	Slope of the linearised relation between river flow and power generated at the thermoelectric power plant in reach k, for period i (in GWh/10^6 m^3)
$\Delta^k_{ij}(d)$	Temperature deviation at a location d meter downstream of the thermoelectric power plant in reach k, for period i of year j (in °C)
ΔR_{ij}	Change in released water volume between period i–1 and i of year j (in 10^6 m^3)
d	Distance from the emission point to the temperature monitoring point in any river reach (in m)
D_{ij}^k	Total water demand for municipal, agricultural, industrial use and dilution of industrial waste in river reach k, during period i of year j (in 10^6 m^3)
γ	Specific weight of the river water (in g/cm^3)
$\hat{G}_{ij}^k$	Power generation target for the thermoelectric power plant in reach k, for period i of year j (in GWh)
H_R^k	Heat rejected per unit power generation for the thermoelectric power plant in reach k (in kcal/GWh)
I_{ij}	Inflow into the reservoir, during period i of year j (in 10^6 m^3)
$K^k_{r,ij}$	Heat exchange coefficient for the thermoelectric power plant in river reach k, during period i of year j (in $days^{-1}$)
$Q^k_{e,ij}$	Discharge withdrawn for cooling the thermoelectric power plant in river reach k, during period i of year j (in 10^6 m^3)
$\hat{R}$	Channel capacity on release (in 10^6 m^3)
R_{min}	Lower physical bound on release (in 10^6 m^3)
R_{max}	Upper physical bound on release (in 10^6 m^3)
S_{min}	Lower physical bound on reservoir storage (in 10^6 m^3)
S_{max}	Upper physical bound on reservoir storage (in 10^6 m^3)
SU_i	Upper storage target for period i, e.g. for recreation or flood control (in 10^6 m^3)
SL_i	Lower storage target for period i (in 10^6 m^3)
$T_{ij}^k(d)$	Average water temperature d meter downstream of the thermoelectric power plant in reach k, for period i of year j (in °C)
$\hat{T}_i^k$	Temperature standard for river in reach k, during period i (in °C)
$T^k_{u,ij}$	Average water temperature immediately upstream of the thermoelectric power plant in river reach k, during period i year j (in °C)
$T^k_{e,ij}$	Average emission temperature of the thermoelectric power plant in river reach k, during period i year j (in °C)
TI_{ij}^k	Total tributary inflow into river reach k, during period i of year j (in 10^6 m^3)
v_{ij}^k	Average stream velocity, for the length of the river between the point of emission and the monitoring point, d meter downstream of the thermoelectric power plant in reach k, for period i of year j (in m/day)
V_{ij}	Water evaporation from the reservoir, during period i of year j (in 10^6 m^3)

Table 4. Decision Criteria in Categories.

Flood protection	
y_1	Maximum violation of channel capacity (in %), minimise $y_1 = \max_{i,j}\left\{R_{ij} - \hat{R}, 0\right\}$.
Dam safety	
y_2	Sum of changes in release rate (in 10^6 m^3), minimise $y_2 = \sum_{i=1}^{m}\sum_{j=1}^{n}\Delta R_{ij}$.
Non-energy water demand	
y_3	Maximum proportion of unsatisfied municipal, agricultural and industrial demand, minimise $y_3 = \max_{i,j}\left\{1 - R_{ij}\left\{\sum_{k=1}^{K} F_{ij}^{k}\right\}^{-1}, 0\right\}$.
Power generation	
y_4^k	Maximum underachievement of power generation target (in GWh), minimise $y_4^k = \max_{i,j}\left\{\hat{G}_{ij}^k - G_{ij}^k, 0\right\}$, $k \in K_T$.
Recreation	
y_5	Maximum undesirable violation of upper storage target (in %), minimise $y_5 = \max_{i,j}\left\{S_{ij} - SU_i, 0\right\}$.
y_6	Average undesirable violation of upper storage target (in %), minimise $y_6 = \frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n}\max\left\{S_{ij} - SU_i, 0\right\}$.
y_7	Maximum undesirable violation of lower storage target (in %), minimise $y_7 = \max_{i,j}\left\{SL_i - S_{ij}, 0\right\}$.
y_8	Average undesirable violation of lower storage target (in %), minimise $y_8 = \frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n}\max\left\{SL_i - S_{ij}, 0\right\}$.
y_9	Sum of all deviations from mean of upper and lower storage target (in 10^6 m^3), minimise $y_9 = \sum_{i=1}^{m}\sum_{j=1}^{n}\left\|S_{ij} - \tfrac{1}{2}\left(SU_i + SL_i\right)\right\|$.

Table 5. Storage, Release and Power Generation Targets for the Shellmouth Reservoir.

	Storage targets ($10^9 m^3$/month)		Channel capacity (10^9 m^3/month)	Power generation (GWh/month)	
	SL_i	SU_i	$\bar{R}$	Wet, average years, G_{ij}^k	Dry years $\hat{G}_{ij}^k$
January	N/A[4]	N/A	134	97.8	145.0
February	N/A	N/A	134	97.8	131.0
March	N/A	N/A	134	97.8	145.0
April	200	200	134	0	140.0
May	333	413	134	0	38.0
June	333	413	134	0	31.0
July	333	413	134	0	19.0
August	333	413	134	0	27.0
September	N/A	N/A	134	0	42.0
October	N/A	N/A	134	0	60.0
November	N/A	N/A	134	97.8	141.0
December	N/A	N/A	134	97.8	145.0

Table 6. Criterion vectors, selfish optimisation, iteration 1.

Criterion (all *min*)	Vector 1-1	1-2	1-3	1-4	1-5	1-6	1-7	1-8	1-9	Ideal	Nadir
Flooding	0%	4%	2%	10%	10%	10%	10%	8%	10%	0%	10%
Stability	1 934	607	1 596	1 598	2 175	2 072	2 258	2 266	2 201	607	2 266
Demand	0%	0%	0%	0%	0%	0%	0%	1%	1%	0%	1%
Power	95	38	145	38	71	72	95	87	95	38	145
Max SU	43%	55%	42%	43%	0%	42%	44%	47%	42%	0%	55%
Ave SU	0%	1%	0%	0%	0%	0%	2%	1%	0%	0%	2%
Max SL	75%	88%	75%	75%	85%	76%	34%	45%	76%	34%	88%
Ave SL	6%	20%	6%	6%	5%	5%	5%	4%	5%	4%	20%
Midtarget	1 400	6 742	1 546	1 571	1 212	1 117	2 887	1 658	779	779	6 742

Table 7. Filtered sample of nondominated criterion vectors, iteration 1.

Criterion (all *min*)	Vector 2-1	2-2	2-3	2-4	2-5	2-6	2-7
Flooding	10%	0%	8%	10%	10%	0%	6%
Stability	1 930	1 922	2 071	1 850	2 108	1 054	1 280
Demand	0%	0%	1%	0%	0%	0%	0%
Power	95	68	95	145	90	145	38
Max SU	28%	14%	48%	0%	41%	43%	63%
Ave SU	0%	0%	1%	0%	0%	0%	2%
Max SL	50%	70%	55%	86%	77%	75%	51%
Ave SL	5%	6%	4%	7%	5%	11%	9%
Midtarget	1 695	1 429	1 844	1 626	867	3 364	3 767

[4] Not applicable.

Table 8. Criterion vectors, selfish optimisation, iteration 2.

Criterion (all *min*)	Vector 3-1	3-2	3-3	3-4	3-5	3-6	3-7	3-8	3-9	Ideal	Nadir
Flooding	0%	4%	5%	5%	5%	5%	5%	5%	5%	0%	5%
Stability	1 565	607	1 771	1 659	1 137	1 024	2 253	2 044	2 224	607	2 253
Demand	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	12%
Power	81	38	94	38	38	54	95	94	95	38	95
Max SU	43%	55%	31%	36%	0%	43%	63%	60%	26%	0%	63%
Ave SU	0%	1%	0%	0%	0%	0%	2%	2%	0%	0%	2%
Max SL	75%	88%	83%	82%	86%	87%	37%	52%	74%	37%	88%
Ave SL	6%	20%	6%	7%	14%	13%	6%	4%	5%	4%	20%
Midtarget	1 717	6 742	1 381	1 784	4 469	4 102	2 801	2 229	867	867	6 742

Table 9. Filtered sample of nondominated criterion vectors, iteration 2.

Criterion (all *min*)	Vector 4-1	4-2	4-3	4-4	4-5	4-6	4-7	2-2
Flooding	5%	0%	0%	5%	0%	0%	5%	0%
Stability	2 224	1 855	613	2 180	1 873	1 597	2 252	1 922
Demand	0%	0%	0%	0%	0%	0%	0%	0
Power	95	38	38	95	38	38	95	68
Max SU	55%	0%	57%	43%	10%	10%	63%	14%
Ave SU	1%	0%	1%	0%	0%	0%	2%	0%
Max SL	47%	85%	87%	75%	74%	75%	37%	70%
Ave SL	4%	7%	20%	5%	6%	8%	6%	6%
Midtarget	1 950	1 794	6 742	867	1 510	2 362	2 739	1 429

Table 10. Criterion vectors, selfish optimisation, iteration 3.

Criterion (all *min*)	Vector 5-1	5-2	5-3	5-4	5-5	5-6	5-7	5-8	5-9	Ideal	Nadir
Flooding	0%	5%	0%	0%	0%	1%	5%	5%	5%	0%	5%
Stability	1 973	1 332	1 711	1 711	1 840	1 947	2 221	2 152	2 224	1 332	2 224
Demand	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Power	38	58	38	38	38	38	95	95	95	38	95
Max SU	10%	43%	12%	12%	0%	0%	55%	44%	26%	0%	55%
Ave SU	0%	0%	0%	0%	0%	0%	1%	1%	0%	0%	1%
Max SL	75%	75%	75%	75%	85%	84%	41%	46%	74%	41%	85%
Ave SL	7%	7%	7%	7%	7%	6%	5%	4%	5%	4%	7%
Midtarget	1 483	1 800	1 675	1 675	1 800	1 623	1 800	1 784	867	867	1 800

Table 11. Filtered sample of nondominated criterion vectors, iteration 3.

Criterion (all *min*)	Vector 6-1	6-2	6-3	6-4	6-5	6-6	6-7	4-2
Flooding	0%	5%	0%	4%	1%	4%	5%	0%
Stability	1 847	2 221	1 556	2 218	2 221	1 584	2 221	1 855
Demand	0%	0%	0%	0%	0%	0%	0%	0%
Power	38	52	92	95	95	95	95	38
Max SU	10%	37%	50%	6%	14%	34%	37%	0%
Ave SU	0%	1%	0%	0%	0%	0%	1%	0%
Max SL	74%	55%	53%	77%	76%	75%	62%	85%
Ave SL	6%	4%	6%	5%	5%	5%	4%	7%
Midtarget	1 578	1 800	1 800	1 232	1 010	1 363	1 509	1 794

Table 12. Complementary Information in Iteration 3.

		Vector 2-2	4-2	6-1	6-3	6-5
Flooding						
No of violations		0	0	0	0	25
Max of violations	(10^6 m^3)	0	0	0	0	4396
Mean of violations	(10^6 m^3)	0	0	0	0	5588
Sum of violations	(10^6 m^3)	0	0	0	0	109 893
Water Demand						
No of violations		0	0	0	0	0
Power Generation						
No of violations		10	9	8	8	5
Max of violations	(GWh)	68	38	38	92	95
Mean of violations	(GWh)	47.2	33.8	37.9	33.1	47.2
Sum of violations	(GWh)	472	304	303	264	236

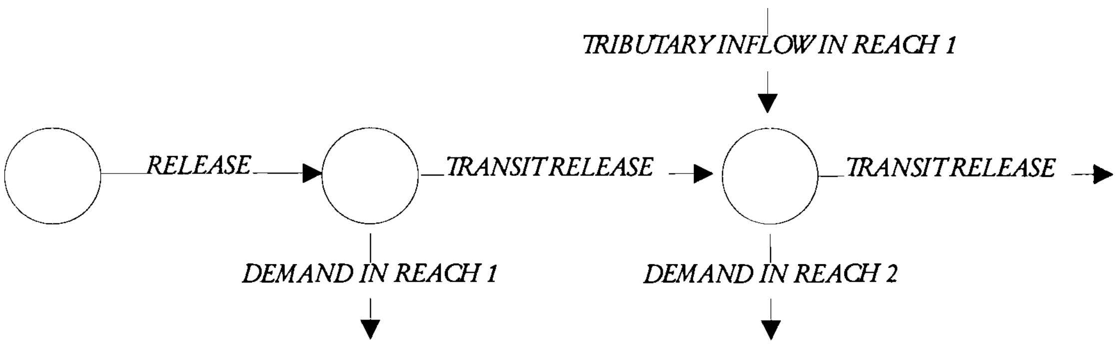
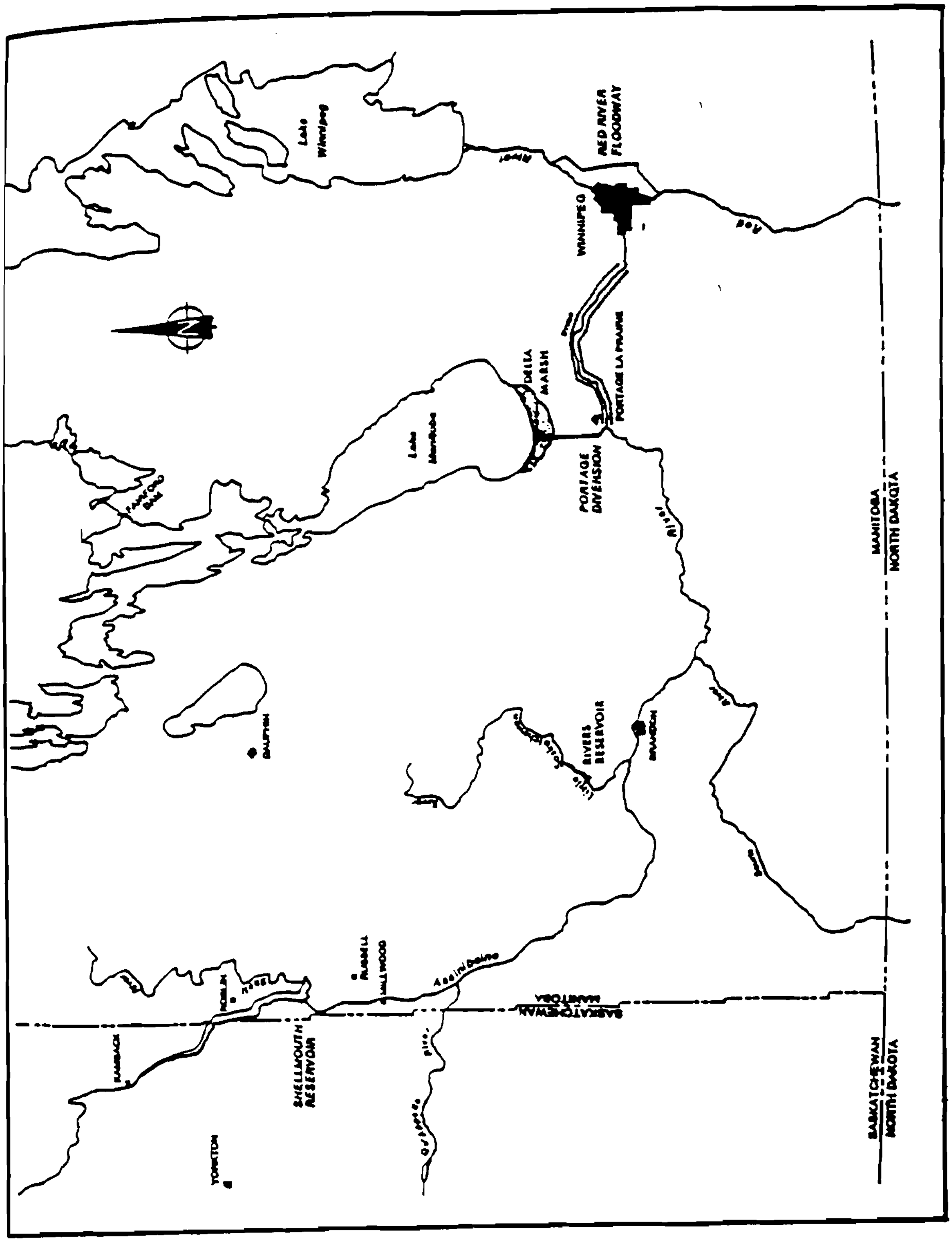


Figure 1. Tributary Inflow to River Reaches.

Figure 2. The Vicinity of the Shellmouth Reservoir, Manitoba, Canada.



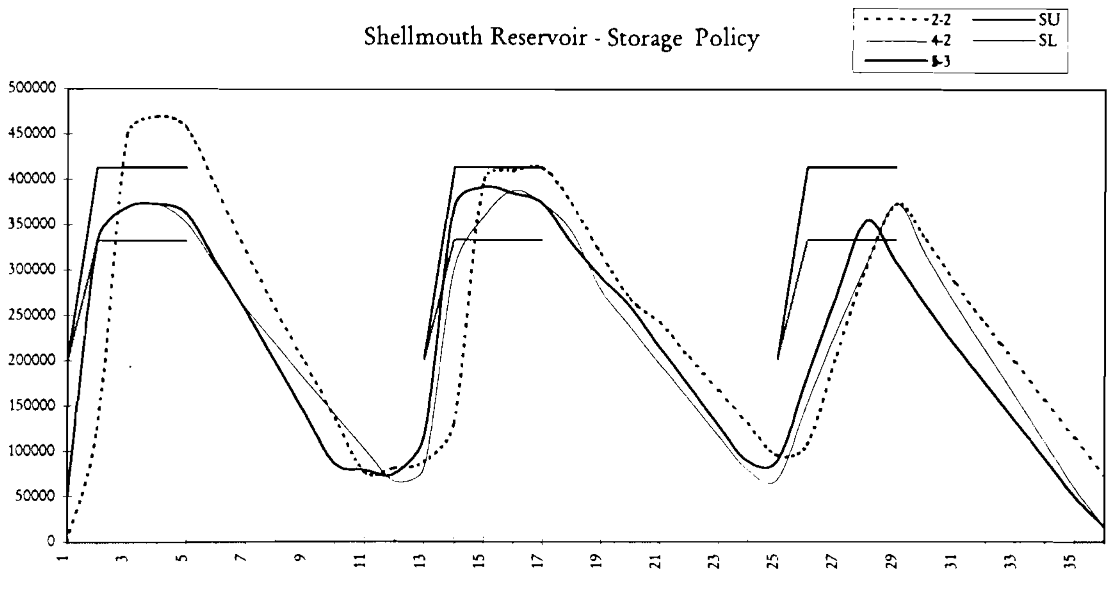


Figure 3. Storage Policies for Solutions 2-2, 4-2 and 6-3.

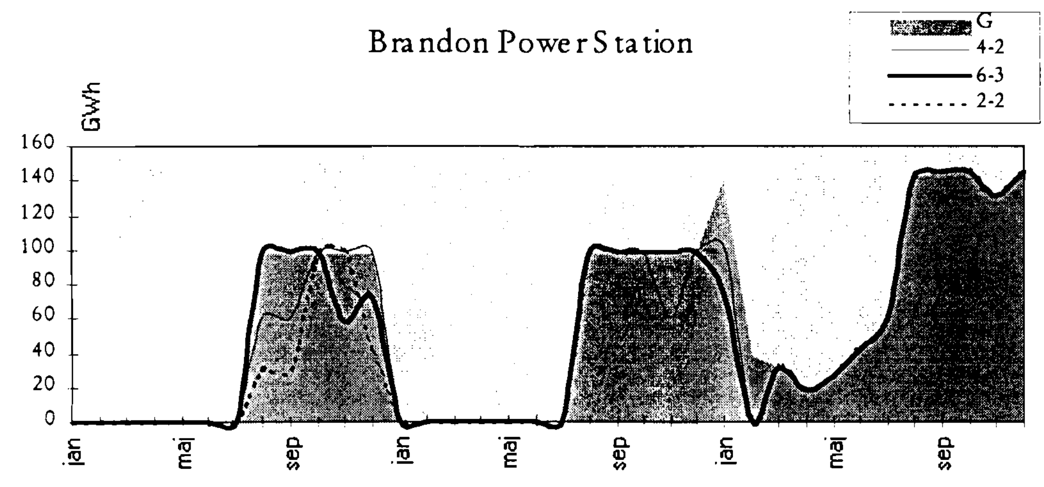


Figure 4. Power Generation Policies for Solutions 2-2, 4-2 and 6-3.