DISSERTATION

PLANNING RESERVOIR OPERATIONS WITH IMPRECISE OBJECTIVES

Submitted by

Enrique Moncada

Department of Civil Engineering

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY ENRIQUE MONCADA ENTITLED PLANNING RESERVOIR OPERATIONS WITH IMPRECISE OBJECTIVES BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Co-Adviser

Adviser

Department Head

ABSTRACT OF DISSERTATION

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Inclusion of soft elements in the formulation of water resource system problems has always received attention by water resource researchers and planners. In the case of reservoir operation, its multipurpose characteristic has been approached through the formulation of a multiobjective optimization problem. However, the non-quantitative nature of some objectives, like environmental and recreational objectives, has always represented a complex issue to deal with either in simulation or optimization models. Imprecise objectives and constraints have not been easily incorporated into a classical crisp model. Fuzzy sets theory allows us to deal with information which is valuable but not precise. Systems analysis tools such as dynamic programming provide the way to find optimal operational policies of a multipurpose reservoir. Hence, a fuzzy dynamic programming technique should allow finding a set of optimal controls or releases when the problem is addressed as a multidecision problem with imprecise objectives.

A methodology is developed based on Bellman and Zadeh's approach. The methodology is tested through its application in a case study. Two cases are considered: deterministic and implicit stochastic.

Grey Mountain Reservoir, a proposed water resource project in the Cache La Poudre River basin, is considered as the case study. The fuzzy goal is represented by the stored volume that the reservoir may have at the end of its yearly operation, and the fuzzy

constraints are represented by the water uses or objectives, like municipal and industrial water supply, flood control space, hydropower, rafting, kayaking, angling and fish habitat, embedded with a subjective linguistic term. Membership functions of the fuzzy goal and fuzzy constraints are developed.

In the deterministic case, fuzzy dynamic programming results show monthly releases and storage levels behaved as expected for reservoir operation problems. The achievement of the fuzzy goal was acceptable and in case of the water uses or objectives, the most achievable were flood control, fish habitat and water supply, while the less achievable ones were rafting, kayaking, angling and hydropower, with a high relative variability in the degree of their achievement.

In the stochastic case, the results show the expected degree of satisfaction for the fuzzy goal was higher than for the deterministic case. In case of the water uses or objectives, the level of the expected achievement was in general similar to the deterministic case results; the most achievable objectives were also flood control, water supply and fish habitat, and the less achievable ones were again rafting, kayaking, angling and hydropower, and the relative variability of the degree of satisfaction was also high in several cases. Monthly storage levels were fit to linear models to obtain operating rules and the estimated values were further used in a simulation model to obtain monthly storage levels and releases. The comparison of simulated and optimal results reveals a good fit. Thus, operating rules can be used to make decisions about monthly releases from the reservoir.

Finally, the results reveal that with the fuzzy approach it is possible to incorporate imprecision and non-commensurate issues in the formulation of objectives and constraints of water resources problems. In addition, the form of the results directly indicates the expected values and the variability in the degree of achievement of those objectives and constraints, providing commensurable and easily-interpreted measures of comparison among diverse and difficult-to-quantify objectives.

Enrique Moncada
Department of Civil Engineering
Colorado State University
Fort Collins, CO 80523
Spring 1999

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DEDICATION

To Rosa Amelia, Enrique Alberto and Ana Lucia

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Reservoirs, one of the most important water resources system components, can be used to meet water requirements for purposes such as water supply, flood control, water quality, hydropower, recreation, etc. Generally, the reservoir storage is divided into three main storage spaces: (1) the dead storage; (2) the active storage; and (3) the flood control storage. Dead storage is used for sediment control; active storage is used to regulate releases for downstream demands like water supply, energy production, recreation, environmental protection, etc.

A basic problem in reservoir operation analysis is to determine the relationship between inflow characteristics, reservoir storage capacity, reservoir releases and reliability of the reservoir operation policies. Thus, reservoir operational rules need to be developed to accomplish the reservoir's purposes, which are usually competitive; for instance, efforts to maximize recreational uses by keeping water in the reservoir may adversely impact irrigation water supply (Johnson, 1990). Hence, decisions about water releases are more difficult to make due to the multiobjective nature of the problem (Changchit and Terrell, 1989).

To deal with the complexity of a multipurpose reservoir, optimization or simulation models should be used to determine its operational rules. Increasing attention has been given in the past 30 years to the application of mathematical models (optimization and simulation) for obtaining operational rules for water resources systems (Loucks and Sigvaldason, 1982). Successful applications of optimization models have been made in reservoir operation studies, usually for planning purposes (Yeh, 1985).

On the other hand, the concept of uncertainty has been usually considered as a synonym of risk associated with inflows and demands probability. Thus, stochastic optimization techniques have been applied to find reservoir operational rules (Yeh, 1985). Stochastic optimization can be divided into explicit and implicit approaches. The explicit case considers the maximization of an expected benefit function or the minimization of an expected cost function; the random inputs, like inflows, are described by their marginal probabilities. The implicit case attempts to determine an optimum sequence of decisions based on generated series of random inputs, like random realizations of inflows.

To deal with other types of uncertainty, like subjective information and qualitative considerations in water resources systems, techniques of multicriteria decision-making (MCDM) (Palmer and Lund, 1985), and multiattribute theory (Keeney and Word, 1977) have been applied. For instance, the analytic hierarchy process used by Palmer and Lund (1985) incorporates subjectivity in terms of evaluating alternatives. It is necessary to develop a set of alternatives relative to a single objective containing the ratios, $a_{i,j}$, of an alternative i relative to alternative j; and the weight, w, to represent the importance of an alternative relative to the objective in question. To deal with multiobjective reservoir operation, methodologies like the weighing technique, goal programming and multiobjective dynamic programming have been applied (Changchit and Terrell, 1989). For instance, Tauxe *et al.* (1979), developed a multiobjective dynamic programming model to deal with multiobjective reservoir operation when quantitative and non-commensurable objectives are present. A drawback of this approach is the larger the number of objectives to consider, the more complex the analysis of non-inferior solutions.

On the other hand, it is well known that in real decision-making situations, objectives and constraints have a considerable amount of subjectivity or vagueness embedded in their formulation. For instance, Mohammadi (1991) presents an extensive literature review about the trends in water resource systems modelling, and he concludes that water resource models are partly based on subjective foundations and, thus, depend heavily on expert knowledge. This statement may be interpreted in one direction as the necessity of developing models which are able to incorporate imprecise information into their formulation. This type of uncertainty is concerned with fuzziness rather than with randomness. Essentially, randomness has to do with uncertainty concerned with membership or non-membership of an object in a nonfuzzy set. Conversely, fuzziness has to deal with classes in which there may be grades of intermediate memberships between a full membership and no membership of an object to a given set (Bellman and Zadeh, 1970; Kandel, 1980). For instance, Flug and Ahmed (1990) point out that recreational, social and environmental objectives have achieved an important status in water resources decision making. Unfortunately, enumeration of specific objectives and quantification of variables that address those objectives have not been satisfactorily performed in real world projects. Thus, social and environmental objectives are not treated comparably in the planning process. They are not quantified in units of flow as are other objectives typical to river and reservoir operation analysis.

Nowadays, fuzzy sets theory represents a promising and alternative way to deal with uncertainty, in the form of subjectivity, in decision-making problems where subjective issues are represented as the ones which are imprecise but valuable. Fuzziness means a type of imprecision in which the transition from membership to nonmembership is gradual rather than abrupt. In fact, a fuzzy sets theory represents a step toward a link between the precision of classical mathematics and the pervasive imprecision of the real world (Kauffman, 1975).

Although a fuzzy sets theory uses precise algebraic expressions, it is able to incorporate imprecise information. This approach contrasts with the standard one, widely used in the past two decades, where objectives and constraints were written in precise algebraic terms, eliminating any element of subjectivity. Regarding subjectivity in water resources issues, Palmer and Lund (1985) point out that "the exclusion of subjective information is particularly detrimental in the design of water resources systems where economic, environmental, political and social objectives must be considered and are often difficult to quantify."

This situation is present either in a mature water economy or in a young water economy: in the former with greater competition among water users and more complex water problems for water managers, and in the latter with developing new water supplies (Stansburry *et al.*, 1991), where objectives and constraints have a vagueness embedded in their formulation due, in some cases, to the lack of a water resources development policy; hence, they are sometimes ill-defined and not fully considered in the context of the planning horizon. For instance, Colby (1990) explains that in the last decade, because many cities have grown rapidly, new opportunities for boating, rafting and fishing are being demanded; hence, almost every state in the USA is concerned with trade-offs between water for offstream uses and keeping water instream for recreational uses, power generation, environmental protection, etc. In addition to that, non-commensurate objectives like environmental protection and recreational uses are not evaluated in units related to the discharge flow but in monetary terms, which are sometimes difficult to agree upon.

In the case of water resources, the concept of fuzziness can be applied to the operation of a multipurpose reservoir. Fuzzy sets allow us to formulate objectives such as "sustainable development of irrigated agriculture," "dependable power generation," or "balanced environmental protection," and constraints like "a critical volume substantially greater than ...," "flood storage in month t should be close to ..." This type of formulation is handled by fuzzy sets through the use of the membership functions. In addition, the fuzzy sets approach can deal with non-commensurable objectives, such as minimization of adverse effects on the environmental quality through the construction of an appropriate membership function which could be further used to evaluate its attainment (Hipel, 1982).

Emerging works have come out in recent years in regard to fuzzy sets applied to water resource systems planning and management. We can cite works developed by Hipel (1982), Bogardi and Bardossy (1983), Slowinsky (1986), Ayyub and McCuen (1987) and Gates *et al.* (1991), who have applied fuzzy sets in multicriteria modelling, regional management of an aquifer under fuzzy environmental objectives, quality and uncertainty assessment of wildlife habitat, water supply system development planning using multicriteria fuzzy linear programming, and an evaluation of irrigation water delivery system performance when subjective notions are attached to it. Conclusions such as "Not only can the technique handle both quantitative and nonquantitative factors, but the point of view of the interest groups can also be considered" (Hipel, 1982); "the main advantages of this method are that it provides for the incorporation of judgement uncertainty and has the ability to show the uncertainty in the final outcome" (Ayyub and McCuen, 1987); and "the use of fuzzy linear programming to water resources systems enlarges the list of efficient applications of fuzzy sets in operations research" (Slowinsky, 1986), state a potential use of this approach in water resources system analysis.

1.2 OBJECTIVES

The main objective of this research is to develop a methodology, based on fuzzy sets theory, for planning reservoir operations when objectives and/or constraints contain imprecise information in their formulation.

A second objective is to test the applicability of this methodology in Grey Mountain Reservoir, a project to be built on the Cache La Poudre River in northern Colorado.

CHAPTER 2

LITERATURE REVIEW

2.1 MULTIOBJECTIVE ANALYSIS METHODS APPLIED TO WATER RESOURCES ANALYSIS

2.1.1 Dynamic Programming

Dynamic programming (DP), a method formulated by Bellman (1957), is probably one of the most extensively used solution procedures for the management of reservoir systems. Dynamic programming is particularly adapted to problems with a multi-stage decision structure such as reservoir operation. Dynamic programming has the advantage that nonlinear and stochastic features which characterize a large number of water resources systems can be translated into a DP formulation. In addition, it has the advantage of effectively decomposing highly complex problems with a large number of variables into a series of subproblems which are solved recursively. According to Yeh (1985) applications of DP to reservoir optimization have been reported by Hall and Buras (1971), Young (1967), and Hall *et al.* (1968).

2.1.2 Goal Programming

Goal programming is an extension of linear and integer programming; however, it is capable of considering multiple goals in the objective function. A goal programming framework can consider economic and environmental objectives.

A goal programming problem may be formulated as a linear programming problem, where the objective function is interpreted as the minimization of the deviation from the desired goals. Original objective functions are transformed into constraints equations by allowing for under-attainment and over-attainment and setting the equation equal to the desired goal level.

The resulting problem is in the form of an objective function with constraints that can be solved via linear programming. However, with goal programming the solutions are satisfactory rather than optimum; i.e., the solution best satisfies the policy levels set for goal attainment (Taylor *et al.*, 1975; North *et al.*, 1984).

2.1.3 Surrogate Worth Trade Off Method

The surrogate worth trade off method is a mathematical programming methodology similar to goal programming. This method provides a means to considering a vector of noncommensurable objective functions.

Given the set of objective functions, the decision-maker assesses the relative value of the trade-off of marginal increases and decreases between any two objectives. The decision-maker must compare one or more objectives and determine which is of the greatest value. This type of decision involves Pareto optimality and non-inferior solution concepts.

To determine this trade-off between objectives, trade-off functions have to be developed through the decision-maker's judgement. Thus,

$$T_{ij} = \frac{\partial f_i\ (x)}{\partial f_j\ (x)} \tag{2.1}$$

where: T_{ij} = trade off function between objectives i and j.

Those objectives may be in noncommensurable units. For instance, $f_i(x)$ may be measured in dollars and $f_j(x)$ in acres of land. The trade off function would be measured in dollars/acre, hence the surrogate worth function is a function of the trade offs which estimate the desirability of one objective over another (Haimes and Hall, 1974; Taylor *et al.*, 1975; Cohon and Marks, 1975).

2.1.4 Utility Function Assessment

According to Goicoechea *et al.* (1982) and Keeney and Wood (1977), a utility function is simply a mapping of the values in the range of an attribute (i.e., an objective) into a cardinal worth scale as determined by the individual.

In the case of several attributes, the function is called a multiattribute utility function (MUF). For multiobjective problems utility functions can, in principle, completely order the set of non-inferior solutions. A utility or worth can be associated with each non-inferior solution, and the solution with the highest utility is referred as the best compromise solution.

A MUF is expressed as $u(x) = u(x_1,\ldots,x_n)$ where x_i, $i = 1,2,\ldots,n$ represents levels of the several attributes. The MUF can be formulated in one of the two ways:

$$u(x) = \Sigma k_i u_i(x_i) \tag{2.2}$$

or,

$$1 + k \cdot u(x) = \Pi[1 + k \cdot k_i \cdot u_i(x_i)] \tag{2.3}$$

where $u = u(x)$ is scaled from 0 to 1; the component utility functions are scaled from 0 to 1; the scaling constants k_i are positive and less than 1; and k is a constant that satisfies the equation:

$$1 + k = \Pi[1 + k \bullet k_i] \tag{2.4}$$

The functional form of Equation (2.3) is additive and Equation (2.4) is multiplicative. The selection of one of them is based on indifference or preference aspects between attribute levels of x_i and x_j. After choosing the functional form of the utility function, the next step is to evaluate the scaling factors k_i and add them up to determine the appropriate form. A more detailed explanation of the method is presented in Goicoechea *et al.* (1982).

Among the difficulties are cited the tedium of calculating the component utility functions and scaling factors; the lack of immediate feedback to the decision-maker of the implications of his preferences and the absence of an efficient procedure to "update" the decision-maker's preferences and conduct sensitivity analysis.

2.2 INCORPORATION OF MULTIOBJECTIVE CHARACTERISTICS IN WATER RESOURCES SYSTEMS ANALYSIS

Tauxe *et al.* (1979) illustrates the application of multiobjective dynamic programming (MODP) by examining the operation of Shasta Reservoir in California. Three objectives were considered: (1) to maximize the cumulative dump energy generated above the level of firm energy, (2) to minimize the cumulative evaporation or loss of the resource, and (3) to maximize the firm energy.

The primary objective was maximized in the recursive equation. The secondary objective, that of minimization of cumulative evaporation losses was represented by a state variable objective. The third objective was formulated as a physical constraint in the two-objective MODP problem. The third objective, that of firm energy, was then parametrically varied outside the MODP, through the decision-maker's judgement.

Changchit and Terrell (1989) applied a goal programming methodology to a system of multipurpose reservoirs in Oklahoma. Several objectives which may be conflicting and non-commensurate such as flood protection, municipal and industrial water supply, hydroelectric power generation, recreation, etc., were considered and stochasticity of the inflows was added to the formulation.

The proposed chance constrained goal programming (CCGP) methodology allows the reservoir manager to incorporate his judgement to rank various goals according to their relative importance. The target levels for the goals are usually available in most systems. Trade-offs among conflicting goals can be evaluated and non-inferior solutions can be obtained. In addition, the use of stochastic inflows can improve the accuracy of the results. They concluded that MODP produces the Pareto-optimal solution set in one solution, and it can be used for qualitatively analyzing a variety of water resources problems involving non-commensurable objectives whose analysis would otherwise provide great difficulties.

Louie *et al.* (1989) used a multiobjective optimization procedure, applying the constraint linear programming technique to assist water resources planners to establish a more unified basin-wide management plan, which will simultaneously consider three major objectives in basin planning: (1) water supply allocation; (2) water quality control; and (3) prevention of undesirable overdraft of the ground-water basin.

The optimization procedure is designed to be applied in concert with one or more simulation models: a groundwater quantity and quality model or a river flow and mass transport model, or both, and a water supply model which routes the water from the supply sources to various demand points. They conclude that the results of this methodology provide a better understanding of the interactive behavior among planning objectives.

Haimes and Hall (1974) illustrate the application of the surrogate worth trade-off method to the well-known Reid and Vemuri's example problem, which is stated as follows:

> "A dam of finite height impounds water in the reservoir and that water is required to be released for various purposes such as flood control, irrigation, industrial and urban use, and power generation. The reservoir may also be used for fish and wildlife enhancement, recreation, salinity and pollution control, mandatory releases to satisfy riparian rights of downstream users, and so forth. The problem is essentially one of determining the storage capacity of the reservoir so as to maximize the net benefits accrued ..."

Through the use of this method, they developed non-inferior solutions for a set of alternatives, and with the aid of a decision-maker, they generated surrogate worth functions. Among the major advantages of the method are the non-commensurable objective functions can be handled quantitatively, and the decision maker interacts with the mathematical model and makes decisions on his subjective preference in the functional space rather than in the decision space.

Keeney and Wood (1977) applied the multiattribute utility theory to evaluate water resource development plans. The Tisza River in Hungary was the case study area. The planning objectives were to satisfy water requirements, to provide flood protection, to provide drainage and used water disposal, to minimize utilization of resources, to minimize environmental impact, and to provide enough flexibility to meet future requirements. Among their conclusions, they state that special attention should be given to assessing utility functions over the subjectively scaled attributes. In addition, they concluded those assessments should be conducted with several people concerned with the water resource system selected as a case study.

2.3 FUZZY SETS IN OPTIMIZATION

2.3.1 Basic Concepts

2.3.1.1 Fuzzy set

A fuzzy set is a class of objects in which there is no sharp boundary between those objects that belong to the class and those that do not. If $X = \{x\}$ denotes a collection of objects (points) denoted generically by x, then a fuzzy set A in X is a set of ordered pairs,

$$A = \{(x, \mu_A(x))\} \quad x \in X \tag{2.5}$$

where: A = the set containing the ordered pairs $(x, \mu_A(x))$; and

$\mu_A(x)$ = grade of membership of x in A.

2.3.1.2 Membership function

A fuzzy set A of X is simply defined by its membership function $\mu_A(x)$. Membership functions are such that $0 \leq \mu_A(x) \leq 1$. The value of $\mu_A(x)$ at a particular element x is called "the grade of membership of x in A."

2.3.1.3 Intersection

The intersection of A and B is denoted by $A \cap B$ and is defined as the largest set contained in both A and B. The membership function of $A \cap B$ is given by

$$\mu_{A \cap B}(x) = \min(\mu_A(x), \mu_B(x)) \quad x \in X \tag{2.6}$$

or,

$$\mu_{A \cap B}(x) = \mu_A(x) \wedge \mu_B(x)$$

where: $\wedge$ = the minimum operator that fuzzy sets use to represent an intersection.

2.3.1.4 Union

The union of A and B denoted by $A \cup B$ is defined as the smallest fuzzy set containing A and B. The membership function of $A \cup B$ is given by

$$\mu_{A} \cup_{B}(x) = \max(\mu_A(x), \mu_B(x)) \quad x \in X \tag{2.7}$$

or,

$$\mu_{A \cup B}(x) = \mu_A(x) \vee \mu_B(x)$$

where: $\vee$ = the maximum operator that fuzzy sets use to represent a union.

2.3.1.5 Fuzzy goal

Given $X = \{x\}$, a set of alternatives, then a fuzzy goal G in X is identified with a fuzzy set G in X.

$$G(x) \subsetneq X \tag{2.8}$$

2.3.1.6 Fuzzy constraint

Given $X = \{x\}$, a set of alternatives, then a fuzzy constraint C in X is defined to be a fuzzy set C in X.

$$C(x) \subsetneq X \tag{2.9}$$

2.3.1.7 Fuzzy decision

Given a fuzzy goal G and a fuzzy constraint C in a space of alternatives X, then G and C combine to form a decision D, which is a fuzzy set resulting from the intersection of G and C. Thus,

$$D = G \cap C \tag{2.10}$$

or,

$$\mu_D(x) = \mu_G(x) \wedge \mu_C(x)$$

where: $\wedge$ = the minimum operator that fuzzy sets use to represent an intersection.

In general, for n goals G1, G2, G3,...,Gn, and m constraints C1, C2, C3,...,Cm, the resulting decision is the intersection of the given goals G_i and constraints C_j.

2.3.1.8 Minimum-type fuzzy decision

It is defined as follows:

$$\mu_D(x) = \mu_{G(1)}(x) \wedge \ldots \wedge \mu_{G(n)}(x) \wedge \mu_{C(1)}(x) \wedge \ldots \wedge \mu_{C(m)}(x) \tag{2.11}$$

for each $x \in X$

2.3.1.9 Weighted-sum type fuzzy decision

It is defined as follows:

$$\mu_D(x) = \Sigma\alpha_i\mu_{Gi}(x) + \Sigma\beta_j\mu_{Cj}(x) \tag{2.12}$$

for each x $\qquad i = 1,\ldots,n$

$j = 1,\ldots,m$

where: α_i = the weight allocated to the goal, G_i ; and

β_j = the weight assigned to the constraint, C_j.

2.3.1.10 Optimal decision

The optimal decision is defined as:

Maximizing decision:

$$\mu_D(x) = \max_{x \in X} \mu_D(x) \qquad (2.13)$$

Minimizing decision:

$$\mu_D(x) = min_{x \in X} \mu_D(x) \qquad (2.14)$$

2.3.2 The Membership Functions

2.3.2.1 Fundamentals

Zadeh (1965) introduced two important aspects of fuzzy sets theory: a) the membership functions, and b) the operators to be applied on these functions.

In spite of its key importance, few articles have concentrated on membership function issues. Membership functions represent a vital component of fuzzy sets theory. They may be viewed as the tool used to represent, in mathematical terms, the measure of uncertainty attached to a fuzzy event. So, to make comparisons, a membership function plays a similar role as a probability function does in probability theory.

By definition, given a universe of discourse $X = \{x\}$ and A = a fuzzy set in this universe, the membership function of A is μ_A: $X \rightarrow [0,1]$, where $\mu_A(x)$ is the grade of membership of $x \in X$, in A, and $0 \leq \mu_A(x) \leq 1$.

This definition makes a clear distinction from the characteristic function definition. Membership function definition establishes a gradual transition from belonging to and/or not belonging to a set; from the full membership ($\mu(x) = 1$) through intermediate memberships ($0 < \mu(x) < 1$) to the full nonmembership ($\mu(x) = 0$) (Bellman and Zadeh, 1970; Kacprzyk, 1983; Dombi, 1990).

For values of $\mu(x) = 1$ and $\mu(x) = 0$, we are really dealing with crisp sets; the fuzziness feature arises in the case of having $0 < \mu(x) < 1$.

Imprecision or fuzziness which may be captured by a membership function can be of different types. First, imprecision due to the generality, which may be defined as the application of a subjective attribute to a multiplicity of objects. Second, imprecision due to the ambiguity, which means to have alternative meanings for a given object. Third, imprecision due to the vagueness of the concept, which may be defined as the lack of clear-cut boundaries of the set of objects to which the symbol belongs (Kacprzyk, 1983).

Vagueness may be represented through the use of a subjective attribute. A subjective attribute differs from an objective attribute in that the latter refers to any attribute, A, which is unambiguously either possessed or not possessed by any object, X, in a domain of discourse, θ. This can be exemplified by those integer numbers which are "GREATER THAN 5..." (see Figure 2.1) as opposed to those which are "SUBSTANTIALLY GREATER THAN 5..." (see Figure 2.2). There is no degree of subjectivity interpretation in the former attribute about the form of the characteristic function representing a crisp set. On the other hand, the latter attribute contains an inherent vagueness which allows a subjective interpretation about the form of the membership function representing this fuzzy set.

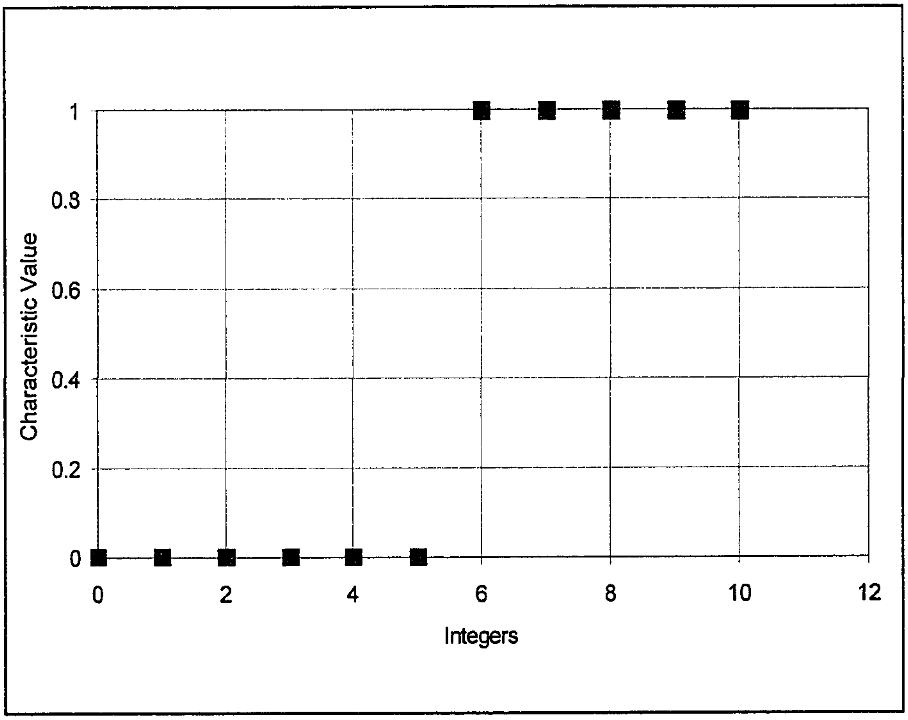


FIGURE 2.1 Characteristic function of integers greater than five.

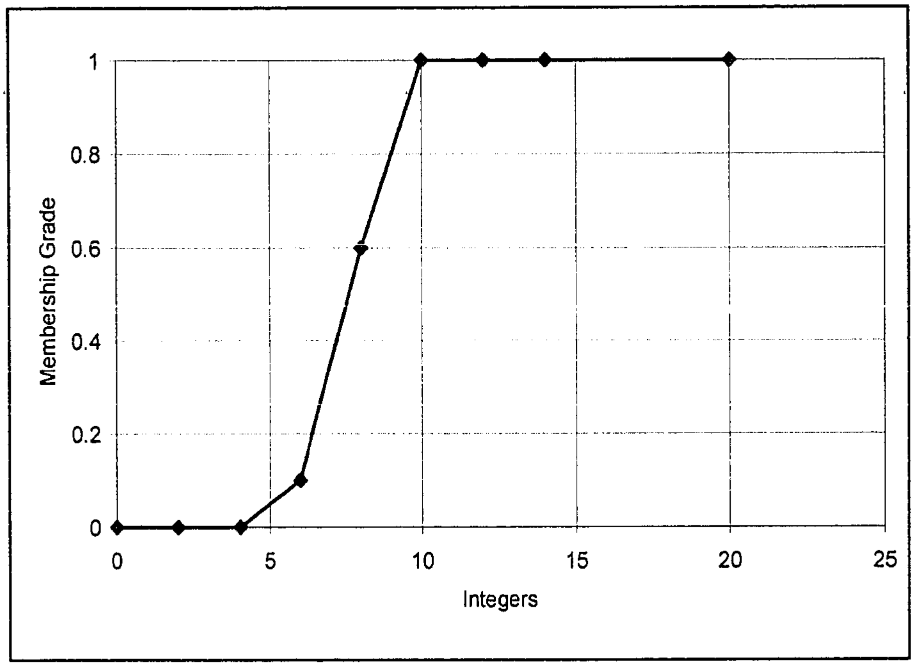


FIGURE 2.2 Membership function of integers *substantially* greater than five.

2.3.2.2 Construction of membership functions

According to Zimmerman (1987) measurement means assigning numbers to objects such that certain relations between numbers reflect analogous relations between objects. Sometimes, as in the case of engineering applications, defining membership functions is often possible without any theoretical background. Dombi (1990) presents some common features found in the fuzzy sets' articles; among them we may cite: (1) all membership functions are continuous; (2) the membership functions map an interval [a,b] to [0,1] or μ[a,b] mapping to [0,1]; (3) the membership functions are (a) either monotonically increasing, or (b) monotonically decreasing, or (c) could be divided into a monotonically increasing or decreasing part; (4) the monotonous membership functions on the whole interval are either (a) convex functions or (b) concave functions, or (c) there exists a point, c, in the interval [a,b] such that [a,c] is convex and [c,b] is concave (called S-shaped functions); (5) monotonically increasing functions have the property $\mu(a) = 0$ and $\mu(b) = 1$, while monotonically decreasing functions have the property $\mu(a) = 1$ and $\mu(b) = 0$.

Norwich and Turksen (1984) established the theoretical basis for the fundamental measurement of the membership function of a fuzzy set. They carried out an empirical study to construct membership functions in accordance with the interval scale. In their experiment, subjects were scaled, not stimuli, which means membership functions were constructed for each individual by having her/him repeatedly (at least nine times) and randomly rate a given stimulus and then average her/his responses. The resulting membership functions were typically monotonically increasing and unimodal.

Kempton (1984) developed interview-based methods to elicit fuzzy categories to study different cultures and qualify objects through their attributes. He carried out his research in the anthropology area and used questionnaires and drawings to stimulate the informants in eliciting their membership values.

Kacprzyk (1982) showed some pre-established shapes of membership functions which may be more useful in practical applications of fuzzy sets. Their shapes ranged from trapezoidal, truncated trapezoidal ascendent to truncated trapezoidal descendent, which are special cases of unimodal and non-decreasing and non-increasing functions, respectively.

Zimmermann (1987) presents two models for determining membership function empirically: type A and type B. They differ with respect to their mapping properties.

In a type A model of the membership function, μ maps an empirical relational structure "$X, S_1,...,S_n$" with a set X of n elements into a numerical relational structure "$[0,1],U_1,...,U_n$" of the same type: μ: "$X,S_1,...,S_n$" $\rightarrow$ "$[0,1],U_1,...,U_n$." An example of this type of membership function is presented below.

Let X be the set of clients, x_i, of a certain bank:

$X = \{x_1, x_2, x_3, x_4, x_5, x_6, x_7\}$

Then, the fuzzy set to define a membership function of "creditworthy clients" might be

$F = \{(x_1,1), (x_2,.4), (x_3,.6), (x_4,1), (x_5,.5), (x_6,.1), (x_7,0)\}$

In a type B model of membership function, two numerical relational structures are given. It maps one numerical structure into another numerical structure of the same type of relations: μ: "$R,T_1,...,T_n$" and "$[0,1],U_1,...,U_n$." It is basically a transformation. An example of this type of membership function is presented below. Let X be the set of noise levels:

$X = \{0, 20, 40, 60, 80, 100, 120)$

Then, the membership function of "acceptable noise levels in streets for a residential area" may be defined by:

F = {(0,1), (20,0.9), (40,0.5), (60,0.05), (80,0), (100,0), (120,0)}

2.3.3 Fuzzy Multistage Programming

In conventional programming we consider a mathematical analysis of any system in terms of a set of decision variables, a set of constraints limiting the choice between alternatives and an objective function which measures the performance or desirability of such alternatives.

Fuzzy programming, in essence, has the same structure as the conventional programming with some basic differences. The objective function as well as the constraints are fuzzy sets, and the decision is considered as a fuzzy set: the desirable alternatives.

Traditional dynamic programming models are generally formulated in terms of state variables, x_i, decision variables, d_i, stage returns, $r_i(x_i,d_i)$, a returns function, $R_N = f(r_1,...,r_N)$ and a state transformation function, $t_i(x_i,d_i)$.

The decision variables, d_i, determine the transformations, t_i. It is assumed that x_i depends only on x_{i+1} and d_{i+1}. Hence we can write the stage return, $r_i(x_i,d_i)$, as $r_i = (x_N,d_N,...,d_i)$ (Dreyfus and Law, 1977).

Some characteristics which are also relevant to a traditional dynamic programming are the crisp decision space, discrete or continuous; the discrete crisp state space; the state variables; the crisp transformation function, deterministic or stochastic; the crisp objective function, separable into stage rewards and monotonically nondecreasing in the stage rewards.

The termination time (planning horizon) is crisp. It is usually finite and specified as the number of decision variables or stages N.

In the case of the fuzzy version of multi-stage decision models, two more distinctive features become relevant:

The operators used to model decisions. In fuzzy models, the question arises as to which operators adequately model the confluence of goals and constraints in decision models.

The general procedure used to solve fuzzy decision problems. First, a fuzzy model of a fuzzy decision problem is designed; then, a crisp model is developed which, in certain aspects, is equivalent to the fuzzy model.

In regard to a fuzzy stochastic multi-stage decision model, the system under control is considered to be stochastic. It is assumed to be a Markov chain whose transition probabilities are governed by a conditional probability function, $P[X_{t+1}/X_t,U_t]$, for t = 1,2..., specifying the probability of attaining a state, X_{t+1}, from a state, X_t, under the decision variable, U_t.

Since the system under control is stochastic, the value of the membership function of the fuzzy decision is a random variable. Hence, some expectation is involved as is usually the case when randomness is present.

Obviously, the scope of fuzzy multi-stage decision models is very wide. Each of those characteristics can be modeled fuzzily, and for all the resulting models, a deterministic and a stochastic case can be developed.

2.4 ANTECEDENTS ON FUZZY SETS APPLIED TO WATER RESOURCE SYSTEMS ANALYSIS

Gates and Alshaikh (1993) present a methodology for optimal design of hydraulic structures in a branched irrigation canal network subject to parametric and objective uncertainty. They use fuzzy membership functions to address subjectivity associated with interpreting expecting values of performance measures in light of water delivery objectives. Those system performance measures were adequacy, efficiency, dependability, and equity of water delivery. They concluded that the method not only achieved an optimal solution but provided a description of the system performance under nonoptimal designs. In addition, such information is useful to assess the expected impact of alternative designs on overall system performance.

Kindler (1992) presents the use of fuzzy linear programming to allocate water resources among different users when the demand is not precisely known in advance. He presents a hypothetical water resource system composed of two cities and two industrial sites. In the formulation of the problem, it is explicitly recognized that the future levels of water requirements can not be precisely known in advance. Thus, fuzzy constraints are defined in terms of water requirements with allowable deficits taken into account. The fuzzy goal, z, is formulated in terms of a prespecified aspiration level, p_z, of the decision-maker; that means he is fully satisfied if p_z is reached, less satisfied with values less than p_z, and not satisfied at some tolerance limit, r_z, $z \leq p_z - r_z$. He used truncated trapezoidal functions, a particular case of non-decreasing functions, as membership functions of the fuzzy constraints.

He found that the model has some features of practical importance as it does not require establishing a hierarchy of water users, and it takes into account the imprecise character of information concerning water requirements.

Savic and Simonovic (1991) present a methodology for handling a problem of selecting risk levels in a chance-constrained reservoir operation modeling. This methodology, based on fuzzy sets, uses two types of membership functions in the formulation of the reservoir long-term planning model; one for the constraints and one for the objective function. The fuzzy objective function is formulated in terms of the importance of the reservoir monthly releases. Thus, the decision-maker's assessment of the importance of the reservoir monthly release is used to derive the coefficients of the objective function. In the case of the fuzzy constraints, they were formulated in terms of the known trends in operating the reservoir in the past and its potential future use. A body of decision-makers assessed the acceptable risk of violating reservoir minimal storage and flood storage.

They selected fuzzy linear programming to model the operation of the reservoir. It was found that the major advantage of the proposed method was the easy incorporation of qualitatively imprecise and subjective input information in a chance-constrained programming model.

Heyder *et al.* (1991) developed an approach for assessing alternative strategies for improving an irrigation water delivery system in the context of multiple planning criteria. For technical performance, fuzzy sets were used to arrive at the criterion function values. Those criteria were adequacy, efficiency, dependability and equity. To calculate the performance criterion, weighted averages of the membership functions values were used.

One of their conclusions was that they were able to capture uncertainty, due to vagueness, in interpreting estimates of defined performance measures.

Duckstein *et al.* (1990) and Chameau (1990) examined potential areas of application of fuzzy logic in water resources systems. Those areas included weather circulation models and detection of climatological changes, fuzzy geomorphology, fuzzy flood forecasting and control, groundwater pollution, salinity intrusion, water requirements analysis under fuzzy conditions, fuzzy reliability of water supply, fuzzy regression analysis of hydrological data, etc. They concluded that in all the cases, fuzzy sets analysis necessitates that membership functions be assessed.

Slowinski (1986) applied multicriteria fuzzy linear programming to a water supply system planning composed by an urban water supply and a wastewater treatment system. He considered the coefficients of the objective function and the constraints as fuzzy numbers. He concludes that a fuzzy approach provides one with a generalized sensitivity analysis which is an excellent aid in choosing the best development alternative.

Bogardi and Bardossy (1983) presented a multiobjective planning model to manage a conjunctive use of a regional aquifer and mineral extraction with a water hazard. Economic and environmental objectives were considered; the former as a quantitative objective and the latter as a fuzzy objective. The fuzzy environmental objective is expressed as the actual underground flows with respect to the natural flows recharging the thermal spring of the aquifer. One of the most important reasons to do so was that social impacts of environmental degradation are very imprecise in long-term planning. The basic principles of Bogardi *et al.*'s methodology is to divide the horizon planning into T stages, and the analysis is carried out in two steps: the first step is used to define an overall cost function based on the (N+1) elements of the objective function and one environmental objective for each site under the N relevant sites. For the second step, N environmental objectives are composed into a single set membership function. Finally, a bi-objective dynamic programming model is used to get the optimal release control policies.

Hipel (1982) presented a comprehensive methodology to determine the preferred solutions in a large-scale wastewater project. This methodology used fuzzy sets linked with multicriteria modelling concepts, and it was applied to a solid waste management problem in Canada. This methodology was also used to find alternative solutions to water resources planning in the Grand River Basin in Ontario, Canada.

The main objectives were: 1) to minimize detrimental effects on the bio-physical environment; 2) to minimize adverse effects on the social environment; and 3) to maximize economic efficiency by calculating the optimum value for the net benefits.

Fuzzy sets were used to qualify attributes like air quality, land quality, water quality, social factors, political factors, etc. When the design step is carried out, each interest group evaluates those attributes on the set of alternatives. These ratings matrices are combined into a single matrix to represent all the opinions of the groups; finally, comparison methods are used to find the best set of alternatives of the preferred solutions. Sensitivity analysis is performed to find out how the final results are affected by the changes in the input data or in the method of analysis.

Loganathan and Bhattacharya (1990) used fuzzy goal programming to find optimal operational rules for the Green River Basin in central Kentucky, a basin composed of four reservoirs. They compared optimal results from fuzzy goal programming with the ones obtained by using preemptive goal programming. They found that fuzzy goal programming approaches the targets more uniformly and focuses on the most preferred values of these targets, for all the goals.

CHAPTER 3

THE PROBLEM AND ITS RESOLUTION

3.1 THEORETICAL FRAMEWORK

3.1.1 Multidecision-making in a Fuzzy Environment

Decision-making in a fuzzy environment is said to be that the goals, constraints and decisions, but not necessarily the system under control, are fuzzy by nature (Bellman and Zadeh, 1970).

The fuzzy goal, G, is defined as a fuzzy set in the set of options X, i.e., $G \subset X$ characterized by the membership function $\mu_G(x)$.

The fuzzy constraint, C, is defined as the fuzzy set contained in the set of options, i.e., $C \subset X$ characterized by the membership function $\mu_C(x)$.

The fuzzy decision is defined as the fuzzy set contained in X, given by the confluence of G and C.

A maximum decision becomes the point in the space of alternatives at which the membership function of the fuzzy decision reaches its maximum value (Kacprzyk, 1983; Bellman and Zadeh, 1970).

3.1.2 Formulation of the Problem

According to Kacprzyk (1983) and Bellman and Zadeh (1970) a multistage decision-making process in a fuzzy environment may be viewed as a system under control A, which is in some initial state, x_o. The state space is represented by the set of options $X = \{s_1,...,s_n\}$, and the control or input to the system is represented by the set of options, $U = \{u_1,...,u_m\}$.

At the initial stage the system is in some initial state, x_o. A control or decision $u_o \in U$ is applied subject to a fuzzy constraint and linked to a state, $x_1 \in X$, by using a given cause/effect relationship to represent the system under control. On x_1, a fuzzy goal, $\mu_{G1}(x_1)$, is imposed; then $u_1 \in U$ is applied, which is subjected to a fuzzy constraint, $\mu_{C1}(u_1)$, and x_2 is obtained, on which $\mu_{G2}(x_2)$ is imposed, etc.

The system under control A is a deterministic system in which the state, x_t, at time $t = 1,2,...$ ranges over a finite set, $X = \{s_1,s_2,...,s_n\}$, and the control, u_t, ranges over a finite set, $U = \{c_1,...,c_m\}$. The temporal evolution of A is described by the state equation

$$x_{t+1} = f(x_t, u_t) \qquad t = 0,1,2,...,N \tag{3.1}$$

where: x_t and x_{t+1} = the states of the system at time, t and t+1, respectively;

u_t = the control or decision variable at time, t; and

f = a given function from X x U to X.

If f is a random function, then A is a stochastic system whose state at time t and t+1 is a probability distribution over X, $P(x_{t+1}/x_t,u_t)$, which is conditioned on x_t and u_t.

At each stage t, a fuzzy constraint, $\mu_C(u_t)$, is imposed on the decision, u_t, and a fuzzy goal, $\mu_G(x_t)$, is imposed on the state, x_t. So, a fuzzy decision, $D(x_o)$, may be expressed as

$$D(x_o) = C_o \sim G_1 \sim ... \sim C_{N-1} \sim G_N \tag{3.2}$$

where ~ represents a fuzzy operator like minimum or maximum aggregator. More explicitly, we can express the fuzzy decision in terms of the membership functions of the fuzzy goal and fuzzy constraints. Thus,

$$\mu_D(u_0,\ldots,u_{N-1}/\, x_0) = \mu_C(u_0)\sim\ldots\sim\mu_C(u_{N-1})\sim\mu_G(x_N). \tag{3.3}$$

The problem of multistage decision-making under fuzziness is to find an optimal sequence of controls or decisions, $u_0,\ldots,u_{N-1}$ for $u^*_t \in U$, $t = 0,1,\ldots,N-1$, so that

$$\mu_D(u^*_0,\ldots,u^*_{N-1}/x_0) = \max_{\mu_0,\ldots,\mu_{N-1}} \mu_D(u_0,\ldots,u_{N-1}/x_0) \tag{3.4}$$

where $\mu_D(u^*_0,\ldots,u^*_{N-1}/x_0)$ is the maximizing decision or policy function in terms of the sequence of optimal inputs or controls, u^*_t, for a given initial state, x_0.

3.1.3 Solution of a Fuzzy Multistage Decision-making Problem by Dynamic Programming

Traditional dynamic programming models are formulated in terms of state variables, x_i, decision variables, u_i, an objective function, F, and a transformation function, $g(x_{t+1}/x_t,u_t)$. The decision, d_i, determines the transformations, g; the total objective function through N stages is a function of individual stage returns from stage N through stage 1. The decision space, state space, transformation function, objective function, and the termination time are crisp.

In case of a fuzzy multistage decision-making problem, the decision variables, state variables, the system under control, and the termination time can be modelled fuzzily.

Bellman and Zadeh (1970) proposed for the first time a fuzzy approach to a dynamic programming model. Kacprzyk (1983) shows a wide variety of multistage decision-making problems under fuzziness and the approach for their solution.

The general framework of a multistage decision-making problem when the system under control is deterministic and the fuzziness is attached to the goals and constraints is presented below. Kacprzyk (1983), Esogbue and Bellman (1982), and Esogbue and Bellman (1984) may be consulted for more detailed information on fuzziness in multistage decision-making.

In this case, the temporal evolution of the system is governed by the state transition equation,

$$x_{t+1} = f(x_t, u_t) \tag{3.5}$$

The initial state is x_o, and $N < \infty$ is the termination time or number of stages. At each stage t, the control or decision variable, $u_t \in U$, is subjected to a fuzzy constraint, $C_t \subset X$ characterized by $\mu_{ct}(u_t)$. At the final stage, $x_N \in X$, a fuzzy goal or target $G_N \subset X$, characterized by $\mu_{G_N}(x_N)$, is imposed. Thus, a fuzzy decision becomes the intersection of the fuzzy goal and the fuzzy constraints, which by definition consists of applying the fuzzy operator min, $\wedge$. Thus,

$$\mu_D(u_o,\ldots,u_{N-1}/x_o) = \mu_{C_o}(u_o)\wedge\ldots\wedge\mu_{C_{N-1}}(u_{N-1})\wedge\mu_{G_N}(x_N), \tag{3.6}$$

where x_N is expressed in terms of $x_o, u_o, \ldots, u_{N-1}$ through the use of the state transition equation.

Then, the problem will be to find an optimal sequence of controls, $u^*_O,\ldots,u^*_{N-1}$ so that

$$\begin{aligned} \mu_D(u_o,\ldots,u_{N-1}/x_o) &= \max_{u_o,\ldots,u_{N-1}} \mu_D(u_o,\ldots u_{N-1}/x_o) \\ &= \max_{u_o,\ldots u_{N-1}} (\mu_{Co}(u_o)\wedge\ldots\wedge\mu_{C_{N-1}}(u_{N-1})\wedge\mu_{G_N}(x_N)) \end{aligned} \tag{3.7}$$

or,

$$\mu_D(u^*_o,\ldots,u^*_{N-1}/x_o) = \max_{u_o,\ldots,u_{N-1}} (\mu_{C_o}(u_o)\wedge\ldots\wedge\mu_{C_{N-1}}(u_{N-1})\wedge\mu_{G_N}(f(x_{N-1},u_{N-1}))) \tag{3.8}$$

We see here that $\mu_{C_{N-1}}(u_{N-1})$ and $\mu_{G_N}(f(x_{N-1},u_{N-1}))$ depend on the control, u_{N-1}; therefore, the maximization problem can be split into two components: one over the control sequences, $u_0,\ldots,u_{N-2}$, and the other over u_{N-1}.

Continuing with this analysis as a backward iteration, the process shows the essence of the dynamic programming approach. The recurrence equations will be as follows:

$$\mu_{G_{N-1}}(x_{N-1}) = \max\,(\mu_{C_{N-1}}(u_{N-1}) \wedge \mu_{G_{N-i+1}}(x_{N-i+1})) \qquad (3.9)$$

with

$$x_{N-i+1} = f(x_{N-1},u_{N-1}) \qquad i = 1,\ldots,N \qquad (3.10)$$

where $\mu_{G_{N-1}}$ may be viewed as the fuzzy goal at time $t = N - i$ induced by the fuzzy goal at time $t = N-i+1$.

3.2 OPTIMAL OPERATION OF A MULTIPURPOSE RESERVOIR AS A SYSTEM UNDER A FUZZY ENVIRONMENT

A typical multipurpose reservoir can serve several uses or purposes such as municipal and industrial water supply, irrigation demand, energy production, flood control, water quality control, fish life maintenance and recreation.

An optimal operation of such a system, on a monthly scale, is mainly focused on finding a set of optimal releases for a given initial volume into the reservoir and a given set of monthly inflows, which should meet the demand targets of the given objectives and optimize an objective function, subject to a set of restrictions on its operation. Of course, these different demands are sometimes competitive or complementary and trade-off issues arise in the operation of a multipurpose reservoir.

A standard formulation of a multipurpose reservoir operation problem has been, for instance, to maximize an objective function, which considers the benefits obtained from the given objectives for a particular set of releases. The solution represents the non-inferior solution of the problem or the compromise solution in which no decrease can be obtained in any of the objectives without causing a simultaneous increase in at least one of the other objectives.

Another way may be to formulate the objective function in terms of penalties which are applied each time the target requirements, for the given set of objectives, are not met; in this case, the objective function attempts to minimize the sum of penalties over the yearly operation of the reservoir. Again, the set of releases optimizes the objective function and represents the non-inferior solution to the problem. In any of these cases the formulation of the problem and the expected solution is expressed in terms of crisp sets.

In the case of considering the operation of a multipurpose reservoir under a fuzzy environment, fuzziness may be attached to the formulation of an objective or water use and/or a constraint or target, considering them as not defined in a precise way, but rather, as characterized by an imprecise feature.

On one hand, this imprecision may be due to a subjective attribute added to their formulation. For instance, traditional water uses like water supply, hydropower and flood control might be susceptible to being formulated imprecisely.

On the other hand, quantifiable but non-commensurate objectives may be treated as objectives characterized by fuzziness. Thus, non-commensurate objectives like environmental and recreational objectives would not need to be expressed in monetary terms to be incorporated into a multiobjective problem.

3.2.1 The Fuzzy Approach

The algorithmic approach for solving a reservoir operation problem under a fuzzy environment is developed around the theoretical framework presented by Bellman and Zadeh (1970) and Kacprzyk (1983).

For the purposes of this research, fuzziness is considered in terms of the imprecision attached to the expected ending volume at the end of the yearly operation of the reservoir and its correspondent water purposes. However, additional constraints or goals may be added to the formulation of the problem: either they are fuzzy in nature or are susceptible to being considered as fuzzy. For instance, monthly target volumes into the reservoir could be considered as fuzzy constraints if their membership functions were available.

3.2.1.1 The fuzzy goal

During reservoir operation planning it is common to assume the reservoir is operated, for N stages, so that it starts full at the beginning of stage 1 and ends full at the end of stage N. In a real situation, the reservoir may start full at stage 1 and usually ends up in the neighborhood of its full active capacity, at the end of stage N. This situation reflects a characteristic of imprecision regarding the target volume to be reached at the end of the planned time horizon.

Such a vagueness referenced above is suitable to be accommodated into Bellman and Zadeh's approach in terms of the fuzzy goal. The stored volume to be reached at the end of the planned time horizon represents the fuzzy goal.

3.2.1.2 The fuzzy constraints

In the case of the formulation of a standard multiobjective problem, the objectives can be accommodated into it as constraints. An analogous procedure can be followed in the case of a fuzzy decision-making problem; the set of objectives or water uses may be incorporated in the formulation of the problem as fuzzy constraints. Fuzziness may be added either as a subjective attribute qualifying, through its respective membership function, the attainment of the fuzzy constraint, or by considering a non-commensurate objective as fuzzy in nature.

Thus, subjective attributes, which are ubiquitous in the daily common language of water resource issues, as *efficient, adequate, reliable, suitable, dependable, very close to,* etc., may be incorporated in the formulation of such fuzzy constraints. For instance, a formulation of a fuzzy constraint may be "an adequate municipal and industrial water supply," "a suitable fish habitat," or "volume at month i should be very close to...," etc.

3.2.1.3 The system under control

The reservoir storage at any month, t, is considered to be the system under control. The mass balance equation becomes the transition relationship to go from storage at month (t) to storage at month (t+1). The state space is non-fuzzy (or crisp space) (Kacprzyk, 1983).

Thus, the state transition equation is represented by the mass balance equation:

In non-inverted form,

$$X_{t+1} = X_t + I_t - Q_t - E_{v_t} - R_t \qquad (3.11)$$

In inverted form,

$$Q_t = X_t - X_{t+1} + I_t - Q_t - E_{v_t} - R_t \tag{3.12}$$

where: X_{t+1} = storage at the beginning of month (t + 1);

X_t = storage at the beginning of month t;

I_t = deterministic inflow at month t;

Q_t = release from the reservoir at month t;

E_{v_t} = evaporation from the surface of the reservoir at month t; and

R_t = other losses from the reservoir or water demands downstream.

3.2.2 The Fuzzy Dynamic Programming Approach

The fuzzy dynamic programming approach to be presented here is intended to be used to solve a multipurpose reservoir operation problem. Two cases are considered:

1. The deterministic case; and
2. The implicit stochastic case.

3.2.2.1 Deterministic case

It is assumed that the state space (reservoir storages), $X = \{x_1,...,x_n\}$, and the control space (releases from the reservoir), $Q = \{q_1,...,q_m\}$, are finite.

The state transitions of the system under control are governed by the inverted form of the mass balance equation,

$$Q_t = X_t - X_{t+1} + E_{v_t} - R_t \tag{3.13}$$

The initial state at time t = 1 is X_1, and the termination time or number of stages is N. At each stage t, a decision variable, $Q_t \in Q$, is subjected to a fuzzy constraint, $C_t \subseteq Q$, (a reservoir purpose in this case) characterized by its fuzzy number, $\mu_{r_t}(Q_t)$. At stage N, a fuzzy goal or target $G_{N+1} \subseteq X$ is imposed on the final state, X_{N+1}, characterized by its fuzzy number, $\mu_{G_{N+1}}(X_{N+1})$.

Then, the decision becomes the intersection of a fuzzy goal and fuzzy constraints. Thus, we will have:

3.2.2.1.1 With minimum operator

$$\mu_D(Q_1,...,Q_N/X_1) = \mu_{C_1}(Q_1)\wedge...\wedge\mu_{CN}(Q_N)\wedge\mu_{GN+1}(X_{N+1}) \quad (3.14)$$

3.2.2.1.2 With weight sum operator

$$\mu_{C_t}(Q_t) = \Sigma w_j \cdot \mu_{Cj} \qquad t = 1,2,...,N \quad (3.15)$$

$$j = 1,2,...,m \text{ objectives,}$$

and

$$\mu_D(Q_1,...,Q_N/X_1) = \mu_{C_1}(Q_1)\wedge...\wedge\mu_{C_N}(Q_N)\wedge\mu_{G_{N+1}}(X_{N+1}), \quad (3.16)$$

where: w_j = weight coefficient assigned to the objective, j; and

$X_{(N+1)}$ = expressed by $X_1,Q_1,...,Q_N$.

If a backward dynamic programming process is used, then the task is to find an optimal sequence of releases from the reservoir, $Q^*_1,...,Q^*_N$, so that,

$$\mu_D(Q_1^*,...,Q^*_N/X_1) = \max_{Q_1,...,Q_N} \mu_D(Q_1,...,Q_N/X_1) \quad (3.17)$$

$$= \max_{Q_1,...,Q_N} (\mu_{C_1}(Q_1\wedge...\wedge\mu_{C_N}(Q_N)\wedge\mu_{G_{N+1}}(X_{N+1}) \quad (3.18)$$

$$\mu_D(Q^*_1,...,Q^*_N/X_1) = \max_{Q_1,...,Q_N} (\mu_{C_1}(Q_1)\wedge...\wedge\mu_{C_N}(Q_N)\wedge\mu_{G_{N+1}}(f(X_N,Q_N))) \quad (3.19)$$

Here we see, for instance, $\mu_{C_N}(Q_N)$ and $\mu_{G_{N+1}}(f(X_N,Q_N))$ depend only on the release Q_N and not on other previous releases. So, the maximization problem can be divided into two parts: one over the release sequence $Q_1,...,Q_{N-1}$, and the other one over Q_N. Thus,

$$\mu_D(Q_1,....,Q_N/X_1) = \max_{Q_1,...,Q_{N-1}}(\mu_{C_1}(Q_1)\wedge...\wedge\mu_{C_{N-1}}(Q_{N1})\wedge\max(\mu_{C_N}(Q_N) \wedge\mu_{G_{N+1}}(f(X_N,Q_N))) \quad (3.20)$$

If we repeat this backward iteration, a dynamic programming process will emerge. Then, the recurrence equation is

$$\mu_{Gt}(X_t) = \max_{Qt}(\mu_{Ct}(Q_t)\wedge\mu_{G_{t+1}}(X_{t+1})) \quad (3.21)$$

subject to:

$$Q_t = X_t - X_{t+1} + E_{v_t} - R_t \quad (3.22)$$

$$Vmin(t) \le X_t \le Vmax(t) \quad (3.23)$$

$$Qmin(t) \le Q_t \le Qmax(t), \quad (3.24)$$

where: X_1 = initial storage at month 1;

Vmin(t) = minimum volume into the reservoir at month, t;

Vmax(t) = maximum volume into the reservoir at month, t;

Qmin(t) = minimum release from the reservoir at month, t; and

Qmax(t) = maximum release from the reservoir at month, t.

3.2.2.2 Implicit stochastic case

As is pointed out by Ouarda (1991) and Bhatti (1990), the implicit stochastic case approach has been widely used for the optimization of reservoir operation (Young, 1967; Roefs, 1968; Croley, 1977; etc.). The idea behind it, in order to avoid the necessity of developing transition or marginal probabilities, is to replace a stochastic problem with a series of deterministic problems.

Three main steps may define an implicit stochastic optimization procedure. First, based on the historical inflows, a time series model can be determined and a large number of synthetic sequences of equally probable inflows can be generated. Second, using a deterministic optimization model, optimal releases and storage levels are found for each inflow sequence. The next step involves fitting the data, generated by the optimization model, either to linear or non-linear regression models. Those models will reflect the stochasticity of either the storages or the releases (Labadie, 1991).

In this case, a number of N realizations of annual sequences of monthly inflows can be generated. Autoregressive models like seasonal time series models might be used to generate a number of possible realizations of stochastic monthly inflows, whose general form is presented in Salas *et al.* (1980).

Once the number of possible realizations has been generated, the deterministic fuzzy dynamic programming model can be applied to find optimal releases and storage levels over the entire period of analysis.

Third, a multiple linear or nonlinear regression analysis can be performed to find monthly operational rules. The dependent variable is usually represented either by the release, Q_t, or the ending stored volume at month t, V_t; and the independent variables may be the releases, Q, the inflows, I, or the ending storages, V, at previous months t-1, t-2, etc. For instance, a decision rule model may be represented as follows:

$$V_t = f(V_{t-1}, I_{t-1}, V_{t-2}, Q_{t-1}, \ldots) \qquad (3.25)$$

or,

$$Q_t = f(V_{t-1}, I_{t-1}, V_{t-2}, Q_{t-1}, \ldots), \tag{3.26}$$

and a linear model with the ending storage at month t, V_t, as a function of the ending storage at month t-1, V_{t-1}, and the inflow at month t-1, I_{t-1}, would be as follows:

$$V_t = a\, V_{t-1} + b\, I_{t-1} + c \tag{3.27}$$

The next step is to apply these models or operating rules to predict either the monthly storages or monthly releases. Then, a simulation model based on the mass balance equation can be applied to find the simulated releases, Q_t, and storages, V_t. In the case of having operating rules to predict storage levels, the simulated releases can be computed as follows.

A mass balance equation will look like this,

$$Q_t = V_t - V_{t+1} + E_{v_t} - R_t \tag{3.28}$$

subject to:

$$V_t + I_t \geq V_{t+1}, \text{ otherwise } \quad V_{t+1} = V_t + I_t \tag{3.29}$$

$$Qmin_t \leq Q_t \leq Qmax_t \tag{3.30}$$

$$Vmin_t \leq V_t \leq Vmax_t \tag{3.31}$$

To know how well the operational rules perform, the final set of simulated storages, V_t, and releases, Q_t, may be compared against the optimal releases and storages.

Next, the simulated storages and releases are used to find the respective membership functions, $\mu(V_t)$ or $\mu(Q_t)$, of the fuzzy goal and/or constraints. Finally, in order to make decisions about the operational policies in the long term, expected values and variation coefficients can be evaluated to assess the achievement of the fuzzy goal and fuzzy constraints.

CHAPTER 4

CASE STUDY

4.1 THE GREY MOUNTAIN RESERVOIR PROJECT

4.1.1 Background

The construction of water storage projects on the Cache La Poudre River have been proposed for many years. The Bureau of Reclamation was responsible for conducting investigations in 1928, 1954, 1959 and 1963. In the 1970's the Poudre River upstream of the canyon mouth was proposed as a part of the National Wild and Scenic River System. As a result, segments of the Poudre River were designated as either wild or recreational for 75 miles of the river's 83 miles above the mouth of the canyon. Thus, the 8 miles of the river between the community of Poudre Park and the canyon mouth have remained potentially available for future water projects.

Under a preliminary permit, the Northern Colorado Water Conservancy District (NCWCD) was given a grant to study the feasibility of considering hydroelectric power generating components in the framework of a multi-purpose project. This proposed configuration was composed of three reservoirs: Glade Reservoir, Grey Mountain Reservoir and Greyrock Mountain Reservoir. As a result of a comparison study of seven proposed alternatives, Grey Mountain Reservoir was selected to be developed in stage 1 (see Figure 4.1). Grey Mountain Reservoir is planned to be placed on the mainstream of the Cache La

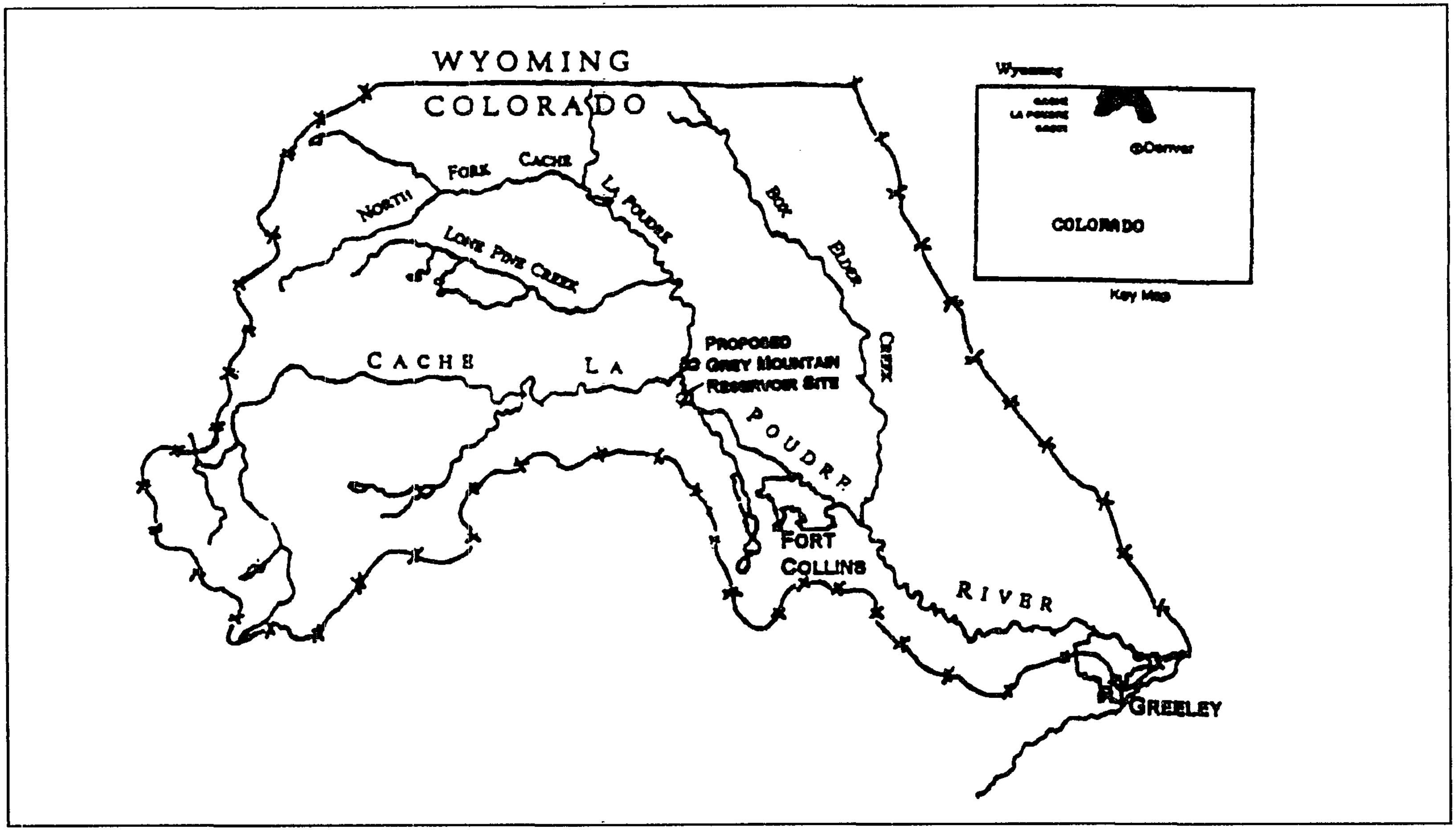


FIGURE 4.1 Grey Mountain Reservoir location.

Poudre River (Harza, 1990; Grigg, 1985). This reservoir would store approximately 200,000 acre-ft of water storage, and it would be used to deliver water by gravity to Glade Reservoir to provide flood protection for the city of Fort Collins, power generation from releases to the Poudre River through a conventional hydroelectric power plant, and afterbay reservoir for a separated pumped-storage hydroelectric power plant placed either above or below ground on the north shore of the reservoir. Grey Mountain Reservoir provides multipurpose features. The purposes identified and evaluated in the basin study extension stage were primarily, municipal and industrial water supply, power generation, recreation, and flood control.

4.1.2 Location

The site for the Grey Mountain Dam is located about two miles upstream from the mouth of the Poudre Canyon on the Cache La Poudre River in northern Colorado. Data extracted from the basin study (Harza, 1987) indicated that a gross storage volume of 195,000 acre-ft (241 MCM) could be provided at the Grey Mountain site, with an estimated maximum normal reservoir water surface elevation (NWS) of 5,630 ft. An active storage of 185,000 acre-ft (229 MCM) would be considered. Additional flood control space of 12 MCM is provided above the active storage. General characteristics of Grey Mountain reservoir are shown in Table 4.1.

4.1.3 Operational Characteristics

According to the final report on the Cache La Poudre River Basin study issued by Harza Engineering Company (1990), the Northern Colorado Water Conservancy District

TABLE 4.1 General characteristics of Grey Mountain Reservoir.

	U.S. CUSTOMARY UNITS	SI UNITS
DAM AND RESERVOIR CHARACTERISTICS		
1. Maximum height	415 ft	126.5 m
2. Total capacity	195,000 acre-ft	241 MCM
3. Active capacity	185,000 acre-ft	229 MCM
4. Flood control space	10,000 acre-ft	12 MCM
5. Spillway capacity	122,000 cfs	3,455 m^3/s
6. Reservoir area at maximum water surface	1,600 acres	634.92 ha
7. Firm yield	41,000 acre-ft/year	51 MCM/year
HYDROELECTRIC POWER PLANT CHARACTERISTICS		
1. Installed capacity	18 to 24 MW	18 to 24 MW
2. Average annual energy production	39 to 52 GWh	39 to 52 GWh
3. Average capacity factor	0.25	0.25

Source: Harza Engineering Company, 1990

carried out hydrologic modeling of the whole reservoir system in the area of the Poudre River Basin. Grey Mountain Reservoir was considered as a component of this system and its operation would involve:

1. Storing high native inflows from Poudre Basin and import water from Colorado-Big Thompson and Windy Gap systems to meet further downstream demands (seasonal regulation) or prevent a potential drought in a subsequent year.
2. Providing flows for recreation purposes such as fishing, rafting, etc.
3. Producing power energy by passing downstream demand releases through a conventional hydroelectric powerplant.
4. Protecting downstream locations from potential floods.
5. Meeting minimum flow requirements for fishing habitat.

Municipal and industrial water supply is considered to have an average annual demand of 41,000 acre-ft (51 MCM). In the case of power generation, releases for downstream demands could be passed through a conventional hydropower plant. An estimated average of 39 to 52 GWh per year would be produced.

Recreation purposes are assumed to be composed of different types of recreation activities such as boating, angling, camping, downstream rafting, kayaking, etc. Boating and angling are recreational activities on the reservoir and kayaking and rafting are activities downstream from the reservoir. The projected number of annual recreation visits is shown in Table 4.2.

TABLE 4.2 Projected number of annual recreation visits.

ACTIVITY	INITIAL	MAXIMUM
1. Power Boating	12,860	42,880
2. Wakeless Boating	6,340	21,120
3. Camping	2,400	12,000
4. Picnicking	2,400	12,000
5. Shore Angling	2,000	10,000

Source: Harza Engineering Company, 1990.

The recreation purpose is analyzed in the report only from what benefits would be generated and how much it would cost to implement recreation facilities.

Minimum flow requirements are considered as one of the assumptions of the simulation model run by NCWCD. Minimum flow requirements are assumed to be in the range of 25 cfs (1.84 MCM/month) to 50 cfs (3.67 MCM/month) for periods from October 14 to April 15 and April 15 to October 14, respectively. However, the study concludes that minimum flow requirements should be determined during future consultations with natural resource agencies. The purpose of flood control is assumed to be met by Grey Mountain

Reservoir. An entire 100-year flood, as it was estimated by the Corps of Engineers, could be stored in the reservoir without any allocation of storage for flood control.

4.2 FORMULATION OF THE RESERVOIR OPERATION PLANNING PROBLEM

Grey Mountain Reservoir is planned to be a multipurpose reservoir. The main purposes identified from the final report issued by Harza Engineering Company (1990) are as follows:

1. Municipal and industrial water supply
2. Energy production
3. Flood control space
4. Recreational use
5. Fish habitat needs

Basically, this water resource project is considered as a case study because of its multipurpose features and the presence of objectives like recreational uses and fish habitat needs, whose achievements are frequently difficult to evaluate. This makes it ideal to be analyzed as a fuzzy optimization problem in which the objective and the constraints are formulated in an imprecise form.

In the case of the Grey Mountain Reservoir, the formulation of its operation is based on starting such operation with the reservoir at full active volume level. In this case, the fuzzy nature of the problem arises from the subjectivity associated with the prescription of the storage goal and in the definition of each constraint as a subjective or linguistically described attribute.

Thus, in accordance with the theoretical framework of a fuzzy decision-making problem, the final stored volume to be obtained at the end of the year may be considered as the fuzzy goal and the set of monthly water uses or objectives as the fuzzy constraints. The fuzzy goal is considered fuzzy by itself and each fuzzy constraint is considered to be qualified by a subjective attribute.

Then, the formulation of the optimization problem would be as follows:

Obtain the fuzzy goal.

Stored volume at the end of September (the end of the water year) will be in the *neighborhood* of the total active volume.

Satisfy the following fuzzy constraints.

1. *Adequate* Municipal and Industrial Water Supply
2. *Dependable* Flood Control Space
3. *Efficient* Hydropower
4. *Enjoyable* Rafting
5. *Enjoyable* Kayaking
6. *Adequate* Angling
7. *Suitable* Fish Habitat

4.3 DATA COLLECTION

4.3.1 Hydrological Data

Hydrological data are represented by monthly inflows from the Poudre River. The final report of the Cache La Poudre River Basin issued by Harza Company (1990) contains the monthly inflows in the Poudre River during the period of 1954–1983 (see Table 4.3).

TABLE 4.3 Monthly inflows in the Poudre River during the period 1954-1983.

GREY MOUNTAIN RESERVOIR

NAME OF RIVER BASIN : CACHE LA POUDRE
NAME OF GAGING STATION: LAPORTE
TYPE OF DATA AND UNITS : Monthly discharges in acre-ft
PERIOD OF RECORD: 1954-1983

NUMBER OF YEARS 30
NUMBER OF SEASONS 12

THE SAMPLE SERIES

	1	2	3	4	5	6	7	8	9	10	11	12
1	3386.000	1940.000	2010.000	1940.000	1554.000	1554.000	2921.000	25403.000	34125.000	15040.000	3722.000	5693.000
2	4970.000	1634.000	1049.000	1208.000	911.000	1228.000	1960.000	21859.000	60321.000	27908.000	15484.000	4316.000
3	3049.000	2287.000	2435.000	1693.000	1396.000	1911.000	3455.000	72052.000	86477.000	24295.000	11553.000	3198.000
4	2020.000	1208.000	1584.000	1277.000	1346.000	1426.000	6989.000	35174.000	134937.000	103554.000	20127.000	9623.000
5	5000.000	2693.000	2614.000	2089.000	2059.000	2663.000	10821.000	91872.000	95169.000	16097.000	4029.000	3227.000
6	3148.000	1861.000	2000.000	1634.000	1980.000	3039.000	11999.000	43709.000	102762.000	24562.000	10712.000	4029.000
7	4485.000	3713.000	1139.000	1059.000	764.000	3000.000	5495.000	49688.000	95783.000	27631.000	6475.000	4188.000
8	2990.000	1697.000	1542.000	2249.000	1643.000	2800.000	7865.000	70100.000	116622.000	31914.000	18735.000	11670.000
9	16178.000	6724.000	3211.000	3595.000	5698.000	5413.000	19215.000	68809.000	84752.000	45892.000	11290.000	2216.000
10	3778.000	2095.000	1760.000	1095.000	1034.000	756.000	3992.000	27255.000	37729.000	12205.000	11684.000	7368.000
11	3707.000	2115.000	982.000	830.000	853.000	1546.000	2297.000	35757.000	65720.000	31409.000	10799.000	4439.000
12	1851.000	1024.000	776.000	832.000	861.000	863.000	2526.000	32272.000	129472.000	77075.000	25457.000	7556.000
13	4008.000	1051.000	1309.000	1166.000	1220.000	1667.000	2814.000	29781.000	33300.000	9708.000	6233.000	5861.000
14	2841.000	1441.000	798.000	737.000	566.000	1093.000	1857.000	26255.000	75731.000	43314.000	7138.000	4172.000
15	1679.000	3271.000	2823.000	2210.000	2525.000	1936.000	2982.000	28793.000	102644.000	40849.000	20251.000	6706.000
16	2566.000	2152.000	1677.000	1168.000	1036.000	1635.000	6279.000	50427.000	74151.000	35585.000	6884.000	7465.000
17	4186.000	1881.000	889.000	871.000	616.000	1437.000	5560.000	59037.000	108563.000	55826.000	17200.000	6249.000
18	4758.000	4202.000	1867.000	1851.000	1352.000	1954.000	11614.000	62231.000	141451.000	56400.000	13319.000	9540.000
19	2477.000	4505.000	2176.000	1632.000	1820.000	2172.000	3966.000	35941.000	85857.000	25336.000	5170.000	6233.000
20	3887.000	2625.000	1590.000	1459.000	1443.000	2051.000	3459.000	89254.000	123196.000	65406.000	22851.000	3742.000
21	5200.000	6506.000	3085.000	2398.000	2935.000	5687.000	7256.000	78705.000	107862.000	36893.000	6562.000	4681.000
22	4736.000	2738.000	1378.000	810.000	739.000	1148.000	2099.000	18757.000	86675.000	78778.000	7222.000	5936.000
23	3231.000	1695.000	1671.000	1535.000	1408.000	1513.000	2293.000	27682.000	64924.000	27284.000	18945.000	3522.000
24	4584.000	1598.000	1004.000	915.000	847.000	1348.000	2964.000	12525.000	39105.000	10484.000	14137.000	3734.000
25	2455.000	2222.000	1632.000	1416.000	1275.000	1616.000	3903.000	36097.000	127571.000	65982.000	19650.000	5839.000
26	2841.000	1786.000	1293.000	1152.000	931.000	1461.000	5013.000	51161.000	122859.000	59314.000	34547.000	8760.000
27	3315.000	1810.000	2643.000	5554.000	4368.000	9122.000	32698.000	158438.000	142085.000	41340.000	16814.000	6203.000
28	5120.000	4328.000	3089.000	1764.000	1093.000	1287.000	4469.000	22501.000	55363.000	20794.000	12294.000	5790.000
29	2156.000	1519.000	1546.000	1208.000	2996.000	1190.000	1956.000	23000.000	87236.000	80277.000	37788.000	9589.000
30	4291.000	2711.000	3412.000	2772.000	3879.000	5871.000	36521.000	108484.000	283199.000	136573.000	43531.000	12458.000

4.3.2 Data Acquisition for the Construction of Membership Functions

Collection of data was needed to build the membership functions of the fuzzy goal and constraints. Interviews of water resource experts and water users were considered as part of this research. The basic assumptions that underlined this activity were:

A. Conduct interviews in order to gain realistic information about the shape and features of the membership functions. Interviews were conducted of a representative group of water resources experts and water users of this region. This group included city managers, reservoir managers, water resource planners, fish and wildlife experts, and water users such as rafters, kayakers, and anglers. Their knowledge about the achievement of water uses was obtained through a questionnaire so their answers reflected their perception of the satisfaction of a particular water purpose.

B. Set up the questionnaires in such a way that they may reflect an acceptable procedure to qualify the achievement of the given goal and constraints considered as fuzzy.

C. Develop membership functions through the fitting of collected data to well-known functions used in fuzzy sets like the logistic function, trapezoidal function, S-shape function, etc. (Dombi, 1990).

To complete the data collection task, a set of questionnaires was prepared based on some of the guidelines presented by Rea and Parker (1992). Those basic guidelines referred mainly to the design of the questionnaires and how to administer them.

Factors like clarity, comprehensiveness and acceptability were considered at the time of the preparation of the questionnaires. First, a draft of the questionnaire was prepared and discussed with some selected water resources experts and water users. These included city water managers in Fort Collins, water resource planners from the Northern Colorado Water Conservancy District, the U.S. Bureau of Reclamation in Loveland, the Division of Wildlife in Fort Collins, the Fish and Wildlife Department in Fort Collins, faculty from the Civil Engineering Department and Natural Resources Recreation Department at Colorado State University, an angler, a rafter, and a kayaker with knowledge of the Poudre River conditions. The experts and water users were asked to contribute their suggestions about what kind of scales should be used in development of the membership functions: in the case of the horizontal scale, to represent the units of the measure of each objective; and in the case of the vertical scale, to represent the achievement of an objective, going from null satisfaction to full satisfaction.

The horizontal scale took advantage of the fact that fuzzy sets can also be defined in different spaces, for example, X_1 and X_2, which in turn are connected by some functional relationship of equivalence (Kacprzyk, 1983). For instance, to define a membership function of extreme temperatures, some people may feel more comfortable expressing their answers in a set X_1 like Fahrenheit degrees, while others may feel more comfortable in giving their answers in a set X_2 like Celsius degrees. However, both scales are clearly connected by a functional relationship of equivalence, and a common membership can be built for such purpose. Thus, water demand percentages, percentages of flood control space, percentages of energy demand, a gauge level in the Cache La Poudre River, and discharges in cfs were used to represent the horizontal scale of the membership function.

On the vertical scale, the membership function must be represented by a scale from 0 to 1, where 0 represents a null achievement and 1 represents full achievement. However, in the questionnaires this scale was set up from 0 to 10, which is considered to be a more appropriate scale for people in the U.S. when they qualify objects.

Before the questionnaire was applied, meetings were scheduled in advance to let the participants know the approach of the research and the objective of the questionnaire. Once they were aware of the basic idea of this research, an interview was scheduled and the questionnaire was administered individually.

Further, the collected data were organized such that they could be analyzed to define the requested membership functions. A copy of the questionnaire applied in the case of urban water supply is shown in Appendix A.

4.4 THE MEMBERSHIP FUNCTIONS

4.4.1 The Membership Function of the Fuzzy Goal

In accordance with Bellman and Zadeh (1970), the fuzzy goal is formulated as a function of the state variable (reservoir storage). For reservoir operation problems, the ideal final volume at the end of the yearly operation is the total active volume; fuzziness can be attached to it if we consider that in a real situation the total active volume is rarely reached precisely. Instead, because of the inflow's uncertainty, the reservoir may be ending either in a neighborhood of the full active volume or just at the total active volume.

Based on this assumption, one way that the fuzzy goal can be formulated is "the stored volume at the end of the water year will be in the neighborhood of the total active volume." The degree of neighborhood will be evaluated on a scale of 0 to 1 through its respective membership function.

4.4.1.1 Data acquisition

Grey Mountain Reservoir is planned to have a full capacity of 241 MCM, an active volume of 229 MCM, and additional flood control space of 12 MCM.

The basic approach for setting up this questionnaire was to establish some defined boundary conditions like, the total active volume and the full capacity of the reservoir. Based on these parameters and considering that the fuzzy goal is formulated in terms of the stored volume at the end of the yearly operation (September), the objective of the questionnaire was to get information from the water resource expert about how he would qualify the achievement of this fuzzy goal on a scale of 0 to 1 if the water volume in the reservoir were at some level either below, equal to or above the total active volume at the beginning of the yearly operation.

The horizontal scale was set up in terms of the stored volumes in MCM units, from 0 MCM to 241 MCM. The vertical axis was scaled from 0 to 1, with 0 representing a null achievement and 1 representing a full achievement.

4.4.1.2 Results and discussion

Two water resource planners who deal with multipurpose reservoir operation were interviewed. One of them works for the U.S. Bureau of Reclamation in Loveland (reservoir operator 1), and the other one used to work in the Fort Collins area (reservoir operator 2). The fact that the theoretical approach of ending the yearly operation of a reservoir with a full active volume is rarely reached in a real situation was discussed with them. They agreed with the goal statement presented above, and that made it possible to construct a fuzzy goal based on this statement.

The two reservoir operators agreed that a full achievement is obtained when the stored volume is between 229 MCM (full active volume) and 234 MCM (it includes a 40% of flood control space); then, reservoir operator 1 said that from 234 MCM to the full capacity (241 MCM), the achievement would decrease proportionally to a 0 achievement when the reservoir was at full capacity. Reservoir operator 2 stated the achievement would decrease to a 0 value when the reservoir was at a level just above 40% of flood control space, say 234.1 MCM. On the other hand, they agreed that a null achievement would be obtained for stored volumes less than or equal to 80% (183 MCM) of the total active volume, and from that level up to the total active volume, the achievement would increase proportionally (see Figure 4.2). Because the fuzzy goal is formulated for the end of the water year, the two operators agreed to restrict the lower limit of the available stored water to at least 80% of the total active volume of the reservoir. They did so because they would not like to start the yearly operation of the reservoir with a volume below such a storage level. On the other hand, they would also like to have some available flood control space because they might be expecting some last storms of the season whose inflows could be stored in the reservoir.

Thus, the shape of the fuzzy goal membership function corresponds to a trapezoidal function which is a type of unimodal function as is shown in Figure 4.2. This type of membership function is commonly mentioned in the literature of fuzzy sets (Kacrpzyk, 1983; Dombi, 1988; Savic and Simonovic, 1991). The range of volumes for achieving the goal with some positive degree of satisfaction was from 183 MCM to 241 MCM.

4.4.2 The Membership Functions of the Fuzzy Constraints

For this case study, and in order to be accommodated into the formulation of the fuzzy multiobjective problem, the objectives for water uses were treated as fuzzy contraints.

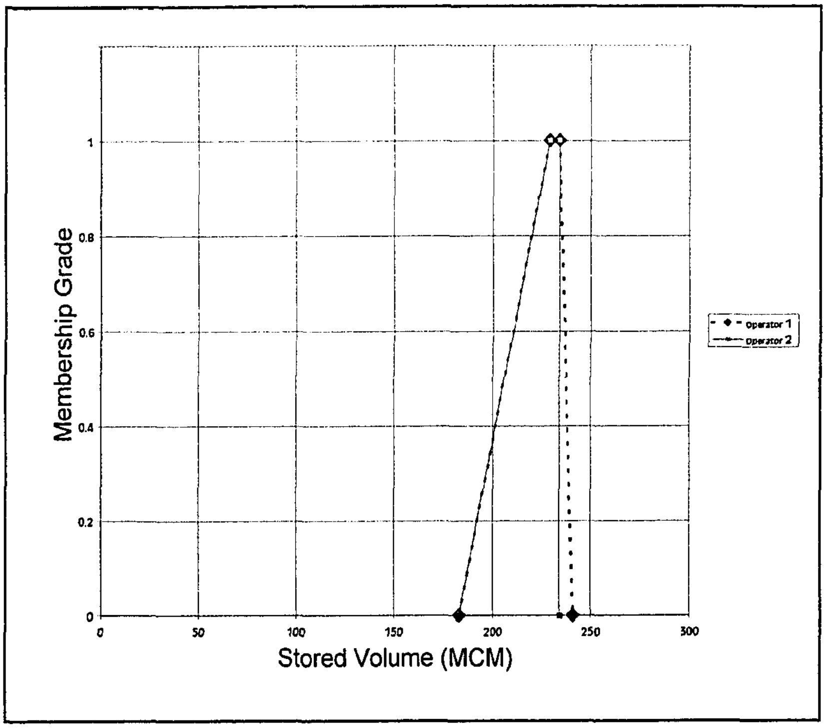


FIGURE 4.2 Membership function of the fuzzy goal.

To agree with the guidelines presented in Section 4.3.2, the collected data may be fitted to a continuous function. Functions like the logistic and the S-shape function with two parameters are evaluated, and the one that fits best is selected.

Piecewise linear functions may also be tried in the case of some objectives like angling and fish habitat. The plot of the collected data gives this type of curve, and an average curve can be found and used later as the appropriate one to be modeled.

4.4.2.1 Adequate municipal and industrial water supply

With this objective, a required annual demand is converted into a required monthly demand by using monthly demand coefficients. A shortage or surplus might occur depending on how much water is being released to satisfy the required monthly demand.

The degree of satisfaction of this objecive is measured in terms of percentages of water demand being met. A 100% value will mean satisfying 100% of the required monthly demand. A percentage less than 100% will mean a shortage is present, which is calculated as the difference between the required monthly demand and the delivered monthly discharge, divided by the required monthly demand. A percentage greater than 100% will mean that a surplus is occurring, which in turn can be computed as the difference between the delivered monthly discharge and the required monthly demand, divided by the required monthly demand. Thus, a required monthly demand will be fully or less satisfied depending on how much water is released from the reservoir.

The subjective attribute **adequate** is intended to be used for qualifying the achievement of the municipal and industrial water supply purpose, considering that the Grey Mountain Reservoir is going to be a part of the Cache La Poudre River in northern Colorado. Thus, the **adequate** attribute is formulated to mean the satisfaction of the monthly urban water demand in cities surrounding the reservoir project.

4.4.2.1.1 Data acquisition

The final report issued by Harza Engineering Company (1990) gives information about the annual required municipal and industrial water demand and the monthly water demand coefficients. The annual required demand is considered to be 41,000 acre-ft (51 MCM). The monthly required water demand can be calculated as a function of the annual required demand multiplied by a monthly demand coefficient. Those water demand coefficients and water demand are presented in Table 4.4.

Two water resource experts were interviewed: the city water manager of Fort Collins and the city water manager of Loveland. The questionnaires were applied in a person-to-person interview.

TABLE 4.4 Municipal and industrial water demand.

MONTH	MONTHLY COEFFICIENT	WATER DEMAND (MCM)
1. January	0.02	1.02
2. February	0.03	1.53
3. March	0.03	1.53
4. April	0.06	3.06
5. May	0.09	4.59
6. June	0.15	7.65
7. July	0.20	10.20
8. August	0.18	9.18
9. September	0.12	6.12
10. October	0.07	3.57
11. November	0.03	1.53
12. December	0.02	1.02

The horizontal scale of the membership function was set up as percentages of the monthly required water demand. Thus, 100% meant that the released water would be equal to the monthly target demand, and values less or greater than 100% meant that water was released in quantities less or greater than those target water requirements.

The questionnaire was set up to collect information on a monthly basis regarding how a water resource expert would qualify the achievement of such an objective.

4.4.2.1.2 Results and discussion

Both managers agreed that a membership function could be formulated for every season (fall, winter, spring and summer). In Figures 4.3, 4.4, 4.5 and 4.6 we see that each developed membership function corresponds to a non-decreasing function.

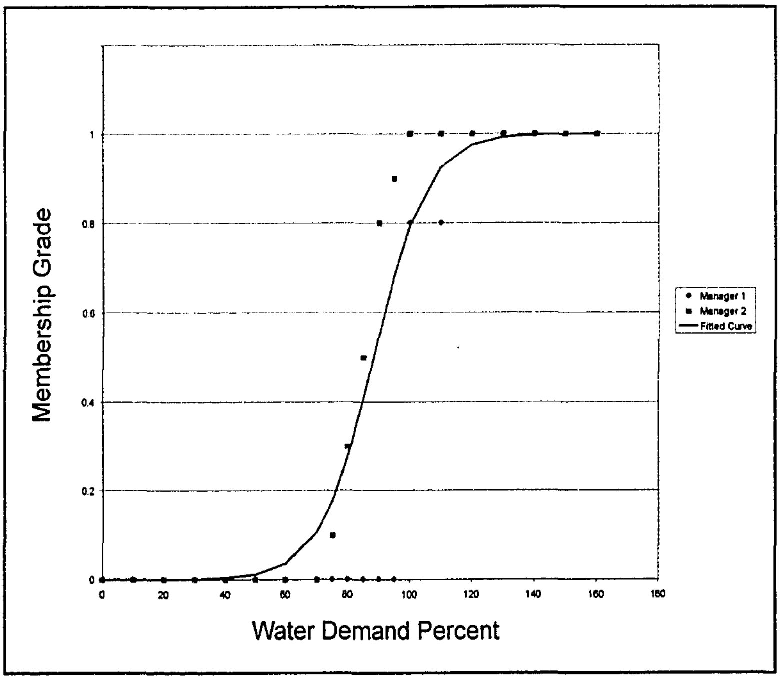


FIGURE 4.3 Adequate municipal and industrial water supply membership functions for fall.

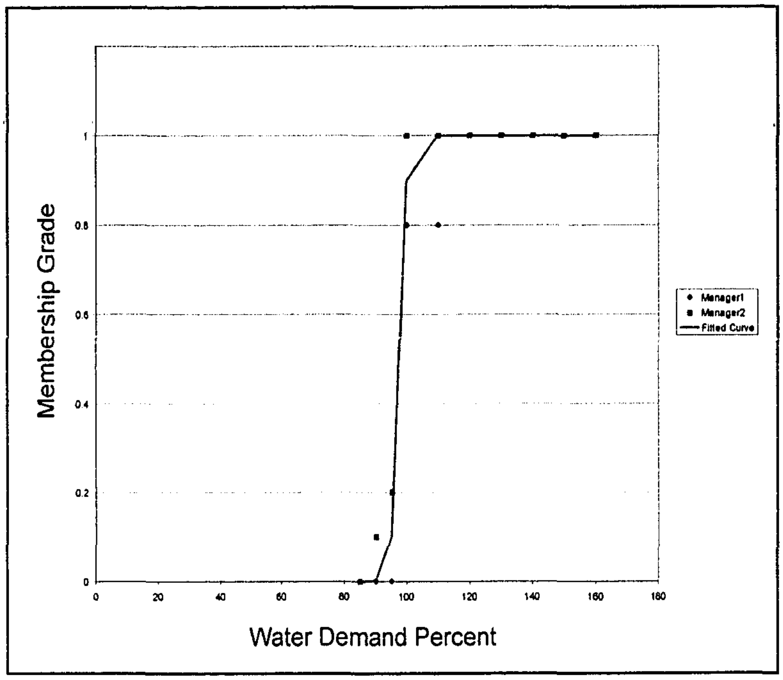


FIGURE 4.4 Adequate municipal and industrial water supply membership functions for winter.

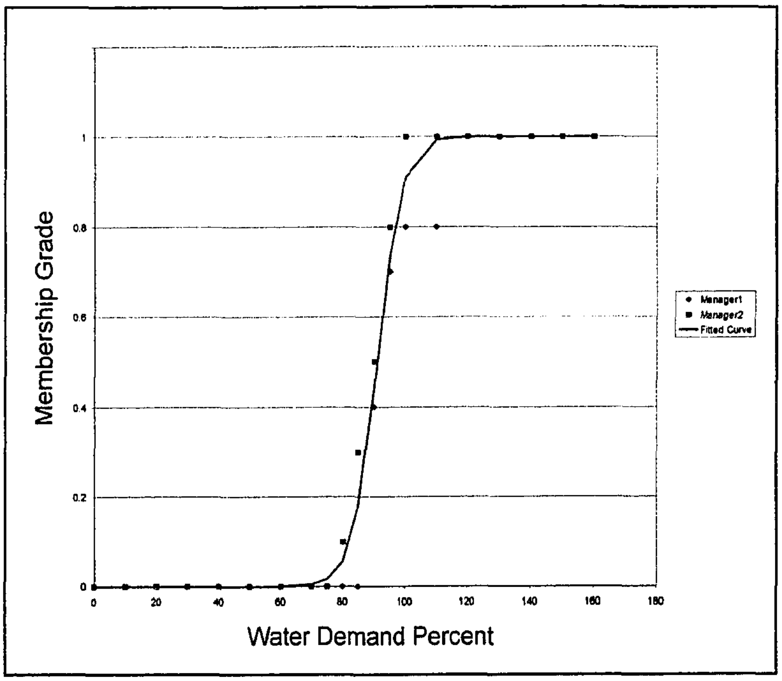


FIGURE 4.5 Adequate municipal and industrial water supply membership functions for spring.

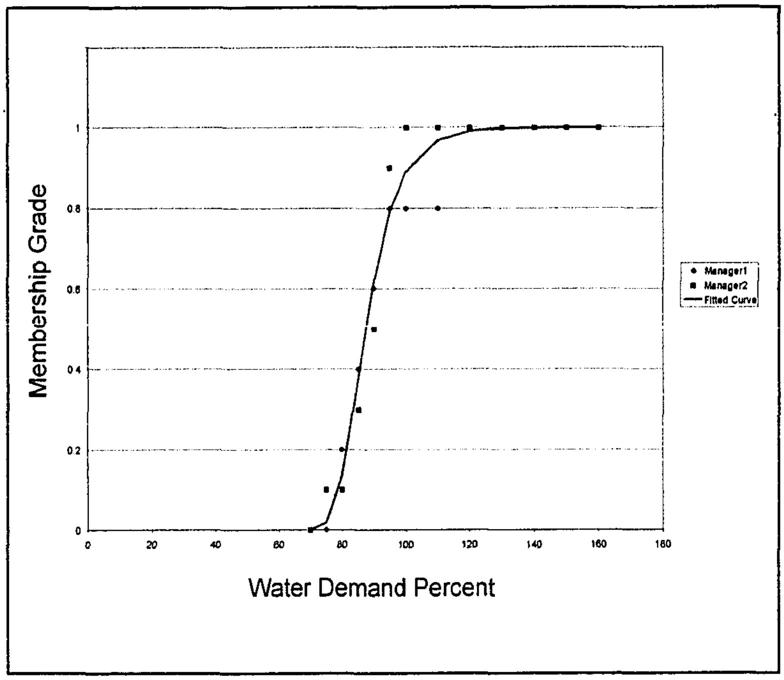


FIGURE 4.6 Adequate municipal and industrial water supply membership functions for summer.

Analyzing these figures, we see that the city managers are willing to accept only small shortages over the year. This is explained by the sharp slope of the curve, and it shows their concern about the great importance of water supply for cities. Moreover, if more water than the required monthly demand were available, because of the delivery system capacity, they would accept only deliveries up to a surplus of 50% or 60% above the required demand. The equations of the functions which presented the best fit are presented in Table 4.5.

TABLE 4.5 Municipal and industrial water supply membership functions.

SEASON	$\mu(x) = 1/(1 + \exp(-a(x - b)))$	R^2
1. Fall	$\mu(x) = 1/(1 + \exp(-0.116(x - 88.33)))$	0.74
2. Winter	$\mu(x) = 1/(1 + \exp(-0.8735(x - 97.49)))$	0.96
3. Spring	$\mu(x) = 1/(1 + \exp(-0.256(x - 90.95)))$	0.95
	$\mu(x) = ((1 - v)^{r-1} (x - a)^r) / ((1 - v)^{r-1} (x - a)^r + v^{r-1} (b - x)^r)$	
4. Summer	$\mu(x) = 0.9^{1.847}(x - 70)^{2.847}/(0.9^{1.847}(x - 70)^{2.847} + 0.1^{1.847}(160 - x)^{2.847})$	0.97

According to Zimmerman (1987), parameter b of the logistic function (fall, winter and spring seasons) can be used for defining the point at which the attitude of the interviewed people, in evaluating the achievement of an objective, changes from positive to negative. In this case, a value of 88.33% of water demand for fall indicates a positive attitude for the achievement of this purpose up to 88%; a value of 97.49% of water demand in the winter indicates a positive attitude up to 97%; beyond those values the attitude toward the achievement is considered negative. This is in accordance with the fact that in the fall the operation of the reservoir starts with a considerable amount of stored water, so more shortages may be allowed for that season than in the winter season.

4.4.2.2 Dependable flood control space

In regard to the objective for flood control space, two seasons are identified: a high season from May to July and a low season from August to April.

The approach used here assumes that the reservoir has a given flood control space, FCS_0, which is equal to the difference between the maximum capacity of the reservoir, Vmax, and the total active volume, Vact.

At the beginning of any month, t, the stored volume X_t may be at any of the three following conditions:

X_t < Vact

X_t = Vact

X_t > Vact

In the case of X_t < Vact, the flood control space in that month, FCS_t, will be greater than the given flood control space, FCS_0, and more than 100% of flood control space will be available.

When X_t = Vact, the flood control space in that month, FCS_t, will match the given flood control space, FCS_0, and 100% of flood control space will be available.

In the case of X_t > Vact, the flood control space in that month, FCS_t, will be less than the given flood control space, FCS_0, and less than 100% of flood control space will be available.

A good operational rule will be to keep the flood control space empty of water as much as possible, especially in the summer season when higher inflows are expected to enter the reservoir.

4.4.2.2.1 Data acquisition

The horizontal scale of the membership function is set up to be a percentage of the given flood control space. So, a value of 100% means that the flood control space at month t is equal to the given flood control space; values less or greater than 100% means that the flood control space at month t is less or greater than the given flood control space, respectively.

The questionnaire was set up on a scale of 0 to 10 to reflect how a water manager would quantify the achievement of this purpose, formulated as a dependable flood control space. The measurement of the achievement of this objective was on a scale from 0 to 10, where 0 meant null achievement and 10, full achievement.

The horizontal scale was set up to consider percentage values from 0% to 160% of available flood control space. A 0% of available flood control space would mean that the active volume would be taking the place of the flood control space and 160% of the available flood control space would be represented by the given flood control space plus some storage space belonging to the active volume storage.

The subjective attribute **dependable** is considered in this case to reflect reliability conditions in regard to preventing floods by storage in the available flood control space over the year, especially in the summer season.

In the case of the Grey Mountain Reservoir, a storage of 12 MCM is considered adequate for flood control purposes, which could store a flood with a 100-year return period.

4.4.2.2.2 Results and discussion

Two reservoir managers were interviewed, a reservoir manager from the U.S. Bureau of Reclamation in Loveland, a water resource manager from the Northern Colorado Water Conservancy District in Loveland, and a water resource manager who used to work in the Fort Collins area and is currently involved in multipurpose reservoir operation activities. Figures 4.7, 4.8 and 4.9 show the membership functions of this fuzzy constraint for the high flow season (May, June and July), with the remainder to be included in Appendix B; we see in this case that the three managers agreed that if 100% of flood control space were available, the degree of membership would be 1. Available flood control spaces, FCS_t, greater than the given flood control space, FCS_o, were also assigned a value of 1.

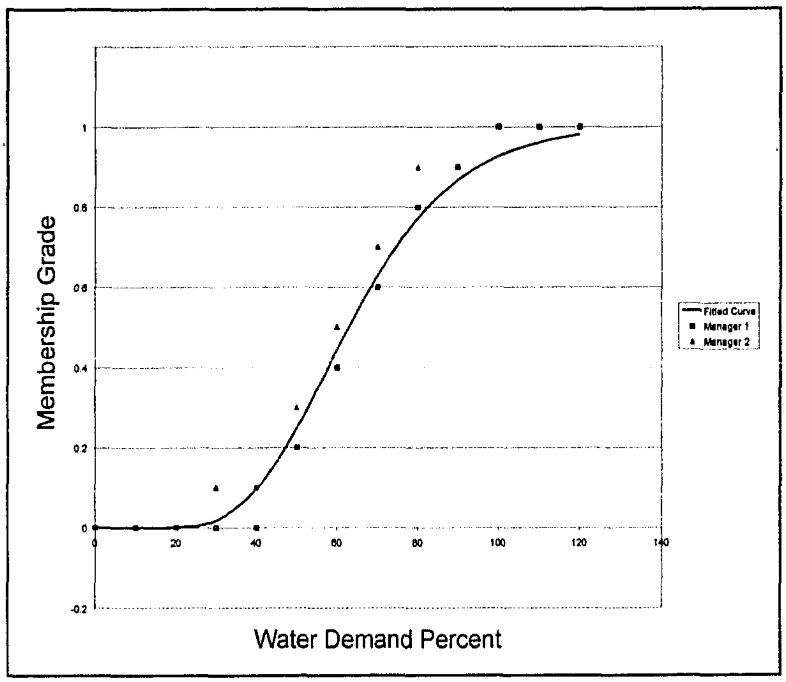


FIGURE 4.7 Dependable flood control space membership function for May.

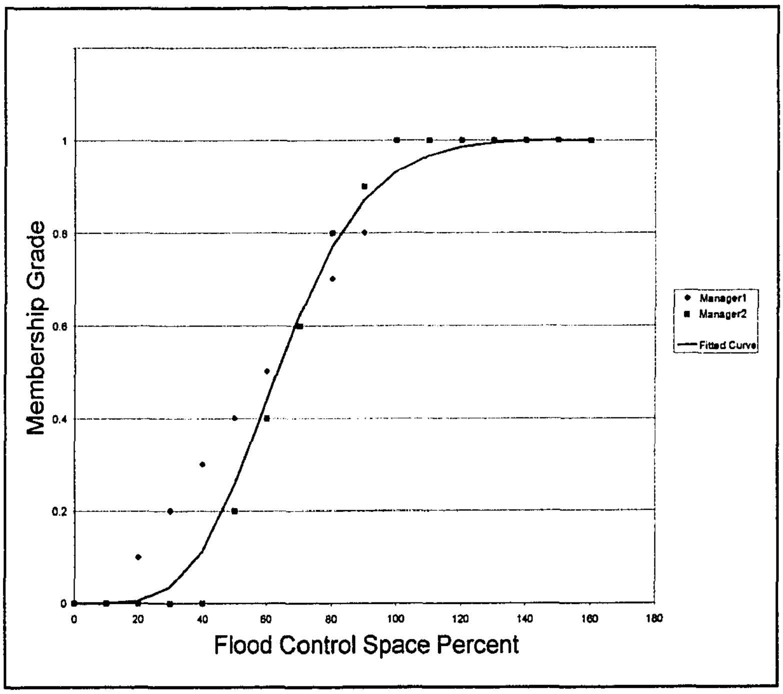


FIGURE 4.8 Dependable flood control space membership function for June.

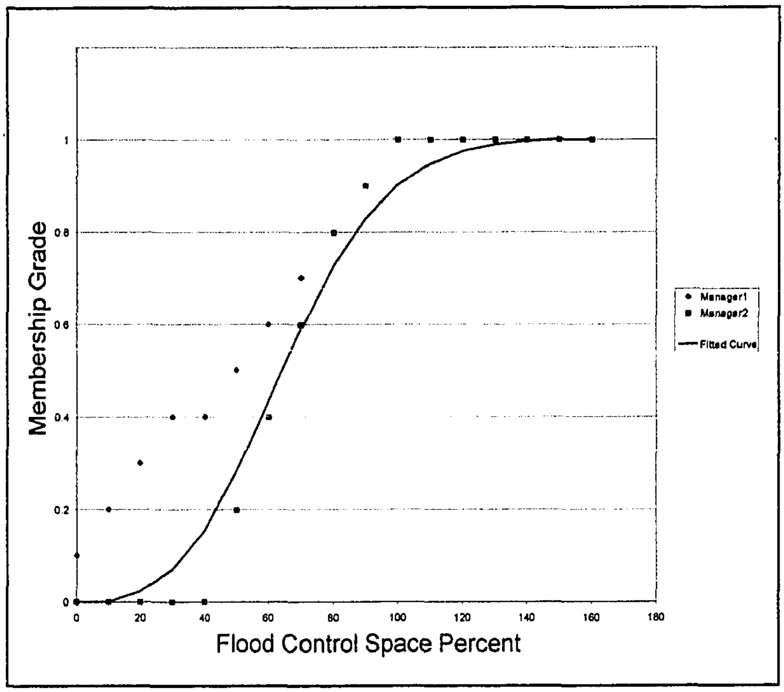


FIGURE 4.9 Dependable flood control space membership function for July.

According to the data shown in those figures, the type of membership function is a non-decreasing function. After evaluating the functions mentioned in Section 4.4.2, the best fit was obtained with the S-shape function. The function and its parameters are presented in Table 4.6.

TABLE 4.6 Dependable flood control space membership functions.

MONTH	$\mu(x)= ((1 - v)^{r-1} (x - a)^r) / ((1 - v)^{r-1} (x - a)^r + v^{r-1} (b - x)^r)$			R^2
October – March	v = 0.043	r = 1.460	[a,b] = [0,160]	0.74
April	v = 0.256	r = 2.100	[a,b] = [0,160]	0.83
May	v = 0.191	r = 2.300	[a,b] = [20,160]	0.97
June	v = 0.275	r = 2.600	[a,b] = [10,160]	0.97
July	v = 0.336	r = 2.430	[a,b] = [0,160]	0.86
August	v = 0.289	r = 2.240	[a,b] = [0,160]	0.90
September	v = 0.216	r = 1.910	[a,b] = [0,160]	0.85

We see in this table that R^2 ranged from 0.74 to 0.97. The parameter, v, ranged from 0.043 to 0.336 and the parameter, r, ranged from 1.46 to 2.6. According to Dombi (1988) the parameter, v, represents the inflexion point of the curve and the parameter, r, represents the sharpness of the curve ($r > 1$). Thus, the membership functions of May, June and July present a greater sharpness than in the other months, which means that the water managers prefer to have more flood control space in the high season than in the other seasons. This statement concurs with the way reservoir operators are used to dealing with the flood control space objective.

4.4.2.3 Efficient hydropower

It is considered that hydroelectric energy production is a function of the energy head in the reservoir, the release through the turbines, the efficiency of the system and the number of hours per day that the system is operated. In this case, only firm energy is considered.

The subjective attribute **efficient** is used here to reflect how the energy provided by this reservoir could satisfy the estimated monthly energy demand. At the same time, it is thought that the reservoir will be part of a reservoir network and that the current energy fully satisfies the demand for energy in the region.

Thus, economic efficiency criteria, energy prices, and energy market criteria should be incorporated into the judgement or analysis at the time that data for this membership function are being elicited.

The monthly energy demand, ME_t, is calculated by using the annual energy demand, AE, and the correspondent monthly energy coefficient, b_t. Monthly energy produced by the reservoir is calculated in terms of MWh and based on power produced by the turbined water, the head in the reservoir, the efficiency of the turbines and the number of monthly hours the water is turbined. Then, the produced energy at any month, t, PE_t, may be at any of these three conditions:

$Pe_t < ME_t$

$Pe_t = ME_t$

$Pe_t > ME_t$

The degree of membership of PE_t relative to the fuzzy constraint *efficient hydropower* will depend on the condition of comparison against ME_t.

4.4.2.3.1 Data acquisition

In the case of Grey Mountain Reservoir, the final report issued by Harza Engineering Company (1990) presents an estimated annual energy demand of 52 GWh. Since it also considers constant energy demand coefficients, it is assumed that the monthly energy demand would be 4,316 MWh.

The horizontal scale of this membership function was set up to be a percentage scale, where 100% means that the produced energy meets the demand for energy. Values less or greater than 100% mean the produced energy is less or greater than the required energy.

To measure the achievement of this objective in the questionnaire, a scale from 0 to 10 is used, where 10 corresponds to a full achievement of the objective and 0 represents a null achievement.

Four seasons are considered: fall, winter, spring and summer. The questionnaire is organized so that the person to be interviewed can choose to elicit a membership for every month or for a whole season. First, 100% of produced energy is considered, and it is asked how well the fuzzy constraint would be achieved. Then, questions are set up in regard to shortage and surplus energy issues and how the objective would be satisfied if the monthly produced energy, in percents, were less or greater than the monthly required energy.

4.4.2.3.2 Results and discussion

Two water resource managers were interviewed, one from the U.S. Bureau of Reclamation who used to deal with reservoir operation and hydropower issues for the

Colorado Big-Thompson Project (manager 1), and the other from the Northern Colorado Water Conservancy District in Loveland who is currently working with hydropower production in the northern Colorado area (manager 2).

Two membership functions were developed: one for the fall and spring seasons and another for the winter and summer (see Figures 4.10 and 4.11).

In analyzing the behavior of the reservoir manager regarding this objective for the fall season, manager 1 is less conservative than the other manager, and it appears he is more acquainted with the fact that shortages of energy may not affect the desirability of this objective, considering that energy is still being produced in sufficient quantities along this region.

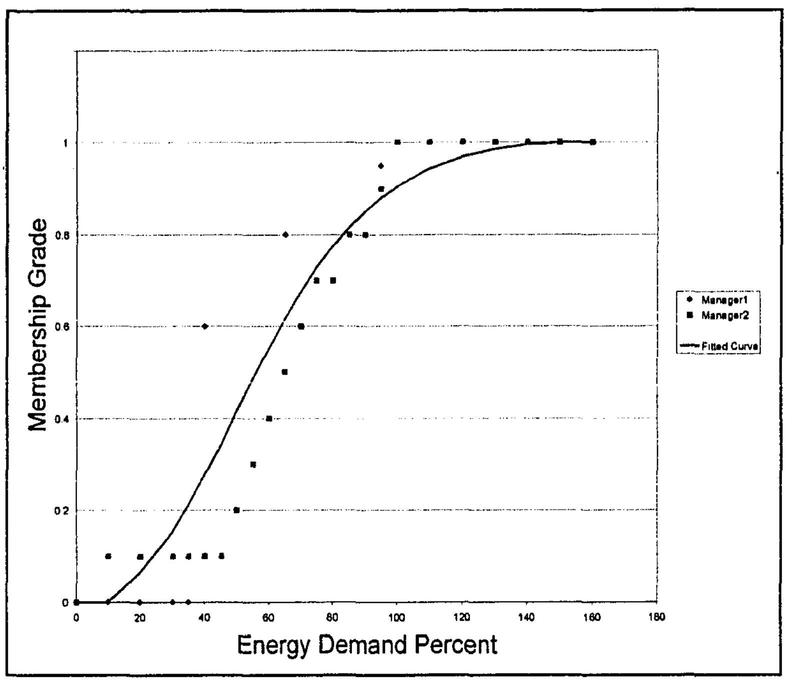


FIGURE 4.10 Efficient hydropower membership function for fall and spring.

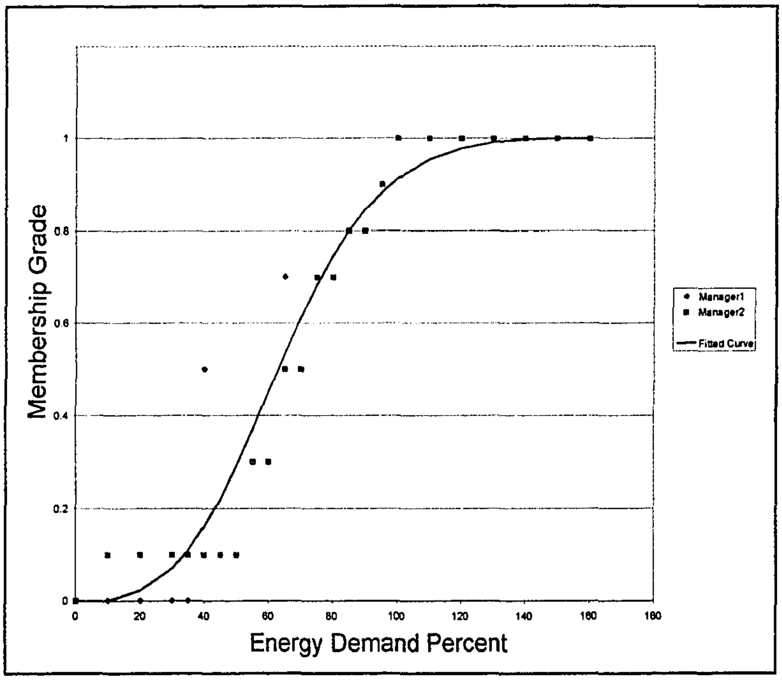


FIGURE 4.11 Efficient hydropower membership function for winter and summer.

S-shape functions were used to fit the collected data and they are presented in Table 4.7 along with corresponding R^2 values.

TABLE 4.7 Efficient hydropower membership functions.

SEASON	$\mu(x) = ((1 - v)^{r-1} (x - a)^r) / ((1 - v)^{r-1} (x - a)^r + v^{r-1} (b - x)^r)$	R^2
Fall & Spring	v = 0.226 r = 2.000 [a,b] = [0,160]	0.91
Winter & Summer	v = 0.328 r = 2.490 [a,b] = [0,160]	0.93

The values of R^2 indicate a good fit of those functions. The parameter, r, indicates that the membership function for winter and summer is sharper than the one for fall and spring. Hence, water managers have more willingness to accept shortages in fall and spring than in winter and summer.

4.4.2.4 Enjoyable rafting

The rafting objective is considered only for the high season of inflows (May, June and July). The subjective attribute **enjoyable** is used here to mean pleasurable, experiencing with joy the practice of this recreational activity.

Information extracted from the final report issued by Harza Engineering Company (1990) shows that appropriate discharges for this recreational objective range from 650 cfs to 2,400 cfs. In the Cache La Poudre River, rafters use a referential scale that goes from 1 to 7 and which is painted on one of the lateral walls of the cross section of the river at Pineview Falls.

4.4.2.4.1 Data acquisition

To facilitate the application of the questionnaire, the gauge at Pineview Falls was used as the reference scale to discretize the river flows. Thus, the reference scale ranged from 1 to 7 as represented in the cross-section of the river.

Inquiries were made at the North Poudre Irrigation Company in Fort Collins to relate this scale to a scale based on river discharges. The approximate relationship between the gauge level and discharges is shown in Table 4.8.

TABLE 4.8 Pineview gauge level and flow discharges relationship.

GAUGE LEVEL	APPROXIMATE DISCHARGE (cfs)
1	700
2	950
3	1,500
4	2,000
5	2,500
6	3,000
7	3,500

To qualify the achievement of the rafting objective, an auxiliary verbal scale was employed; this scale considered four achievement levels: *ideal*, *acceptable*, *tolerable* and *unacceptable*. They graded the achievements of the rafting objective, considering the verbal scale and keeping in mind the measuring of the attribute enjoyable when they play this recreational sport. The four considered achievement levels were used each at the time, and the interviewed people graded them on a scale from 0 to 100 for each month of the rafting season. Finally, these grades were converted to a scale from 0 to 1. Examples on how to complete the questions were included in this questionnaire.

4.4.2.4.2 Results and discussion

Two experienced rafters were interviewed. Both of them were accustomed to rafting in the Cache La Poudre River, other rivers in Colorado, and rivers in other states.

The type of membership function corresponds to a non-decreasing function (see Figure 4.12). Both rafters estimated a null degree of membership for a discharge of 700 cfs.

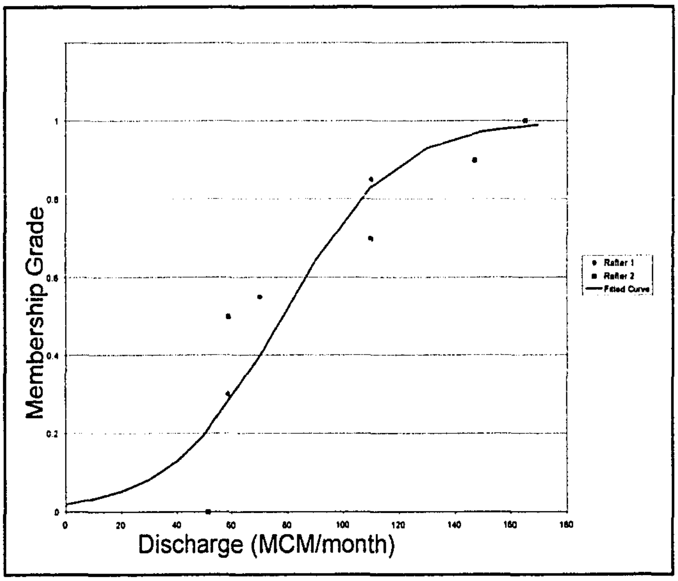


FIGURE 4.12 Enjoyable rafting membership function.

A full degree of membership was allocated for discharges equal to or greater than 3,500 cfs. Intermediate degrees of membership were allocated for discharges between 700 cfs and 3,500 cfs. The equation of the fitted curve is shown in Table 4.9.

TABLE 4.9 Enjoyable rafting membership function.

SEASON	$\mu(x) = 1/(1 + \exp(-a(x - b)))$	R^2
May, June, July	$\mu(x) = 1/(1 + \exp(-0.05(x - 78.29)))$	0.86

This logistic function presents a good fit to the data, with a R^2 of 0.86. Parameter b can be used to analyze when the achievement attitude of a certain objective changes from positive to negative. In this case, rafters have a positive attitude toward the achievement of this purpose up to an approximate monthly discharge of 78.3 MCM (1,020 cfs). Below that discharge the attitude is considered negative.

4.4.2.5 Enjoyable kayaking

This objective has analogous characteristics to the rafting objective. The selected group of kayakers were experienced kayakers.

As in the case of rafting, kayakers use the gauge at Pineview Falls as a reference scale to measure what type of kayaking conditions are present in the Poudre River for a given discharge.

The proposed season for kayaking is from May to July, when kayakers expect to have the most appropriate conditions to practice this recreational sport.

The attribute **enjoyable** is used here to reflect the pleasure and excitement that kayakers experience when they practice this sport. The level of satisfaction of this objective is a function of the river discharge.

4.4.2.5.1 Data acquisition

Information extracted from the final report issued by Harza Engineering Company (1990) shows that for the Cache La Poudre River, ideal conditions for kayaking are present at a discharge of 1,850 cfs and minimum conditions for a discharge of 250 cfs.

The gauge at Pineview Falls, which is used also by kayakers as a reference scale, was used as the reference scale to discretize the river flows. Thus, in order to apply the questionnaire, the reference scale ranged from 1 to 7 as represented in the cross-section of the river.

Interviewed people performed the grading of this water use in the same way as rafting use was graded.

4.4.2.5.2 Results and discussion

Four kayakers were interviewed. All of them are used to kayaking in the Cache La Poudre River and in other rivers in Colorado. Figure 4.13 shows the membership functions elicited by those kayakers in regard to this objective. The type of membership function corresponds to a non-decreasing function.

The lowest level of achievement is reached in all the cases for a discharge of 700 cfs. The highest achievements are reached for discharges between 2,000 and 2,500 cfs. The selected function is presented in Table 4.10.

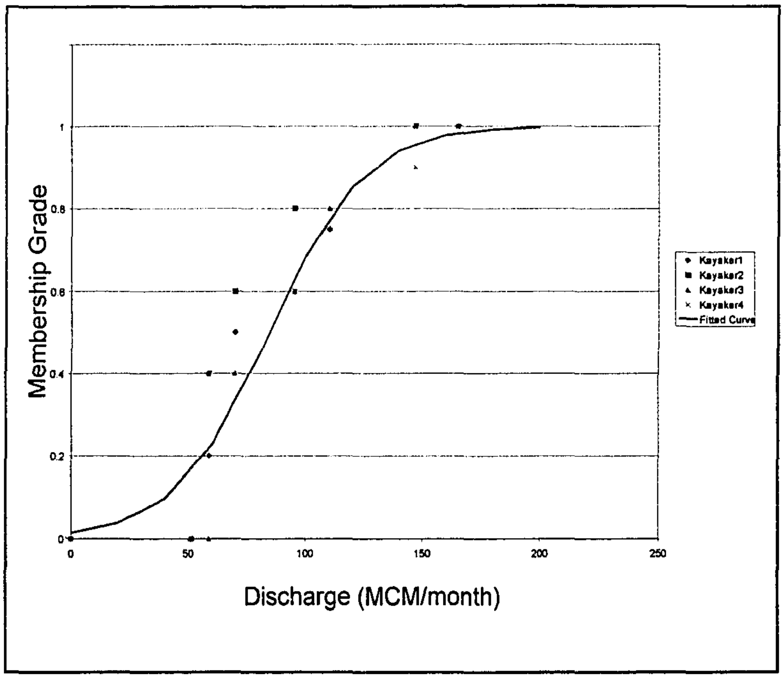


FIGURE 4.13 Enjoyable kayaking membership function.

TABLE 4.10 Enjoyable kayaking membership function.

SEASON	$\mu(x) = 1/(1 + \exp(-a(x - b)))$	R^2
May, June, July	$\mu(x) = 1/(1 + \exp(0.05(x - 84.70)))$	0.84

According to this logistic function, kayakers show a positive attitude toward the achievement of this objective up to an estimated monthly discharge of 85 MCM, which corresponds to an approximate discharge of 1,160 cfs. Below that discharge the attitude may be considered negative.

4.4.2.6 Adequate angling

Information extracted from the final report of the Cache La Poudre River study issued by Harza Engineering Company (1990) is used to set up the general guidelines of this objective. The most appropriate conditions are said to be at a discharge around 485 cfs and a minimum or null satisfaction for discharges greater or equal to 750 cfs.

The subjective attribute **adequate** is used here to mean how a discharge level satisfies suitable fishing conditions. Thus, the satisfaction of this objective is basically considered to be a function of the river discharge.

4.4.2.6.1 Data acquisition

The interviewed people were asked to qualify the achievement of an adequate angling objective in terms of the river discharge in cfs. These discharges ranged from 0 to 1,800 cfs.

An auxiliary verbal scale was also used in this case. Four levels of this scale were formulated: *ideal*, *acceptable*, *tolerable* and *unacceptable*. The selected group of anglers was in charge of grading, for each level of such a verbal scale, in a scale from 0 to 100, the achievement of this objective for a particular month of angling season. Then, this scale was converted to a 0-1 membership function scale.

4.4.2.6.2 Results and discussion

Three anglers were interviewed, one of them with 40 years of experience in this recreational sport, and the others with more than 15 years fishing experience in the Cache La Poudre River. Two of them considered the ideal season for practicing this recreational sport to be from March to July, except June, which is discarded due to the turbidity of the water.

The type of membership function for all the cases corresponded to a unimodal function (see Figure 4.14). From the practical point of view, it is considered that average data may be useful to create a single function which can be further used for modelling purposes. Then, on the average, there is full achievement of this objective for discharges between 500 cfs and 600 cfs. A null achievement is considered for discharges around 0 cfs and equal to or greater than 900 cfs. Anglers perceived they would not have suitable conditions for angling when discharges would be equal or greater than 900 cfs. The average unimodal curve is also shown in Figure 4.14.

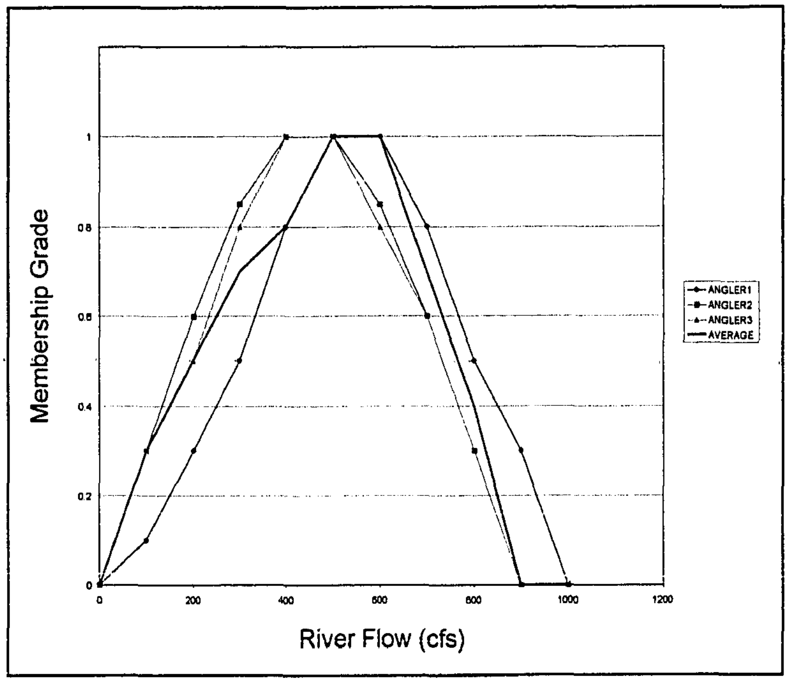


FIGURE 4.14 Adequate angling membership function.

4.4.2.7 Suitable fish habitat

The fish habitat objective is considered important for the Grey Mountain Reservoir. The most important species are said to be brown trout and rainbow trout. Extensive data are presented in the study developed by Harza Engineering Company (1990) study in regard to flow conditions which should be present in the river over the year. Suitability conditions for all ages of those species are measured by using the so called Weighted Usable Area (WUA) Index, which has been developed by the Fish and Wildlife Service, Department of the Interior. Basically, the WUA Index is calculated as a function of hydraulic conditions in the river, like the velocity and the cross sectional area of flow, and is expressed in terms of the discharge in cfs. The units of this index are (sq ft/1,000 ft) and high WUA values mean more suitable conditions for fish habitat. Detailed information about this index is presented in Milhaus (1980).

The subjective attribute **suitable** is intended to reflect the most appropriate habitat conditions, for brown trout and rainbow trout species, as a function of the river discharge over the year.

4.4.2.7.1 Data acquisition

Data were tabulated in a format that fish and wildlife experts were accustomed to presenting it. Experts had enough background about what the most appropriate river flows might be over the year. Thus, the table was set up with the horizontal scale being represented by the months and the vertical scale by the river flows (cfs).

In order for the experts to be able to reflect suitable objective in terms of the river discharge, an auxiliary verbal scale was used. Four levels of this verbal scale were formulated: *ideal* or *optimal*, *acceptable*, *tolerable* and *unacceptable* conditions. Thus, four tables were set up, one for each level of the verbal scale. So, for each level of the verbal scale, experts plotted the most appropriate discharge for each month. Finally, they were asked to grade the four levels of the verbal scale on a range of 0 to 100, whose grades will be used to construct the vertical scale of the membership function.

Membership functions for suitable fish habitat can be built for each month. For a particular month, the horizontal scale represents the river discharges in cfs. The vertical scale is constructed in such a way a given grade of a particular verbal scale level becomes the membership grade of an analyzed discharge river.

4.4.2.7.2 Results and discussion

Data for brown trout and rainbow trout were gathered through the interviews of two fish and wildlife experts. After meeting with water resource experts in the Division of Wildlife in Fort Collins and the Fish and Wildlife Service of the U.S. Department of the Interior, two of them agreed that they would come up with the appropriate answers to construct such membership functions. They drew one set of tables for the rainbow trout and another one for brown trout species.

For purposes of this research, only the rainbow trout was selected to be modelled. Figure 4.15 shows the membership function in the month of May. Figure 4.16 shows the membership function in June and July. The other membership functions are included in Appendix B.

Those figures show that a full degree of membership is perceived for river flows between 350 and 450 cfs. The membership grade is zero in May for flows greater or equal to 1,100 cfs, and null achievements are reached for no flow and for flows equal to or greater than 1,900 cfs in June and July.

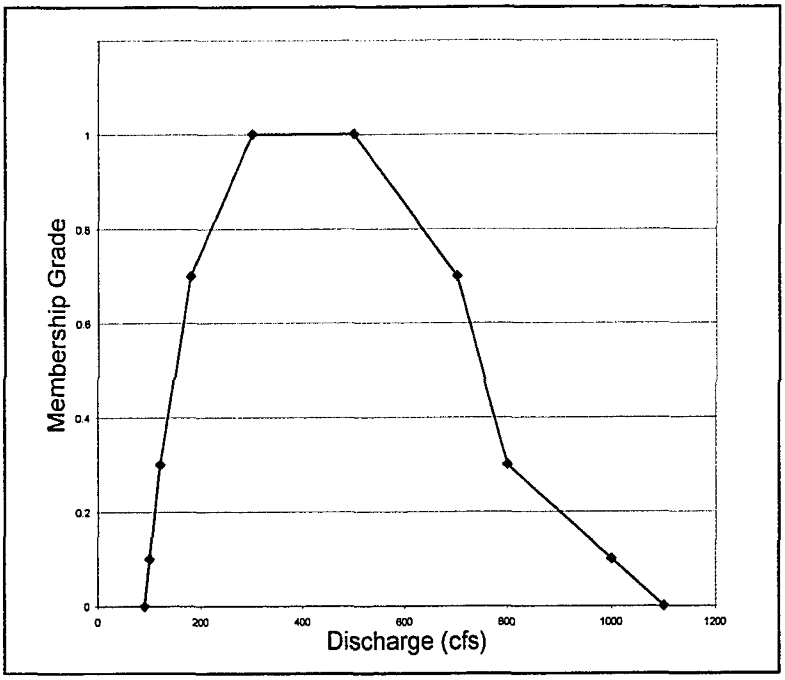


FIGURE 4.15 Suitable fish habitat membership function for May.

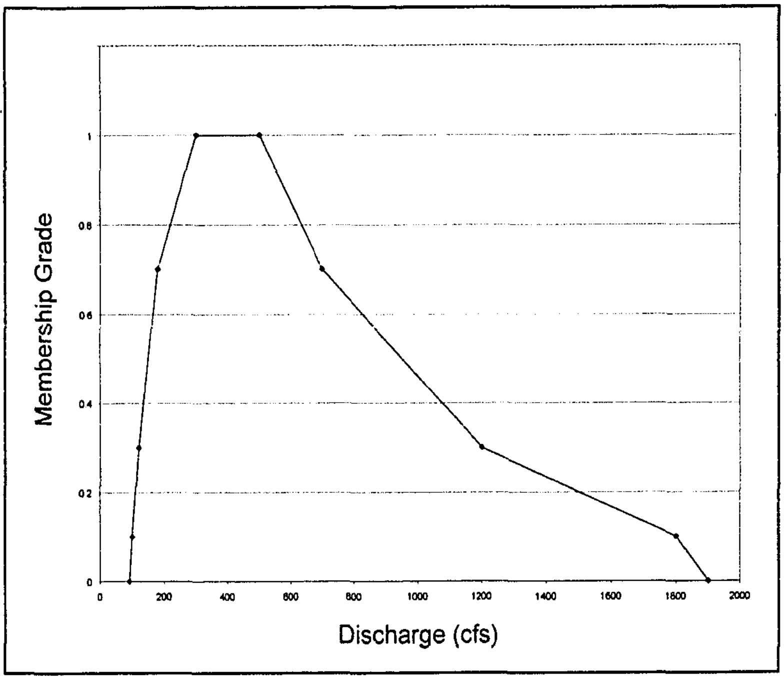


FIGURE 4.16 Suitable fish habitat membership function for June and July.

4.5 DETERMINISTIC CASE

The deterministic case is first used to test the applicability of fuzzy dynamic programming for reservoir operation problems. In this deterministic case, fuzzy dynamic programming is applied with the weight operator; the case of max min operator is addressed in the stochastic case. The computer code used to solve this problem is CSUDP, a code developed at Colorado State University by Labadie (1987). The code of the subroutines is presented in Appendix C.

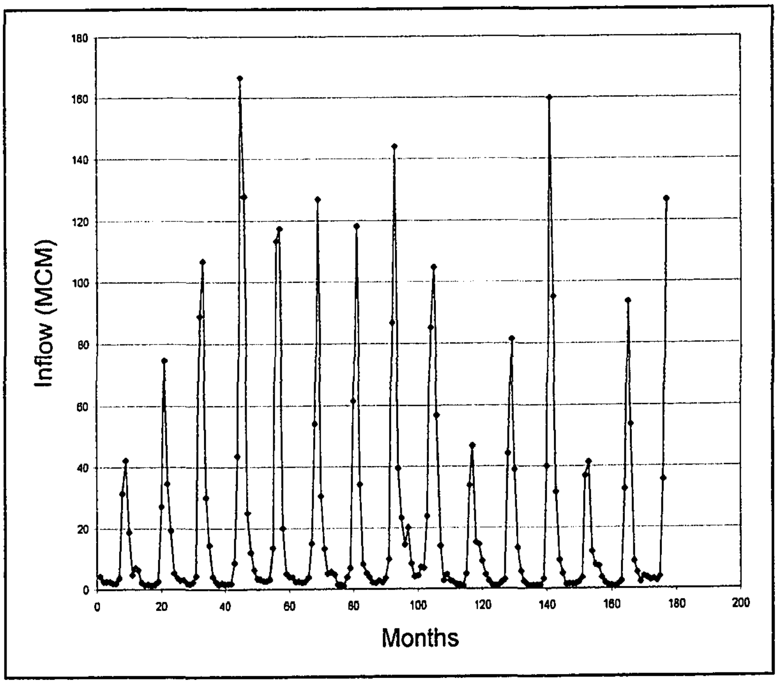
General information for this problem was extracted from the Harza Engineering Company (1990) report:

1. Thirty years record of monthly historical inflows in the Poudre River were available (1954-1983) (see Figure 4.17).
2. The reservoir will be operated such that senior water rights will be met downstream of the reservoir (see Figure 4.18).
3. Full capacity of the reservoir is 241 MCM, the full active volume is 229 MCM, and the flood control space is 12 MCM.
4. An annual municipal and industrial water demand of 51 MCM is assumed. Monthly distribution of the water supply demand is shown in Table 4.10.
5. An annual energy demand of 52 GWh and constant monthly demand coefficients of 0.083 are assumed.
6. The head-capacity curve for the reservoir can be represented as follows:

   $H = 14.53\ V^{0.783}$

   where: H = reservoir head (m); and,

   V = reservoir volume (MCM).



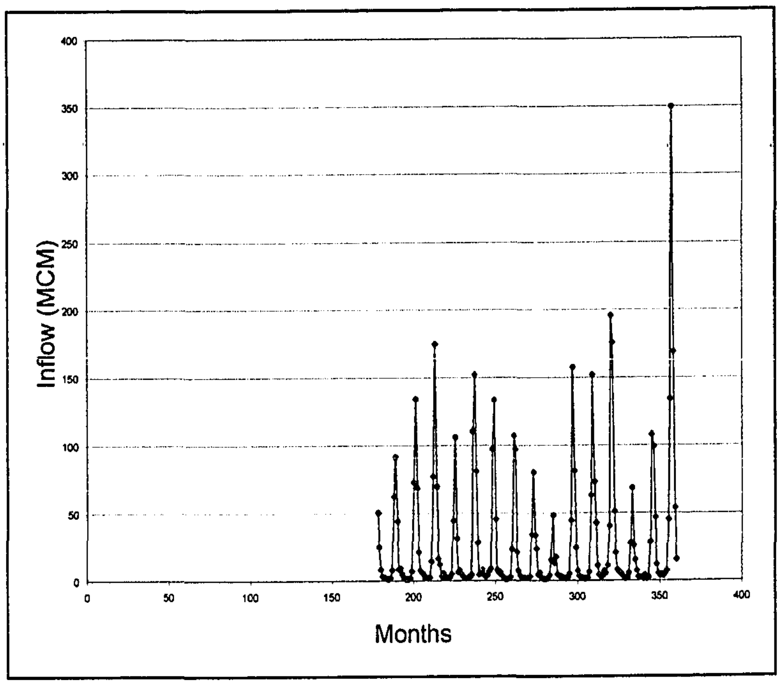


FIGURE 4.17 Monthly inflows in Poudre River (1954-1983).

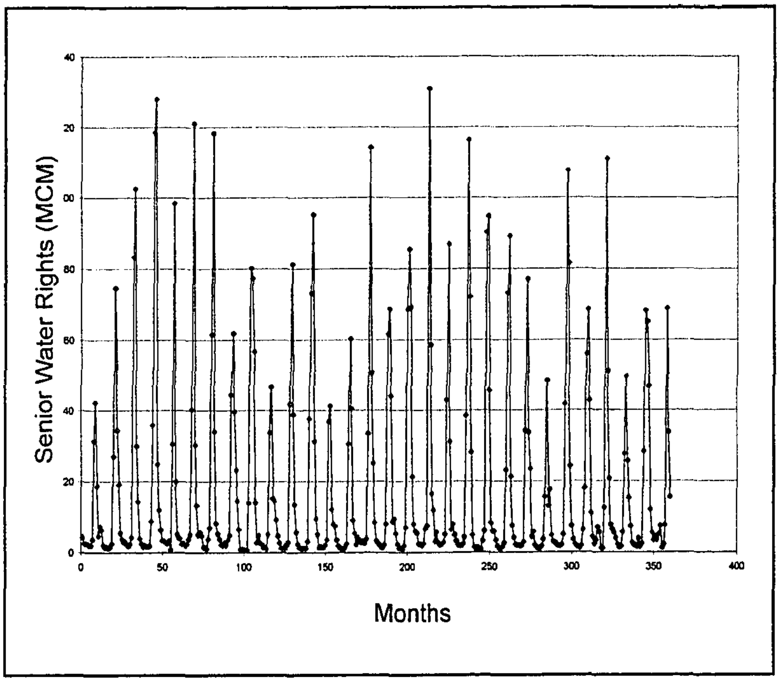


FIGURE 4.18 Monthly senior water rights (1953-1984).

7. The mass balance equation is formulated in the inverted form. Since good estimates of the evaporation rate and seepage rate were not readily available and exclusion of these terms would not impact the objectives of this study, zero evaporation and seepage rates were assumed. Thus, the mass balance equation is

$Q_t = X_t - X_{t+1} + I_t - WR_t$ (MCM units)

where: Q_t = release at month t in excess of senior water rights;

X_t = beginning storage at month t;

X_{t+1} = beginning storage at month t+1;

I_t = deterministic inflow at month t; and

WR_t = required release to senior water rights downstream of the reservoir.

8. The initial month to operate the reservoir is considered to be October.
9. The initial volume for analyzing the 30-year period is assumed to allow an empty flood control space.

Data related to the Grey Mountain Reservoir, like hydrological data, physical data, limits on volume and releases, increments of the state variable, and membership function data of the fuzzy goal and fuzzy constraints, were set up according to the requirements of the CSUDP code. An example of the CSUDP input data is shown in Appendix C.

TABLE 4.11 Monthly municipal and industrial water demand.

MONTH	DEMAND (MCM)
1. October	3.57
2. November	1.53
3. December	1.02
4. January	1.02
5. February	1.53
6. March	1.53
7. April	3.06
8. May	4.59
9. June	7.65
10. July	10.20
11. August	9.18
12. September	6.12

4.5.1 Fuzzy Dynamic Programming with Weight Operator

The fuzzy decision is the result of the intersection of the weighted sum of the given fuzzy goal and fuzzy constraints, with the respective value of the objective function at the previous stage. The weight sum operator is used to reflect the relative importance of one purpose over another.

For the Grey Mountain Reservoir problem, the formulation of the fuzzy dynamic programming problem is as follows:

At each time step of the dynamic programming problem, the intersection of fuzzy constraints is defined by

$$f_i\,(X_i,Q_i) = \sum \alpha_j.\mu_{Cj}(X_i) \tag{4.1}$$

$i = 1,\ldots 12$ months

$j = 1,\ldots,7$ constraints (objectives)

At the end of September, the fuzzy constraints are combined with the fuzzy goal. So, if October is denoted as month 1, the overall objective function can be formulated as follows:

$$Z = \max\{\min[f_1(X_1, Q_1\,), f_2(X_2, Q_2),\ldots,f_{12}(X_{12}, Q_{12}), \mu_G]\} \tag{4.2}$$

The fuzzy dynamic recursion relation using a forward solution procedure can then be written as follows:

$$F^*_{i+1}(X_{i+1}) = \max_{Xi}\,[\min\,(f_i\,(X_i,Q_i), F^*_i\,(X_i))] \tag{4.3}$$

subject to

$$F_1(X_1) = \mu_G \tag{4.4}$$

$$Q_i = X_i - X_{i+1} + I_i - WR_i \text{ (mass balance equation)} \tag{4.5}$$

$$Xmin_i \le X_i \le Xmax_i \tag{4.6}$$

$$Qmin_i \le Q_i \le Qmax_i \tag{4.7}$$

X_1 = initial reservoir storage

where: $F^*_i(X_i)$ = optimal value function at month i with reservoir storage, X_i;

$f_i(X_i,Q_i)$ = stage (month) return function combining the membership grades, μ_{Cj}, for the respective seven constraints, (j = 1,...,7), listed before, associated with reservoir storage, V_i, and release, Q_i;

I_i = inflow volume in the Poudre River at month i (MCM);

α_j = relative weight associated with the jth fuzzy constraint, such that $\sum \alpha_j = 1$, for j = 1,...,7;

X_{min} = minimum allowed storage for month i (MCM);

X_{max} = maximum allowed storage for month i (MCM);

Q_{min} = minimum allowed release volume for month i (MCM);

Q_{max} = maximum allowed release volume for month i (MCM);

WR_i = required release volume to senior water rights downstream (MCM); and

Q_i = release volume from the reservoir, at month i (MCM).

The value of the relative weights were selected in accordance with guidelines established in the final report of the Cache La Poudre Basin Study (1990). Thus, the highest weights are assigned to municipal and industrial water supply and fish habitat objectives, the lowest weights to rafting, kayaking and angling, and intermediate weights were allocated to flood control space and energy production. The selected weights are shown in Table 4.12.

TABLE 4.12 Relative weights of fuzzy constraints.

OBJECTIVE		WEIGHT
1. Municipal and industrial water supply		0.25
2. Flood control space		0.15
3. Energy production		0.15
4. Rafting		0.05
5. Kayaking		0.05
6. Angling		0.10
7. Fish habitat		0.25
	TOTAL	1.00

4.5.2 Results and Discussion

A general operational rule for a multipurpose reservoir may consider the operation of the reservoir in such a way that the releases should be made to meet the different downstream demands, and at the same time, the reservoir storage should be managed so that it may be partially emptied in the low season to have enough room in the high season to store expected high inflows. Of course, the uncertainty of the inflows makes it more difficult to follow a pre-established procedure, especially if the operation of such a water resource system is multipurpose.

4.5.2.1 Storage trajectory

The storage trajectory is expected to have a seasonal pattern. In general, the multiple downstream water use demands vary over time, and which may not coincide with the seasonal variability of the inflows. In this case, an optimal operational rule will attempt to meet downstream water requirements, adding water from the active pool or conservation zone to the current inflows if they are not enough in the low season, and emptying the storage to have enough room for the expected incoming inflows in the high season, and finally, ending the yearly operation in some pre-specified target storage level.

With the application of fuzzy dynamic programming with a weight operator (FDP), optimal results were obtained for a period of thirty years. The trajectory of monthly average storages are shown in Figure 4.19. The horizontal scale goes from month 1 (October) to 12 (September) and the vertical scale is storage levels. The storage trajectory shows that the storage level drops in fall and winter months of reservoir operation and rises in the summer season (May, June, July). This result is in accordance with the general operating rule of reservoir operation, which assumes an emptying period and a filling period coincident with a period of high inflows.

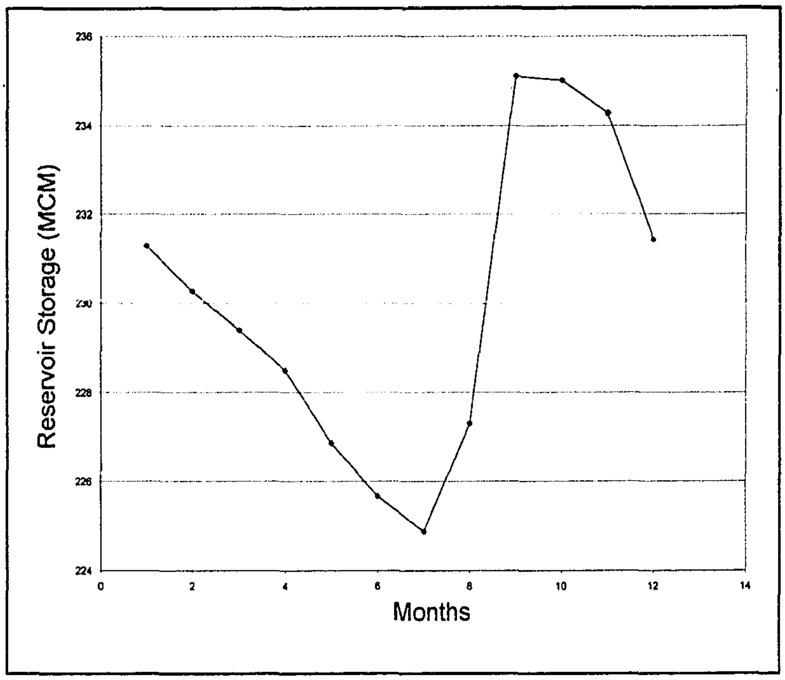


FIGURE 4.19 Trajectory of monthly average optimal storages.

The ending storage in September was considered important to be analyzed. Figure 4.20 shows the monthly storages reached at the end of the water year; these values ranged between 200 MCM and 241 MCM, which means that ending storages were always in the neighborhood of the ideal volume at the end of the yearly operation of the reservoir. This behavior is in accordance with the formulation of the fuzzy goal.

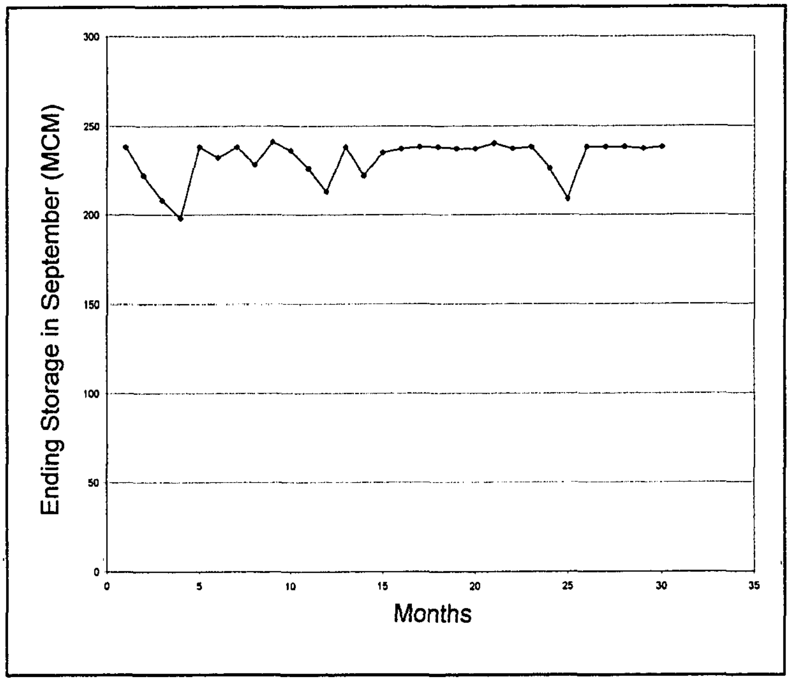


FIGURE 4.20 Optimal storages at the end of September.

4.5.2.2 Releases trajectory

Generally, the primary uses of municipal and industrial water supply, energy production, flood control space and, lately, the providing of appropriate fish habitat conditions are intended to be met as a first priority. Additional availability of water may allow satisfaction of remaining water uses such as recreational uses. To reflect the importance of one water use over another, weights are used to help produce an optimal pattern of releases.

Figure 4.21 illustrates the trajectory of monthly average optimal releases. Those releases are made to meet downstream demands from the reservoir. The horizontal scale goes from month 1 (October) to 12 (September) and the vertical scale is monthly release. The pattern of those releases is as expected; that means lower releases in the low season and higher releases in the high season (May, June, July). In fact, optimal releases calculated by using FDP respond to a concept of satisfaction, which is intrinsically embedded in the fuzzy formulation of the goal and constraints and is represented through their respective membership functions.

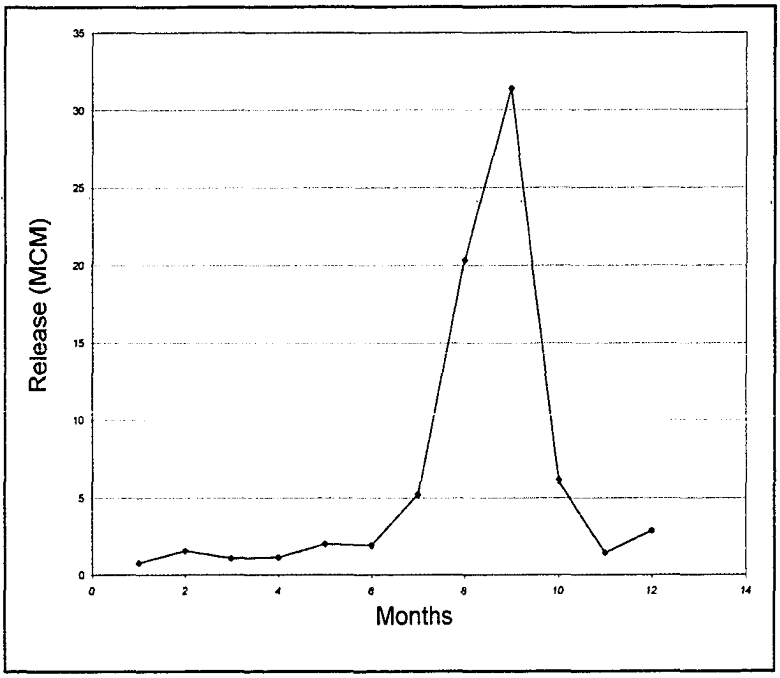


FIGURE 4.21 Trajectory of monthly average optimal releases.

4.5.2.3 Achievement of the fuzzy goal and constraints

The impact of any release decision or storage rule on a given fuzzy goal or fuzzy constraint can be measured through the evaluation of its respective membership function value. The achievement of the fuzzy goal and fuzzy constraints in average terms is shown in Figure 4.22. This figure shows that flood control obtains the higher membership grades over the year, and it is followed by water supply, energy, fish habitat, rafting, kayaking and angling. These results for the release based objectives are in accordance with the preferences or weights previously established during the formulation of the optimization problem. However, the flood control purpose depends entirely on the stored volume in the reservoir. The high value of achievement indicates that violating this flood control space would not enhance the release based objectives.

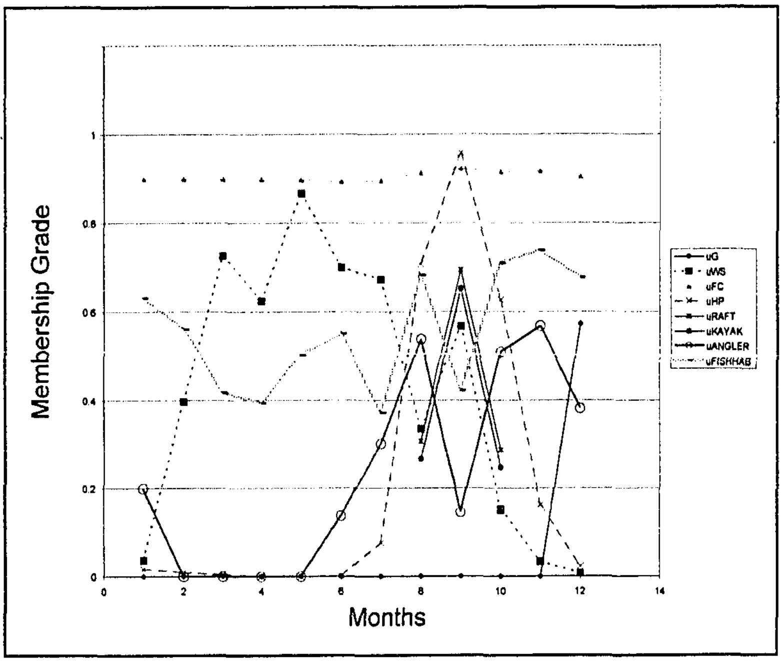


FIGURE 4.22 Average membership grades for a fuzzy goal and constraints.

A summary of statistics of optimal membership grades for a fuzzy goal and constraints is presented in Table 4.13. These results reveal that:

- The achievement of the fuzzy goal, on the average, was 0.53 with a variability measured by the coefficient of variation (COV) of 0.34, which represents a high variability in the set of its membership grades.
- In flood control, the average achievement ranged from 0.89 in March, with a variability of 0.02, to 0.92 in June, with a variability of 0.04. The minimum membership grade was achieved in April (0.79) and the maximum membership grade was in March (0.95).
- The average achievement for the water supply objective ranged from 0.01 in September, with a variability of 5.38, to 0.87 in February, with a variability of 0.39. A minimum membership grade (0) was obtained in all months; a maximum grade (1) was also reached in all months except in September, in which the maximum grade was 0.21. The maximum COV for the membership grades was obtained in August (COV = 1.39) and the minimum COV was in June (COV = 0.10).
- In rafting, the average membership grades ranged from 0.29 in July, with a COV = 0.97, to 0.69 in June, with a COV = 0.42. The membership grades varied between 0.04 (May) and 1 (May and June).
- Average membership grades for kayaking ranged from 0.25 in July, with a COV = 1.08, to 0.65 in June, with a COV = 0.47. A minimum membership grade (0.03) was obtained for May and June, and a maximum grade (1) was also reached in those months.

TABLE 4.13 Summary statistics of optimal membership grades for a fuzzy goal and constraints with historical series.

PERIOD OF APPLICATION	MINIMUM	MAXIMUM	MEAN	COV
Storage Goal				
End of water year (September)	0.37	1	0.57	0.34
Adequate Water Supply				
January	0	1	0.63	0.24
February	0	1	0.87	0.39
March	0	1	0.70	0.66
April	0	1	0.67	0.56
May	0	1	0.34	1.40
June	0	1	0.57	0.87
July	0	1	0.15	2.26
August	0	1	0.03	5.39
September	0	0.21	0.01	4.89
October	0	1	0.04	1.15
November	0	1	0.40	0.28
December	0	1	0.73	
Dependable Flood Control				
January	0.83	0.92	0.90	0.02
February	0.83	0.92	0.90	0.02
March	0.83	0.92	0.89	0.02
April	0.79	0.93	0.90	0.04
May	0.80	0.95	0.91	0.04
June	0.84	0.95	0.92	0.04
July	0.82	0.93	0.91	0.03
August	0.84	0.93	0.92	0.03
September	0.83	0.92	0.91	0.03
October	0.84	0.91	0.90	0.02
November	0.84	0.92	0.90	0.02
December	0.84	0.92	0.90	0.02
Efficient Hydropower				
January	0	0.01	0	5.39
February	0	0.01	0	5.39
March	0	0.01	0.00	3.00
April	0.01	0.68	0.08	2.23
May	0.11	1	0.71	0.38
June	0.68	1	0.96	0.10
July	0.03	1	0.63	0.57
August	0.01	0.88	0.16	1.39
September	0.01	0.09	0.02	0.88
October	0.01	0.15	0.02	1.54
November	0	0.03	0.01	0.71
December	0	0.01	0.00	1.31
Enjoyable Rafting				
May	0.04	1	0.31	0.93
June	0.13	1	0.69	0.42
July	0.04	0.99	0.29	0.97
Enjoyable Kayking				
May	0.03	1	0.27	1.05
June	0.10	1	0.65	0.47
July	0.03	0.99	0.25	1.08
Adequate Angling				
March	0.10	0.24	0.14	0.27
April	0.15	1	0.30	0.69
May	0	1	0.54	0.78
July	0	1	0.51	0.76
Suitable Fish Habitat				
January	0.21	0.92	0.39	0.35
February	0.36	0.94	0.50	0.23
March	0.39	0.97	0.55	0.27
April	0.07	0.97	0.37	0.60
May	0.08	1	0.68	0.51
June	0.11	0.96	0.42	0.62
July	0.13	1	0.71	0.37
August	0.35	1	0.74	0.32
September	0.37	1	0.68	0.31
October	0.46	0.97	0.63	0.21
November	0.43	1	0.56	0.24
December	0.23	0.60	0.42	0.25

- The angling objective obtained average membership grades which ranged from 0.14 in March to 0.54 in May. The COVs of the membership grades varied between 0.27 and 0.78, a minimum grade (0) was obtained in May and July, and a maximum grade (1) was obtained in April, May and July.
- The average membership grades for the fish habitat objective ranged from 0.37 in April (COV = 0.60) to 0.74 in August (COV = 0.32). A minimum membership grade (0.11) was obtained in June, and a maximum grade (1) was obtained in July, August and September.

  In terms of the average membership grades, the flood control objective obtained the highest values followed by energy, water supply, fish habitat, rafting, kayaking, and angling.

  For the COVs, flood control presented the lowest values, followed by fish habitat, angling, kayaking, rafting, energy and water supply.

For all the cases there was at least one month in which a 0 (zero) membership grade or a membership grade of one was reached.

In the light of these overall results, it appears that FDP can be used to optimally operate a multipurpose reservoir. An advantage of FDP over crisp optimization problems is that FDP is flexible enough to search for common solutions in one stage and through the various stages using the concept of fuzzy decision and for incorporating objectives through the use of membership functions.

4.6 IMPLICIT STOCHASTIC FUZZY DYNAMIC PROGRAMMING CASE

The deterministic optimization used only a historical inflow record. The goal of using optimization is to develop a set of optimal results from which general reservoir operating rules can be derived. The set of optimal results are greatly expanded through the consideration of stochastic inflows and water rights data. For the Grey Mountain Reservoir problem, the implicit stochastic case considers the use of about 600 possible realized annual series of inflows ($I_i(\omega)$) and required releases to senior water rights downstream ($WR_i(\omega)$). Actually, 600 series cannot be run in a single optimization model and must be applied in a series of sequential optimizations. Due to this sequential process, the effective number of realizations is 580 as will be discussed. The formulation of the optimization problem for Grey Mountain Reservoir is in essence analogous to the deterministic one, but the mass balance equation is as follows:

$$Q_i = X_i - X_{i+1} + I_i(\omega) - WR_i(\omega) \tag{4.8}$$

where: $I_i(\omega)$ = stochastic inflow volume in the Poudre River (depending on event ω in probability) for month i (MCM); and

$WR_i(\omega)$ = required release volume to senior water rights downstream (depending on event ω in probability) for month i (MCM).

The variables $I_i(\omega)$ and $WR_i(\omega)$ were cross correlated.

The basic tasks carried out in this regard were as follows:

a. A time series analysis of the 30 years of monthly inflow of the Poudre River and water rights downstream of the Grey Mountain Reservoir, was performed to allow synthetic generation of two stochastic series with 600 possible realizations of monthly inflows, $I_i(\omega)$, and senior water rights, $WR_i(\omega)$.

b. Data that was used for the deterministic case, except inflow and senior water rights data, were also used in this approach.

c. Fuzzy dynamic programming was applied to obtain 580 possible realizations of optimal monthly releases and storages.

d. Statistical analysis of the degree of satisfaction of the fuzzy goal and constraints was conducted through computation of the mean, the coefficient of variation, the minimum and the maximum membership grades.

e. Monthly operating rules were determined.

f. Monthly operating rules were applied to predict either monthly storages or releases for a period of 580 years.

g. Either predicted storages or releases were simulated under the monthly operating rules.

h. Basic statistical analysis (mean, coefficient of variation, maximum, minimum) of the membership grades of the fuzzy goal and fuzzy constraints was conducted for the simulated storages and releases.

4.6.1 Hydrologic Time Series Modeling

Synthetic generation of data to be used in reservoir operation is commonly considered when stochastic issues arise in water resource problems. According to Salas *et al.* (1980), in the stochastic approach a type of model is assumed aimed to represent the most relevant characteristics of the historic series. Time series modeling has been extensively used in hydrology and water resources since the early 1960's for modeling annual and periodic hydrologic time series. Time series modeling has mainly two uses in hydrology and water reservoirs: 1) for generation of synthetic hydrologic time series, and 2) for forecasting future hydrologic series. For instance, to analyze the operation of a reservoir, monthly inflows to such reservoirs must be generated. In addition, if there are other hydrological variables placed in the surrounding region of the reservoir, and they may affect the operation of such a reservoir, then a multivariate modeling of monthly time series should be the choice.

4.6.1.1 Synthetic generation of inflows and water rights

The available time series for the synthetic generation of 600 possible realizations of monthly data were 30 years of inflows in the Cache La Poudre River in Northern Colorado and the senior water rights diversions downstream of the Grey Mountain Reservoir. The two series are dependent because the water rights will be drawn from the available flow. Due to the nature of senior and junior rights, most of the current flow is already allocated. Therefore, higher inflows will have associated higher water rights demands. Because of this dependency the series were generated, considering them to be cross-correlated. Those time series were considered as bivariate time series and a AR model with lag-two (p = 2) and periodic coefficients were fit to the data.

Computer programs developed by Salas (1992), to deal with time series modeling, were used. The time series modeling process was performed as follows:

a) Parameters were estimated for each historic time series and the model was tested by using CSU003 code.

b) Synthetic generation of time series was performed based on the parameters estimated in a) and by using CSU004 code.

c) The numbers of generated samples was twenty and each sample was twenty years.

Results from the estimaation and generation of synthetic time series are shown in Appendix D.

4.6.2 Fuzzy Dynamic Programming Results

The most relevant issue in this approach is the analysis of statistical characteristics of storage levels and releases to define operational rules which may be used in long-term planning. Hence, there is a need for using a large number of realizations of annual series of hydrological and senior water rights data.

In order to analyze the behavior of fuzzy dynamic programming with both maximum-minimum and weight operators, a sample of 20 years of synthetically generated data was used. For this particular case study, the maximum-minimum stage return function (Equation (3.14)) did not perform well. In this case, because some of the reservoir objectives could not be satisfied at all in certain months for any combination of reservoir storage, membership grades could be zero and, therefore, the stage return function also would be zero. Since the objective function also has a maximum-minimum formulation, if the return function in any stage is zero, then the objective function also will be zero. In this situation, the final results have no meaning in the context of an optimal reservoir operation. Figure 4.23 shows the behavior of monthly average storage levels with maximum-minimum and weight operator; the horizontal scale goes from month 1 (October) to 12 (September). With the maximum-minimum operator, the reservoir storage was almost at full capacity throughout the year, and it did not allow practically any releases from it;

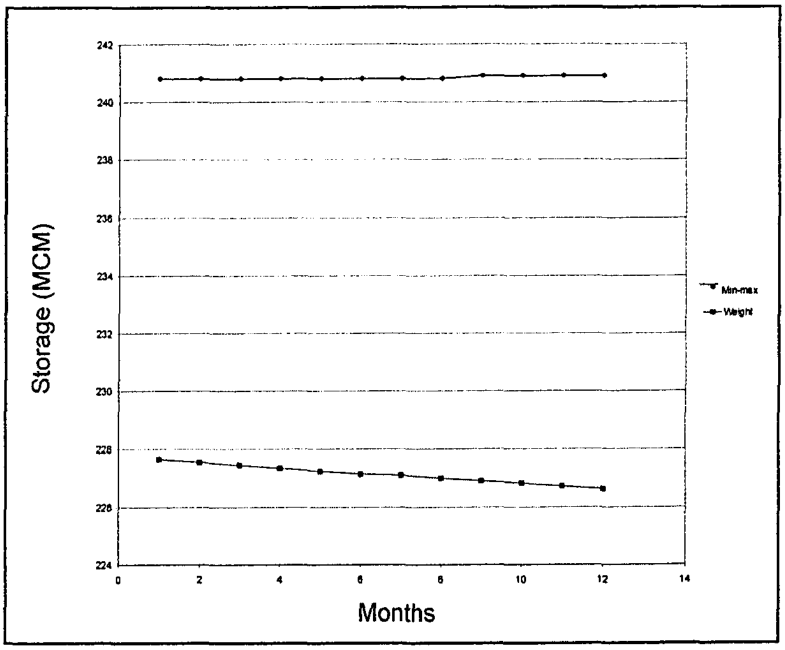


FIGURE 4.23 Fuzzy dynamic programming results with maximum-minimum and weight operators.

therefore, the reservoir does not perform well in terms of satisfying all its water uses. However, in the case of the weight operator, optimal results show the reservoir was allowed to release according to the different water demands over the year.

The CSUDP code was used to solve this fuzzy dynamic programming problem as in the deterministic case with the weight operator. Equations (4.9) to (4.12) were used to set up the dynamic programming problem. In order to be accommodated into the CSUDP code, the 600 possible realizations of monthly inflows and senior water rights were used in sets of 30 years, with the last year of each set being discarded; so, the storage at the end of year 29 was used as the beginning storage for the next series. By doing so, the process was approximated as the analysis of a continuous series of 580 years, and it allowed minimization of the impact of ending boundary conditions on the dynamic programming results.

The results produced 580 possible realizations composed of optimal monthly volumes at the beginning of month t, optimal monthly releases, and membership grades for the fuzzy goal and constraints. Summary statistics of fuzzy membership grades for the fuzzy goal and constraints are presented in Table 4.14.

Results reveal that the storage goal may be expected to achieve about 70% satisfaction with a relative variability of around 31%. The flood control objective had consistently high membership grades over the year. The average degree of satisfaction of this objective ranged from 0.88 in March and April, to 0.92 in June. Water supply and fish habitat objectives had the next highest average membership grades over the year; in water supply, the average degree of satisfaction of this objective ranged from 0.12 in September to 0.94 in February; and for fish habitat, those values ranged from 0.3 in June to 0.81 in October. Degrees of satisfaction for rafting, kayaking and angling may be considered as fairly good; their average membership grades were in the range of 0.12 to 0.6, and they were higher for May, June, July and August.

The hydropower objective obtained the lowest degree of satisfaction over the year. Its average membership grade ranged from 0 or values close to zero in six months, to values higher than 0.6 in May, June and July.

In terms of the COV, the flood control objective appears to provide the highest confidence in its achievement in the long term. The COV ranged from 0.02 in October, November, December and January, to 0.05 in May, which means a very low variability in the long term of the degree of satisfaction of this objective.

TABLE 4.14 *Summary statistics of stochastic membership grades of fuzzy goal and constraints (implicit stochastic case).*

PERIOD OF APPLICATION	MINIMUM	MAXIMUM	MEAN	COV
Storage Goal				
End of water year (September)	0.29	1	0.68	0.31
Adequate Water Supply				
January	0	1	0.71	0.28
February	0	1	0.94	0.25
March	0	1	0.88	0.37
April	0	1	0.80	0.36
May	0	1	0.48	1.00
June	0	1	0.66	0.68
July	0	1	0.19	1.86
August	0	1	0.05	3.48
September	0	0.21	0.12	2.03
October	0	1	0.16	1.54
November	0	1	0.82	0.43
December	0	1	0.78	0.19
Dependable Flood Control				
January	0.83	0.92	0.89	0.02
February	0.83	0.92	0.89	0.03
March	0.80	0.92	0.88	0.03
April	0.75	0.93	0.88	0.04
May	0.59	0.95	0.90	0.05
June	0.70	0.95	0.92	0.04
July	0.81	0.93	0.91	0.03
August	0.81	0.93	0.91	0.03
September	0.82	0.92	0.90	0.03
October	0.84	0.91	0.89	0.02
November	0.84	0.92	0.89	0.02
December	0.84	0.92	0.89	0.02
Efficient Hydropower				
January	0	0.06	0	0.00
February	0	0.16	0	8.00
March	0	0.03	0	4.48
April	0	1	0.05	2.60
May	0.02	1	0.63	0.48
June	0.16	1	0.96	0.12
July	0.02	1	0.64	0.53
August	0.01	0.99	0.17	1.24
September	0	0.21	0.02	1.00
October	0	0.19	0.02	0.76
November	0	0.05	0.01	0.59
December	0	0.03	0	1.33
Enjoyable Rafting				
May	0.03	1	0.24	1.04
June	0.05	1	0.68	0.43
July	0.03	1	0.30	0.97
Enjoyable Kayaking				
May	0.02	1	0.21	1.17
June	0.03	1	0.64	0.49
July	0.02	1	0.26	1.08
Adequate Angling				
March	0.07	0.45	0.15	0.29
April	0	1	0.27	0.46
May	0	1	0.57	0.63
July	0	1	0.53	0.73
Suitable Fish Habitat				
January	0.18	1	0.44	0.36
February	0.24	1	0.53	0.29
March	0.29	1	0.59	0.27
April	0.00	1	0.39	0.69
May	0.00	1	0.65	0.59
June	0.00	1	0.30	0.93
July	0.00	1	0.69	0.45
August	0.10	1	0.80	0.23
September	0.17	1	0.77	0.20
October	0.37	1	0.81	0.19
November	0.32	1	0.62	0.24
December	0.12	1	0.45	0.33

The highest COVs were found in the case of hydropower and water supply. The COV for hydropower membership grades ranged from 0 in January to 0.08 in February; they were higher or equal to one in 6 of 12 months. In the case of water supply, its COV ranged from 0.19 in December to 3.48 in August, being higher or equal to one in 4 of the 12 months.

The variability in the degree of satisfaction for rafting, kayaking and angling was, in most cases, high; their COV values were in some months higher than one, which means the achievement of those objectives has poor reliability in the long term.

Compared to the deterministic case, the stochastic case shows similar results in terms of membership grades and COV, for both the fuzzy goal and the fuzzy constraints. For instance, in the case of the fuzzy goal, mean membership grades were 0.57 (deterministic case) and 0.68 (stochastic case), and COVs were 0.34 (deterministic case) and 0.31 (stochastic case). In the case of the fuzzy constraints, the most achievable objectives were in both cases, deterministic and stochastic, water supply, flood control and fish habitat, while the less achievable were hydropower and recreation objectives like rafting, kayaking and angling. In terms of mean membership grades and COVs, results show the same pattern over the year.

4.6.3 Optimal Operating Rules

Solving an implicit stochastic fuzzy dynamic programming problem yielded 580 possible annual realizations of optimal monthly reservoir storages and releases. According to Young (1967), Revelle (1969) and Ouarda (1991), decision rules can be developed as an aid in postoptimal analysis. The basic concept is to use regression analysis to relate optimal storage levels and releases for a particular month to previous information on storage levels, releases and inflows. Such a rule might be further used as a tool for reservoir management, for defining in a particular month either a level of storage to be kept or the amount of water to be released. Linear or non-linear decision rules can provide a good fit to relate optimal releases or storage levels to previous storage levels, releases and inflows.

The general approach to find a reservoir operating rule is to find, for a particular month, t, a linear relationship among the ending storage and the beginning storage, previous releases and inflows. The ending storage plays the role of dependent variable and the others the roles of independent variables.

The idea behind this approach is to assume that the storages are time dependent on previous storages, inflows and/or releases. That characteristic of stochasticity may help us to define operational rules based only on previous conditions in the operation of a reservoir.

The proposed Grey Mountain Reservoir is situated in a semiarid area with significant variation in annual inflows. The amount of inflow that can be stored in the reservoir is heavily dependent on the required downstream releases to meet senior water rights demands. That means that only an excess of water above such demands is susceptible to being either stored or released. Another feature of the optimal operation of this reservoir is that the reservoir should be kept almost full most of the year, so that optimal releases are very dependent on the current inflow and downstream demand conditions. In this situation, it appeared more reliable to develop operating rules to predict the beginning storage for month, t, based on the beginning storage of the previous month.

Table 4.15 summarizes the set of operating rules. In the case of June and July, there was a considerable scatter of the optimal storage levels and releases, and it was difficult to get a good fit to a linear model. Different combinations of independent variables were tried like the previous releases, inflows and demands. The fit to those models was poor and they were discarded as representative operating rules. Instead, for both months, target storage level was set up in terms of the average of the optimal stochastic storage levels.

TABLE 4.15 Reservoir operating rules.

MONTH	OPERATING RULE EQUATION	R^2
1. October	$X_{t+1}(OCT) = 0.9882 * X_t(SEP) - 0.6765$	0.9786
2. November	$X_{t+1}(NOV) = 1.0236 * X_t(OCT) - 6.7218$	0.9762
3. December	$X_{t+1}(DEC) = 1.0059 * X_t(NOV) - 2.776$	0.9808
4. January	$X_{t+1}(JAN) = 1.0085 * X_t(DEC) - 2.9906$	0.9964
5. February	$X_{t+1}(FEB) = 1.0146 * X_t(JAN) - 4.4652$	0.9913
6. March	$X_{t+1}(MAR) = 1.0229 * X_t(FEB) - 7.009$	0.9882
7. April	$X_{t+1}(APR) = 1.0026 * X_t(MAR) - 2.0319$	0.9832
8. May	$X_{t+1}(MAY) = 1.0042 * X_t(APR) - 0.9802$	0.7788
9. June	$Q_t(JUN) = 0.7476 * X_t(JUN) + 0.27 * Q_{t-1}(MAY) + 0.555 * I_{t-1}(MAY) - 168.35$	0.493
10. July	-----	----
11. August	$X_{t+1}(AUG) = 0.97 * X_t(JUL) + 4.48$	0.89
12. September	$X_{t+1}(SEP) = 0.992 * X_t(AUG) + 0.3557$	0.9047

Figure 4.24 illustrates the storage decision rule for March, whose linear model has an R^2 of 0.988, and Figure 4.25 presents the storage decision rule for May, whose linear model has an R^2 of 0.778. The other figures of the operating rules are shown in Appendix E.

The values of R^2 ranged from 0.778 to 0.996 That indicates a good fit of the regression models with the data. The best fit was found in the case of the operating rule for January (R^2 = 0.996). These linear models have the beginning storage level at month t as a function of the beginning storage level in the previous month.

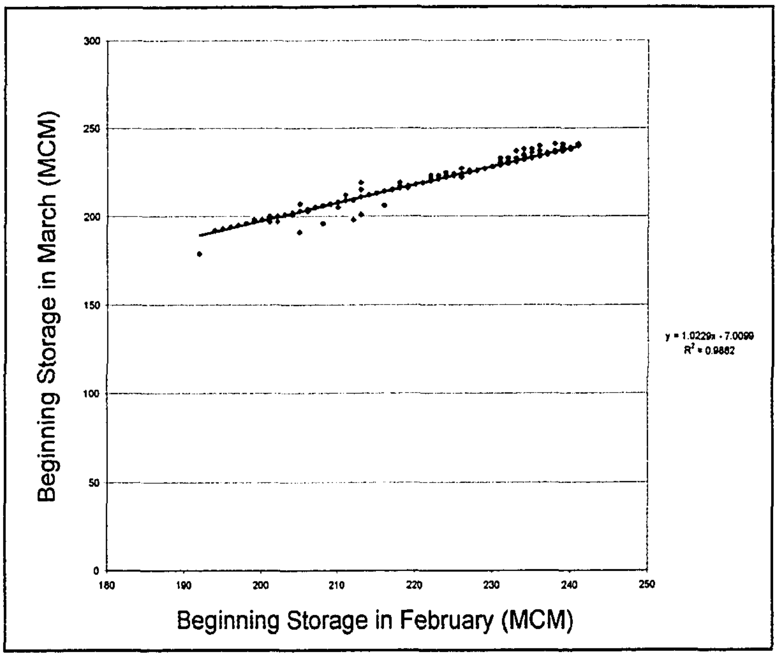


FIGURE 4.24 Reservoir operating rule in March.

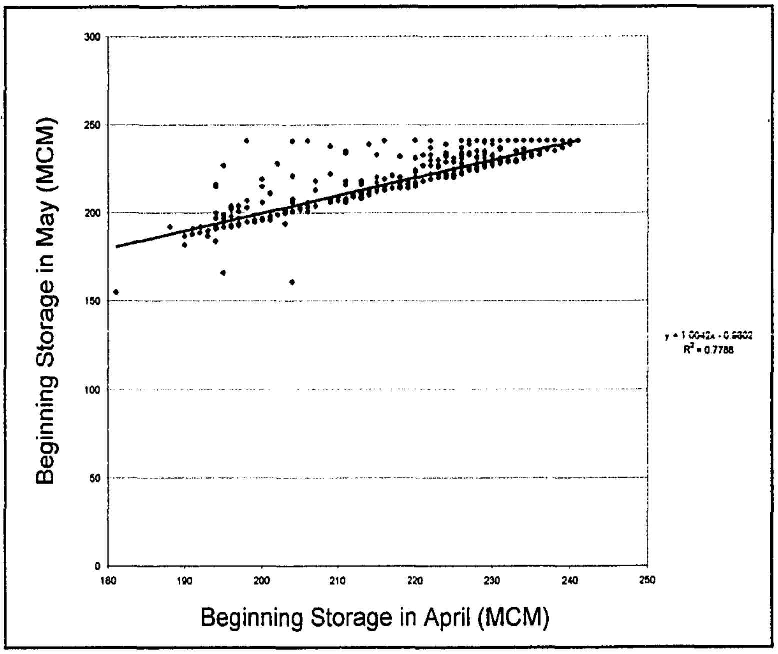


FIGURE 4.25 Reservoir operating rule in May.

4.6.4 Simulation of Operating Rules

The equations presented in Table 4.17 are used to predict the initial storage levels for each month, t. Then, a simple simulation model is applied to operate the reservoir for a period of 580 realizations.

The simulation is performed on a monthly basis for each of the 580 annual realizations. The formulation of this model is as follows:

$$Q_i = X_i - X_{i+1} + I_i(\omega) - WR_i(\omega) \tag{4.9}$$

$$i = 1,2,...,12$$

subject to

$$X_{min} < X_i < X_{max} \tag{4.10}$$

$$X_6 = 238 \text{ MCM} \tag{4.11}$$

$$X_7 = 234 \text{ MCM} \tag{4.12}$$

The model is based on the mass balance equation, which, in a particular month, i, calculates the release, Q_i, as a function of the beginning storage, X_i, the ending storage, X_{i+1}, the stochastic inflow, $I_i(\omega)$, and senior water rights, $WR_i(\omega)$. October is set up as month 1, and September as month 12. The ending storage in September is carried over to the first month of the next year as an initial storage. The simulation process takes into account not to violate the boundary conditions on storage levels, X_{min} and X_{max}, for each month. Because it was not possible to find an appropriate operating rule, the storage level for June and July was set up in terms of the optimal average storage level obtained from dynamic programming results (implicit stochastic case) for those months. Thus, the storage level for June is 228 MCM and for July is 234 MCM.

Once the simulated storage levels and releases are obtained, the membership functions of the fuzzy goal and constraints are used to calculate their respective achievements or membership grades.

Figure 4.26 illustrates both simulated and optimized monthly average releases. Figure 4.27 presents both simulated and optimized monthly average storage levels.

In the case of releases, both simulated and optimized releases present the same pattern over the year, which means the simulation model was able to simulate the predicted storage levels. The tendency over the year is to have less releases in the low season of inflows and high releases in the high season. Average simulated releases were very close to their respective optimal ones.

Two months were selected for analysis, to compare the individual simulated releases with their corresponding optimal ones. November was selected for the low season (see Figure 4.28) and June for the high season (see Figure 4.29).

For November, optimal releases ranged from zero to seven MCM, and the simulated ones ranged from zero to values very close to seven MCM. In both cases, those values correspond to releases for a typical low season; however, in the case of simulation results, the set of releases are more variable than the optimal ones. Optimal releases in November appear to be more conservative due to the fact the system is entering in a low season of inflows.

Figure 4.29 shows the comparison of optimal releases and simulated releases for June. They had the same tendency over the years. Simulated releases always produced good estimates of low and high optimal releases.

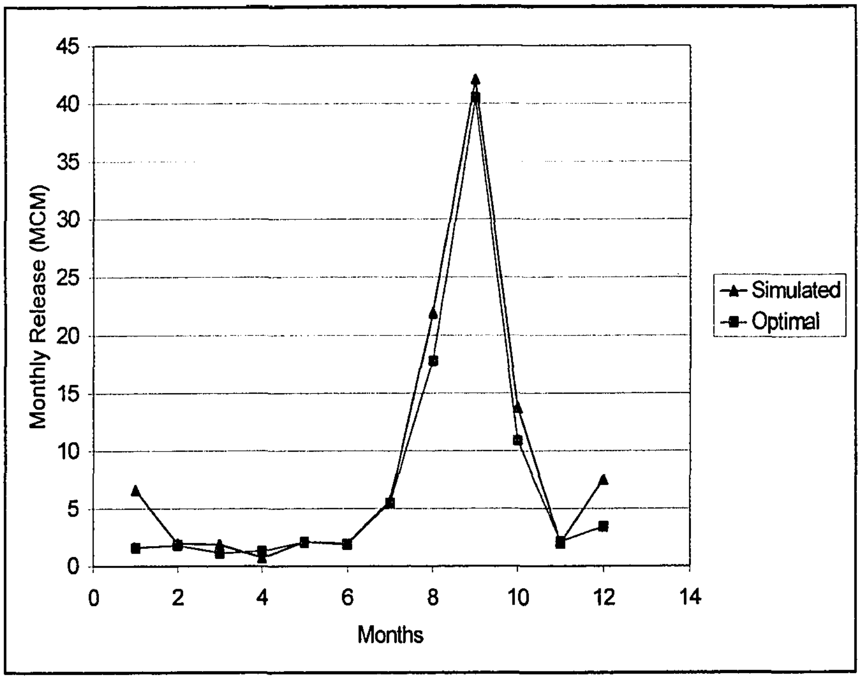


FIGURE 4.26 Monthly average releases (simulated and optimal).

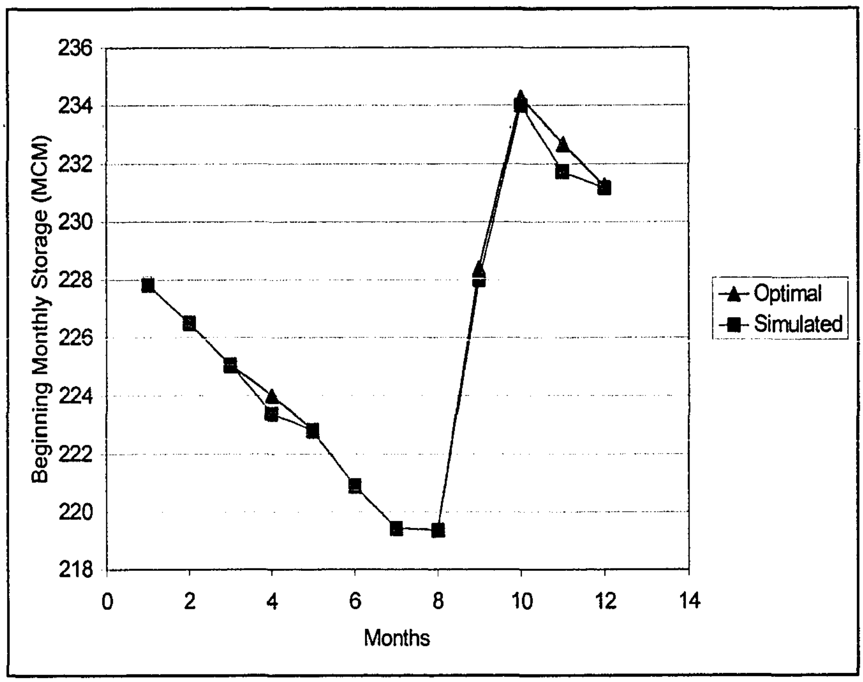


FIGURE 4.27 Monthly average storages (simulated and optimal).

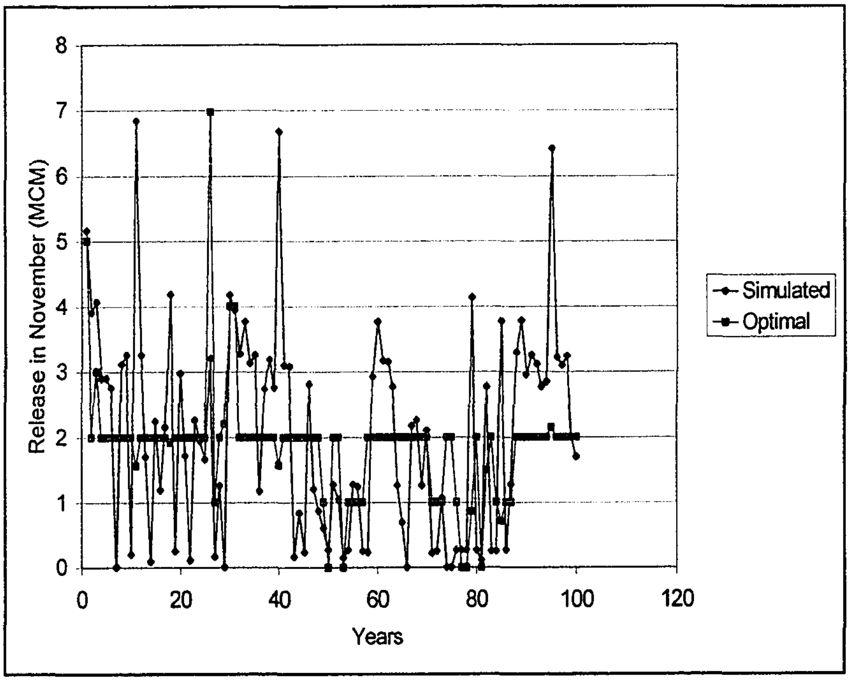


FIGURE 4.28 Releases in November (simulated and optimal).

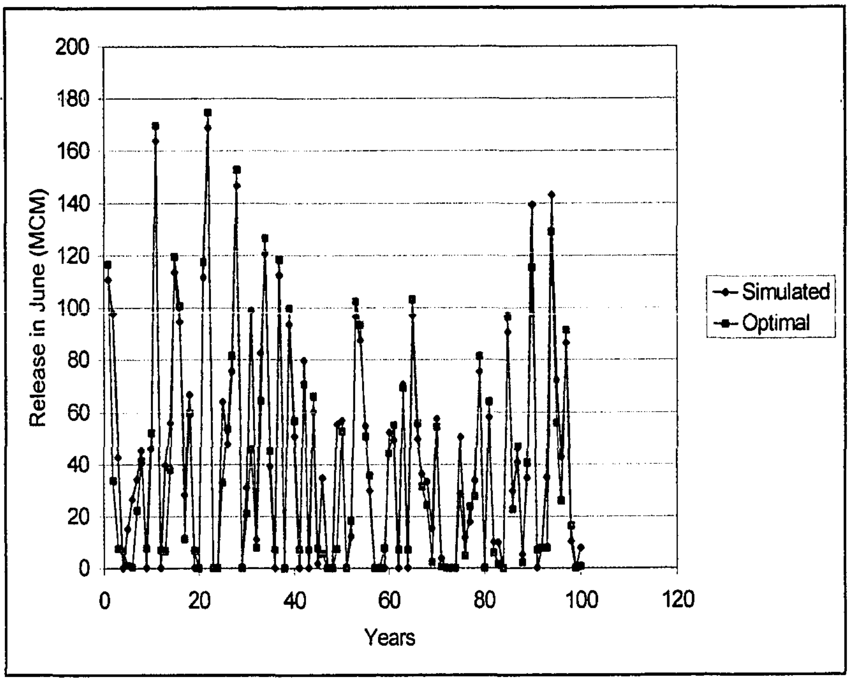


FIGURE 4.29 Releases in June (simulated and optimal).

In the case of storage levels (Figure 4.27), in average, simulated and optimal storage levels presented the same tendency over the year, emptying the reservoir in the low season and filling it up in the high season. Simulated average storage levels were slightly greater than the optimal ones.

Two months were also analyzed to compare the simulated and optimal storage levels. November was selected for the low season (see Figure 4.30) and August for the high season (see Figure 4.31). In both months simulated results followed the pattern of the optimal values. It appears this good fit is because the good fit of the monthly operating rules.

Although storage levels for June and July were previously set up as constant values for the whole period of analysis, the simulation results showed the appropriateness of the operating rules to analyze the operation of the reservoir in the long term.

Additional figures comparing simulation and optimization results are shown in Appendix D.

4.6.4.1 Degree of satisfaction of fuzzy goal and constraints

The membership functions of the fuzzy goal and constraints were used to calculate the membership grades of such objectives. Simulated releases and predicted storage levels comprised the input data to those membership function equations. A summary of statistics of those membership grades is shown in Table 4.16.

In the case of the fuzzy goal, stored volume at the end of September, for both simulated and optimal results, the average degree of satisfaction reached a value of 68%

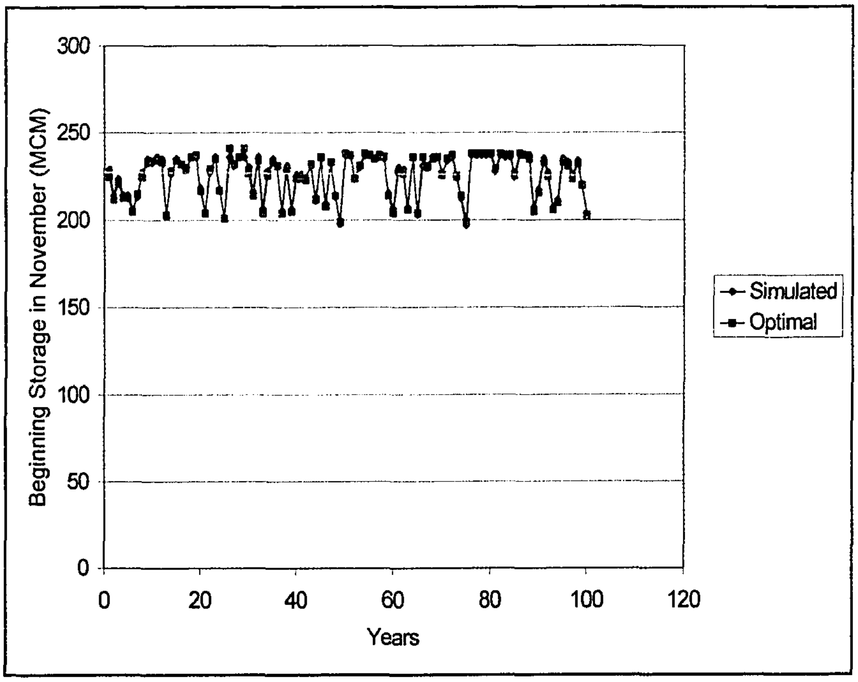


FIGURE 4.30 Storage level in November (simulated and optimal).

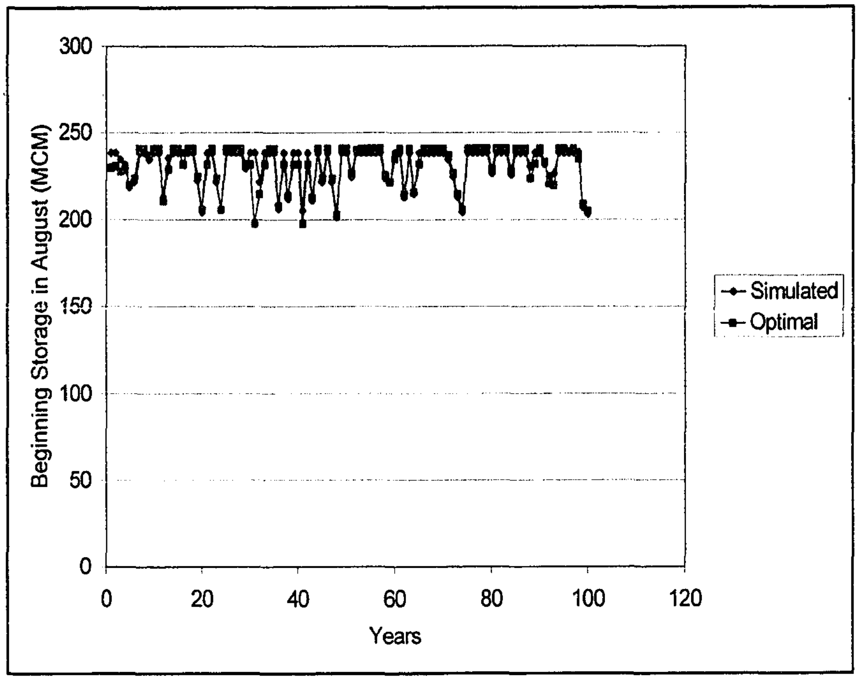


FIGURE 4.31 Storage level in August (simulated and optimal).

TABLE 4.16 Summary statistics of membership grades for a fuzzy goal and constraints (simulation case).

PERIOD OF APPLICATION	MINIMUM	MAXIMUM	MEAN	COV
Storage Goal				
End of water year (September)	0.28	1	0.68	0.31
Adequate Water Supply				
January	0	1	0.16	2.12
February	0	1	0.92	0.17
March	0	1	0.70	0.50
April	0	1	0.26	1.67
May	0	1	0.53	0.93
June	0	1	0.64	0.74
July	0	1	0.35	1.32
August	0	1	0.06	3.02
September	0	1	0.40	1.22
October	0	1	0.38	1.26
November	0	1	0.58	0.81
December	0	1	0.86	0.39
Dependable Flood Control				
January	0.01	1	0.85	0.25
February	0.05	1	0.86	0.24
March	0.10	1	0.90	0.19
April	0.09	1	0.93	0.16
May	0	1	0.93	0.19
June	1	1	1	0
July	0.65	0.65	0.65	0
August	0.23	1	0.50	0.70
September	0.11	1	0.51	0.82
October	0.32	1	0.68	0.46
November	0.27	1	0.74	0.35
December	0.09	1	0.79	0.30
Efficient Hydropower				
January	0	0.19	0.00	2.19
February	0	0.20	0.01	1.76
March	0	0.22	0.01	1.74
April	0	1	0.07	2.40
May	0.11	1	0.68	0.44
June	0.25	1	0.96	0.10
July	0.04	1	0.74	0.37
August	0	1	0.25	0.95
September	0	0.68	0.06	2.19
October	0	0.92	0.10	1.65
November	0	0.36	0.01	1.60
December	0	0.05	0.01	0.63
Enjoyable Rafting				
May	0.02	1	0.28	0.97
June	0.05	1	0.69	0.42
July	0.03	0.99	0.31	0.87
Enjoyable Kayaking				
May	0.02	1	0.24	1.09
June	0.04	1	0.65	0.48
July	0.02	0.99	0.27	0.98
Adequate Angling				
March	0.04	0.59	0.12	0.55
April	0	1	0.22	0.87
May	0	1	0.51	0.77
July	0	1	0.10	2.56
Suitable Fish Habitat				
January	0.14	1	0.37	0.47
February	0.25	1	0.53	0.33
March	0.21	1	0.57	0.36
April	0	1	0.24	1.40
May	0	1	0.60	0.65
June	0	1	0.37	0.87
July	0	1	0.74	0.37
August	0	1	0.63	0.56
September	0	1	0.61	0.62
October	0.30	1	0.76	0.29
November	0.16	1	0.62	0.35
December	0.13	1	0.56	0.26

with a variability of 31% in its membership grades, over 580 realizations. The achievement of this goal may be considered as relatively good in the long term.

In the case of the fuzzy constraints, flood control, water supply and fish habitat appear as the most achievable ones in the long term. In terms of the variability of their membership grades over 580 realizations, in general, fish habitat and flood control present lower coefficients of variation; and therefore, they may be considered as the most reliable ones in their achievement. Rafting, kayaking and angling appear to have a less achievable degree of satisfaction with relatively high variability in their achievement. Hydropower presented the poorest degree of satisfaction over the year and very high variability in its membership grades. A comparison of statistics of membership grades is made in the case of water supply, flood control and hydropower, for both simulation and optimization results. The mean and COV were selected for comparison. The horizontal scale for those figures goes from month 1 (October) to 12 (September).

In the case of water supply, Figure 4.32 shows a comparison of the means; they present the same tendency over the year: the mean membership grades of the optimal results reveal higher achievements than in the case of the simulation results. Figure 4.33 shows the behavior of the COV. Both optimal and simulated results have the same tendency over the year: less variability in the low season and high variability in the high season. Simulation results present higher variability in the low season than optimal results.

In months 4 (January) and 7 (April), the mean of the membership grade for the simulated case is significantly lower than for the optimal case; this is due to the simulated release volumes being lower than their respective optimal ones. Figure 4.33, where the

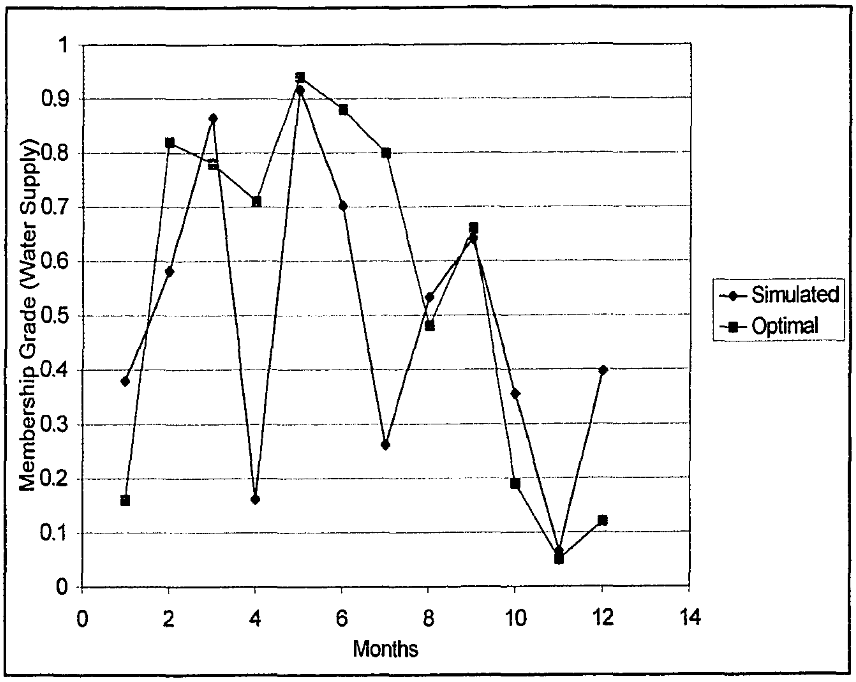


FIGURE 4.32 Means of membership grades of water supply (simulated and optimal).

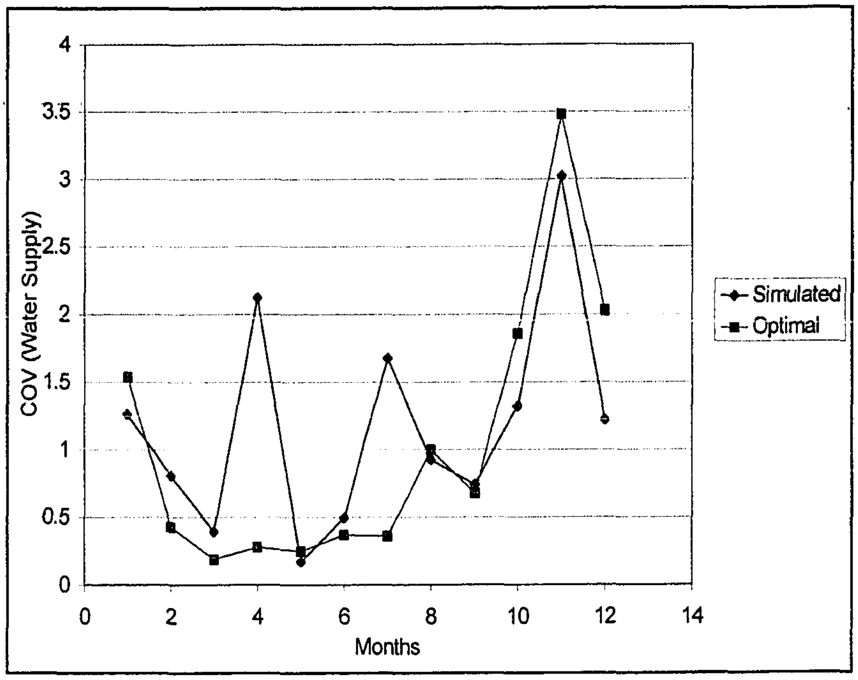


FIGURE 4.33 COV of membership grades of water supply (simulated and optimal).

COV values for such months are very high and significantly different from their respective optimal ones, may also explain such a situation.

The means of the membership grades for flood control are presented in Figure 4.34; means of membership grades range from 0.88 to 0.92. However, simulation results present means in a wider range, from 0.71 to 1, and higher achievements in the low season than in the high season. In month eleven, the mean for the simulated case is significantly higher than the one for the optimal case; this difference is due to greater variability in the simulated storage levels for this month. In the case of the COV, Figure 4.35 presents the COV of both simulated and optimal membership grades. The COV of optimal membership grades range from 0.02 to 0.05; however, in the case of simulation results, the COV of the membership grades reveal a greater variability, especially in months eleven and twelve with values greater than 0.7. This significant difference is also due the high variability of the simulated storage levels in this month. The zero values for COVs in June and July are due to storage levels which were set as constant values for the 580 annual realizations.

In the case of hydropower, Figure 4.36 shows the means of membership grades and Figure 4.37 presents the COV of those membership grades. For the means, both simulated and optimal present the same tendency over the year, high degrees of satisfaction in the summer season and poor achievements in the low season. In the case of the COV, the tendency over the year is the same in both cases: the variability is very high for all the months and is extremely high in the summer season. For the optimal case, in February, despite the average membership grade of zero, the COV is significantly higher than the respective one for the simulated case; this situation occurs due to the high variability of optimal releases for this month. It may be said the achievement of this objective is not reliable in the long term.

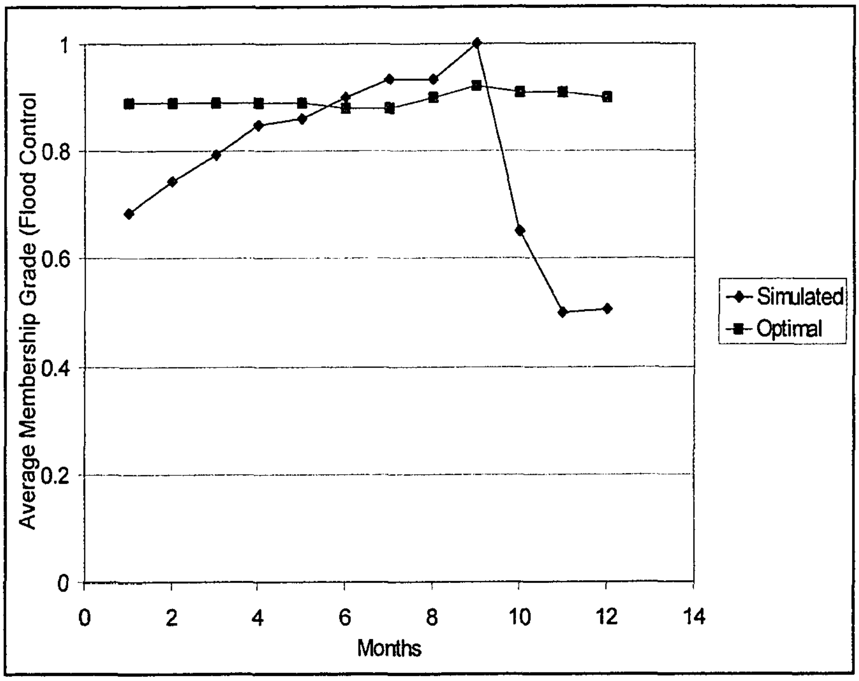


FIGURE 4.34 Means of membership grades of flood control (simulated and optimal).

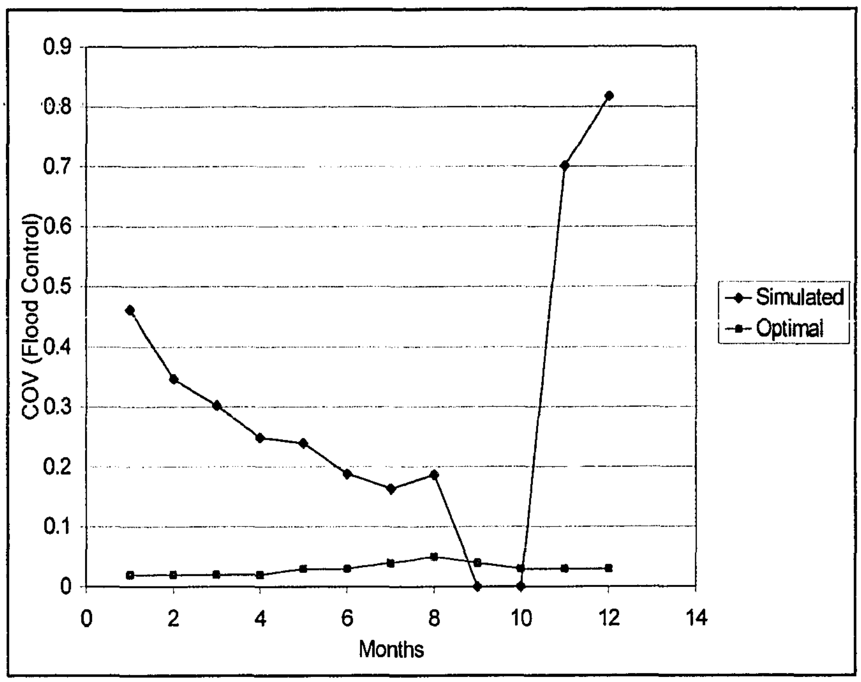


FIGURE 4.35 COV of membership grades of flood control (simulated and optimal).

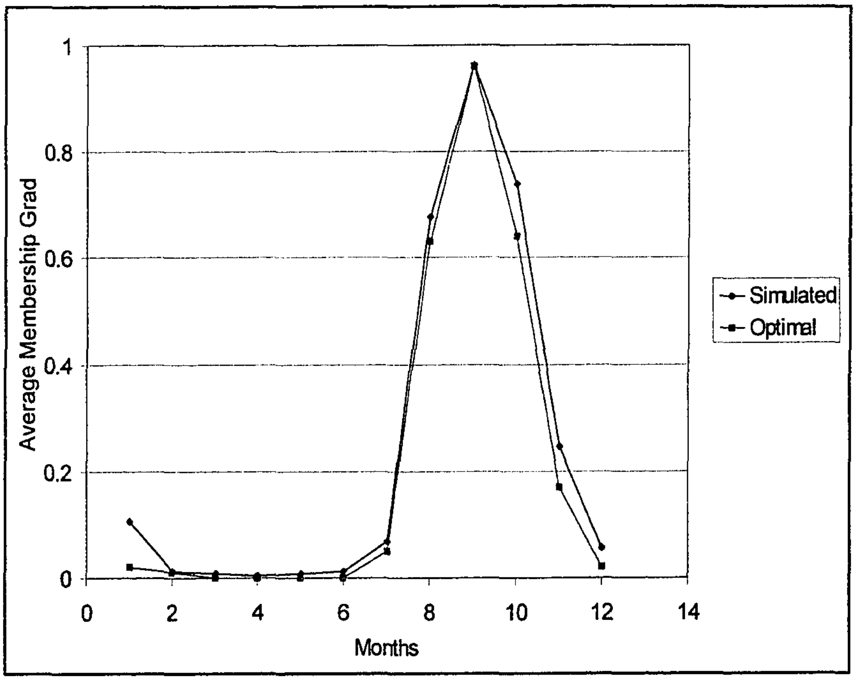


FIGURE 4.36 Means of membership grades of hydropower (simulated and optimal).

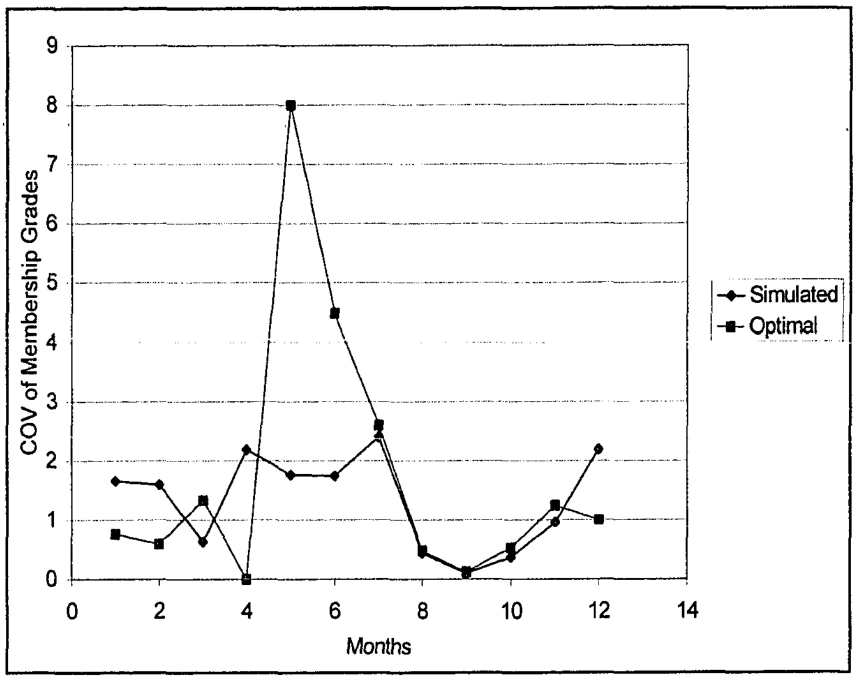


FIGURE 4.37 COV of membership grades of hydropower (simulated and optimal).

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY

Bellman and Zadeh's approach to decision-making in a fuzzy environment was used to develop a methodology to find optimal monthly operational rules of a multipurpose reservoir. The methodology was tested, using the weight operator, in the deterministic case. Furthermore, it was extended to the implicit stochastic case.

The Grey Mountain Reservoir project was selected as the case study. The fuzzy goal was the storage level to be reached at the end of September and the fuzzy constraints were represented by the water uses or objectives of the reservoir. Membership functions for the fuzzy goal and seven objectives were developed through interviews of a selected group of water resource experts and water users who are settled around the Fort Collins and Loveland area. Questionnaires were developed to accomplish this task.

The results of the deterministic case show that the fuzzy approach can produce storage levels and releases trajectory as expected in the case of reservoir operation problems. The advantage of fuzzy dynamic programming is that the form of the results directly indicates the degree of satisfaction of objectives through commensurable and easily interpreted measures of comparison among different kind of objectives.

The implicit stochastic case used a large number of possible annual realizations of inflows and senior water rights. In this case, fuzzy dynamic programming with the weight operator yielded a large sequence of optimal storage levels and releases. For this case study, it was considered that operating rules should be developed to predict storage levels based on previous storages. The linear models had a good fit except for June and July; so, it was decided to set up a volume equal to the optimal average volume for those months.

Finally, those operating rules were tested through a simulation model. The comparison of membership grades of a fuzzy goal and constraints, for both simulated and optimal cases, showed similar trends in the degree of satisfaction of particular objectives. For instance, flood control and water supply appear as the most achievable goals in the long term; however, except for flood control there was, in general, a high variability in the achievement of the objectives.

5.2 CONCLUSIONS

The proposed methodology, to find optimal monthly operational rules of a multipurpose reservoir in a fuzzy environment, represented a new and promising alternative to deal with objectives and constraints formulated in an imprecise form.

Membership functions represented an advantageous way to represent the perception of stakeholders in water issues. The statement that fuzzy sets can be imposed in different spaces enables the horizontal scale of the membership function to deal with non-commensurate objectives like the recreational and environmental ones.

For this case study, it was possible to develop membership functions to represent the subjective perceptions of a variety of water users and managers familiar with the reservoir planning problem.

Through storage level and release trajectory, the results of the deterministic case provided enough evidence that it could yield similar results to crisp optimization formulation, with the advantage that we were now able to easily assess the degree of satisfaction of the fuzzy goal and constraints through the use of membership functions.

In the implicit stochastic case, the results showed that only flood control and water supply objectives were found to have a reasonable expectation of success over the operating season. There was a highly relative variability in the predicted degree of satisfaction of the other objectives, which makes the Grey Mountain Reservoir controversial in terms of its multipurpose feature.

On the other hand, stochastic results allowed development of reliable operating rules to predict storage levels, except for June and July. Finally, simulation results of releases and storage levels showed the reliability of such operating rules through the comparison of statistics of simulated membership grades with their respective optimal stochastic ones.

5.3 RECOMMENDATIONS

1. It is recommended this research be extended to the application of fuzzy sets in the operation of multiple reservoir systems with a multipurpose characteristic. Additional operators like the maximum operator of fuzzy sets should be considered in this case.

2. Further research is recommended to shape with more accuracy the membership functions of fuzzy goals and fuzzy constraints. Moreover, it may be advisable in the future to configure work teams to include both social science experts and water users.

3. In the case of the operation of a multipurpose reservoir, developing the explicit stochastic case and the case when the fuzziness is attached to the state of the system is recommended.

4. Explore the use of neural network approaches and fuzzy control methodologies for the purpose of developing improved operational rules from the results of stochastic fuzzy dynamic programming.

REFERENCES

Ayyub, B., and McCuen, R. (1987). "Quality and Uncertainty Assessment of Wildlife Habitat with Fuzzy Sets." *Journal of Water Resources Planning and Management, ASCE*, 113(1), January.

Bellman, R.E. (1957). Dynamic Programming. Princeton University Press, Princeton, NJ.

Bellman, R.E., and Zadeh, L. (1970). "Decision-Making in a Fuzzy Environment." *Management Science*, 17:B141.

Bhatti, M.A. (1990). "Hybrid Expert System and Optimiration Model for Multipurpose Reservoir Operation." Ph.D. Dissertation, Colorado State University, Fort Collins, CO.

Bogardi, I., and Bardossy, A. (1983). "Regional Management of an Aquifer for Mining under Fuzzy Environmental Objectives." *Water Resources Research*, 19(6), December.

Chameau, J.L. (1990). "Fuzzy Sets in Civil Engineering: A Tutorial." Proceedings of the 17th Annual National Conference, Division of Water Resources Planning and Management, ASCE, Forth Worth, TX, April, pp. 17-21.

Changchit, C., and Terrell, P. (1989). "CCGP Model for Multiobjective Reservoir Systems." *Journal of Water Resources Planning and Management*, ASCE, 115(5), September.

Cohon, J.L., and Marks, D.H. (1975). "A Review and Evaluation of Multiobjective Programming Techniques." Water Resources Research, II(2):208-220.

Colby, B.G. (1990). "Enhancing Instream Flow Benefits in an Era of Water Marketing." *Water Resources Research*, 26:1113-1120.

Croley, T.E. (1977). "Sequential Stochastic Optimization in Water Resources." Ph.D. Dissertation, Colorado State University, Fort Collins, CO, Fall.

Dombi, J. (1990). "Membership Function as an Evaluation." Fuzzy Sets and Systems.

Dreyfus, S.B., and Law, A. (1977). "The Art and Theory of Dynamic Programming." *Mathematics in Science and Engineering*, Academic Press, p. 130.

Duckstein, L., Bogardi, I., and Bardossy, A. (1990). "Fuzzy Sets Theory in Water Resource Systems." Proceedings of the 17th Annual National Conference, Division of WRPM, ASCE, Forth Worth, TX, April 17-21.

Esogbue, A.O., and Bellman, R. (1982). "Contributions to Fuzzy Dynamic Programming." Procceedings of 2nd Conference on Maths, In the Service of Man, Las Palmas.

Esogbue, A.O., and Bellman, R. (1984). "Fuzzy Dynamic Programming and its Extensions." *TIMS Studies in Management Science*, 20:147-164.

Flug, M., and Ahmed, J. (1990). "Prioritizing Flow Alternatives for Social Objectives." *Journal of Water Resources Planning and Management, ASCE.*

Gates, T.K., and Alshaikh, A.A. (1993). "Stochastic Design of Hydraulic Structures in Irrigation Canal Networks." *Journal of Irrigation and Drainage, ASCE*, 119(2):346-363.

Gates, T.K. *et al.* (1991). "Multicriteria Strategic Planning for Improved Irrigation Delivery, I: Approach." *Journal of Irrigation and Drainage, ASCE*, February.

Goicochea, A., Hansen, D.R., and Duckstein, L. (1982). Multiobjective Decision Analysis with Engineering and Business Applications. John Wiley & Sons Ed.

Grigg, N.S. (1985). Water Resources Planning. McGraw Hill Book Company.

Haimes, Y.Y., and Hall, W.A. (1974). "Multiobjective in Water Resource Systems Analysis: The Surrogate Worth Trade Off Method." *Water Resources Research*, 10(4):615-624.

Hall, W.A., and Buras, N. (1961). "The Dynamic Programming Approach to Water Resources Development." *Journal Geophysical Research*, 66(2):510-520.

Hall, W.A., Butcher, W.S., and Esogbue, A. (1968). "Optimization of the Operations of a Multipurpose Reservoir by Dynamic Programming." *Water Resources Research*, 4(3):471-477.

Harza Engineering Company (1990). "Cache La Poudre River Basin, Study Extension." Final Report.

Harza Engineering Company (1987). "Cache La Poudre River Basin, Water and Hydropower Resources Management Study." I and II, January.

Heyder *et al.* (1991). "Mulcriterion Strategic Planning for Improved Irrigation Delivery. II: Application." *Journal of Irrigation and Drainage, ASCE*, February.

Hipel, K.W. (1982). "Fuzzy Sets Methodologies in MultiCriteria Modeling." In Fuzzy Information and Decision Processes (M. Gupta and E. Sanchez, Eds.), North-Holland Publishing Company.

Johnson, L. (1990). "Computer-Aided Planning for Multipurpose Reservoir Operating Policies." *Water Resources Bulletin*, 26(2), April.

Kacprzyk, J. (1983). "Multistage Decision-Making under Fuzziness." Systems Research Institute, Polish Academy of Sciences, Warsaw, Poland, Verlag TUV Rheinland, Germany.

Kacprzyk, J., and Straszak, A. (1982). "A Fuzzy Approach to the stability of Integrated Regional Development." Internal document.

Kandel, A. (1990). "Fuzzy Statistics and Policy Analysis." In Fuzzy Sets: Theory and Applications to Policy Analysis and Information Systems (P.P. Wang and S.K. Chang, Eds.), Plenum Press, pp. 133-145.

Kauffman, A. (1975). Introduction to the Theory of Fuzzy Sets. Academic Press, New York, NY.

Keeney, R. and Wood, E. (1977). "An Illustrative Example of The Use of Multiattribute Utility Theory for Water Res. Planning." *Water Resources Research*, 3(4), August.

Kempton, W. (1983). "Interview Methods for Elliciting Fuzzy Categories." *Fuzzy Sets and Systems Journal.*

Kindler, J. (1992). "Rationalizing Water Requirements with Aid of Fuzzy Allocation Model." *Journal of Water Resources Planning and Management*, ASCE, 118(3), May, June.

Labadie, J.W. (1987). "Computer-Aided in Water Control and Management," Class Notes, Fall, Civil Engineering Department, Colorado State University, Fort Collins, CO.

Labadie, J.W. (1991). "Class Notes on Optimal Control in Water Management." Civil Engineering Department, Colorado State University, Fort Collins, CO.

Loganathan, G.V., and Bhattacharya, D. (1990). "Reservoir Operation by Fuzzy Goal Programming." Proceedings of the 17th Annual National Conference, Division of Water Resources Planning and Management, ASCE, Forth Worth, TX, April 17-21.

Loucks D., and Sigvaldason, O.T. (1982). "Multiple-Reservoir Operation in North America." In Operation of Multiple Reservoir Systems, (Z. Kaczmarek and J. Kindler, Eds.), International Institute for Applied System Analysis, Laxenburg, Austria.

Louie, P.W.F., Yeh, W., and Hsu, N. (1982). "Multiobjective Water Resources Management Planning." *Journal of Water Resources Planning and Management*, 110(1):39-56.

Milhous, R. (1981). "User's Guide to the Physical Habitat Simulation System." Dept. of Interior, Fish and Wildlife Service, Washington DC, Information Paper No. 11.

Mohammadi, A. (1991). "Guidelines for Development and Use of Computer-Based Models in Water Resources Systems." Ph.D. Dissertation, Colorado State University, Fort Collins, CO.

North, R.M. *et al.* (1984). "Goal Programming Applications in Water Resources Project Analysis." In Multiobjective Analysis in Water Resources,(Y.Y. Haimes and D. Allee, Ed.), pp. 125-152.

Norwich, A.M., and Turksen, I.B. (1984). "A Model for the Measurement of Membership and the Consequences of its Empirical Implementation." *Fuzzy Sets and Systems Journal*.

Ouarda, T. (1991). "Stochastic Optimal Operation of Large-Scale Hydropower Systems." Ph.D. Thesis, Civil Engineering Department, Colorado State University, Fort Collins, CO.

Palmer, R., and Lund, J. (1985). "Multi Objective Analysis with Subjective Information." *Journal of Water Resources Planning and Management*, ASCE, III(4), October.

Rea, L.M., and Parker, R.A. (1992). Designing and Conducting Survey Research: A Comprehensive Guide. Jossey-Bass Publishers, San Francisco, CA.

Revelle, C., Joeres, E., and Kirby, W. (1969). "The Linear Decision Rule in Reservoir Management and Design: 1, Development of the Stochastic Model." *Water Resources Research*, 5(4):767-777.

Roefs, T.G. (1968). "Reservoir Management: The State of the Art." IBM, Washington, Scientific Center.

Salas, J.D., Delleur, J.W., Yevjevich, V., and Lane, W.L. (1980). Applied Modeling of Hydrologic Time Series. Water Resource Publications, Fort Collins, CO.

Salas, J.D., and Markus, M. (1992). "Modeling and Generation of Multivariate Seasonal Hydrologic Data (Program CSU003 and CSU004)." Technical Report 3, Computing Hydrology Laboratory, Engineering Research Center, Colorado State University, Fort Collins, CO.

Savic, D.A., and Simonovic, S.P. (1991). "Selecting Risk Levels in Chance-Constrained Reservoir Operation Modeling: A Fuzzy Set Approach." *Water Resources Management*, 4:251-271.

Slowinsky, R. (1986). "A Multicriteria Fuzzy Linear Programming Method for Water Supply System Development." *Fuzzy Sets and Systems Journal.*

Stansburry, J., and Woldt, M. (1991). "Decision Support System for Water Transfer Evaluation." *Water Resources Research*, 27(44):443-451, April.

Tauxe, G. *et al.* (1979). "Multiobjective Dynamic Programming: A Classic Problem Redressed." *Water Resources Research*, 15(6), December.

Taylor, B.W., Davis, R., and North, R.M. (1975). "Approaches to Multiobjective Planning in Water Resource Projects." *Water Resources Bulletin*, 11(5):999-1008.

Yeh, W. (1985). "Reservoir Management and Operation Models; A State-of-the-Art Review." *Water Resources Research*, 1797-1818.

Young, G.K. (1967). "Finding Reservoir Operating Rules." *Journal of Hydraulic Division, ASCE*, 93(HY6):297-321.

Zadeh, L. (1965). "Fuzzy Sets." *Information Control*, 8:338-353.

Zimmermann, H.J. (1987). Fuzzy Sets, Decision Making and Expert Systems. Kluwer Academic Publishers.

APPENDIX A

ADEQUATE MUNICIPAL AND INDUSTRIAL WATER SUPPLY QUESTIONNAIRE

INTRODUCTION

We are carrying out a research in developing monthly operational rules for a multipurpose reservoir, when these purposes or objectives have embedded subjective attributes. The selected case study is the Grey Mountain Reservoir Project, a project in the feasibility stage, which is planned to be located below the Canyon Mouth of the Cache La Poudre River, at the Fort Collins area.

The purposes or objectives considered are agricultural water supply, municipal and industrial water supply, rafting, angling, kayaking, hydropower, flow requirements for fish habitat and flood control.

To accomplish one of the stages of this research, we are interviewing experts in the different areas related to each of the reservoir objectives.

In the case of the municipal and industrial water supply objective, you have been selected as one of the experts whose background and knowledge will provide the needed information to build a function which would show how subjective attributes like ADEQUATE and RELIABLE may influence the achievement of an objective, as in this case, municipal and industrial water supply.

In the case of this objective, and for planning purposes, we are considering an annual demand for municipal and industrial water supply which can be converted into a monthly demand(Qd_i) by using monthly distribution coefficients(α_i).

This monthly demand or required demand (Qd_i) will be fully or less satisfied depending on the released flow or discharge(Qr_i). So, a shortage or a surplus can be calculated as the resulting rate of dividing the difference between Qd_i and Qr_i, over Qd_i. Then, if S_i is the variable accounting for either a shortage or a surplus, we should have:

If $S_i = 0$ means Qd_i is being met by Qr_i

$S_i > 0$ means $Qd_i > Qr_i$, and demand is not being met by Qr_i (shortage).

$S_i < 0$ means $Qd_i < Qr_i$, and release is greater than demand (surplus).

In the next series of questions we will be trying to find out how you qualify the achievement level of this objcctive, when the delivered flow Qr_i is either equal or different from the demand Qd_i. Remember, your individual answers to these questions are strictly confidential and will never be released to any private individual or commercial interest.

Please, take the time to complete this questionnaire. There are no correct or incorrect answers, only your much-needed opinions.

Thank you for your assistance.

1.- Suppose that the released water Qr_i, in month i, meets the required demand Qd_i. On a scale from 0 to 10, how would you measure the achievement of an objective of an ADEQUATE Municipal and Industrial Water Supply ?

(You should consider a value of 10 means 100%, and 0 means 0%)

1.- Ten........ 2.- Other..........

Shortage

2.- In case of having a shortage, for instance in July (summer season), in your opinion how would the shortage be affecting the achievement of an ADEQUATE Municipal and Industrial Water Supply objective (in a scale 0 - 10).

Ex: A shortage equal to 20% may means a 8.5 grade of achievement of this objective.

Shortage(%)	Achievement of this objective (Scale 0 - 10)
1) 1 - 5	....
2) 6 - 10	....
3) 11 - 15	....
4) 16 - 20	....
5) 21 - 25	....
6) 26 - 30	....
7) 31 - 35	....
8) 36 - 40	....
9) 41 - 45	....
10) 46 - 50	....
11) 51 - 55	....

12) 56 - 60 ....

13) 61 - 65 ....

14) 66 - 70 ....

15) 71 - 75 ....

16) 76 - 80 ....

17) 81 - 85 ....

18) 86 - 90 ....

19) 91 - 95 ....

20) 96 - 100 ....

3.- Shortages can be present at any month i. Even tough the shortage at month i can be the same as the one at month j, the impact on the achievement of an ADEQUATE Municipal and Industrial Water Supply objective may be different, depending sometimes on the season in which the shortages occur.

Do you agree with this statement?

1.- Yes .... 2.- No ....

4.- Following the procedure shown in question 2, please indicate the level of achievement of an ADEQUATE Municipal and Industrial Water Supply (in a scale 0 - 10), as a function of the shortage taking place in a month i. (You may decide on using a pattern for each season; if you decide to do so, you should fill out only one month for each season).

FALL | WINTER | SPRING | SUMMER

Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Shortage

% Level of Achievement of the objective (Scale 0 -10)

1) 1 - 5 ... ...

2) 6 -10 ... ...

3) 11 -15 ... ...

4) 16 -20 ... ...

5) 21 -25 ... ...

6) 26 -30 ... ...

7) 31 -35 ... ...

8) 36 -40 ... ...

9) 41 -45 ... ...

10) 46-50 ... ...

11) 51-55 ... ...

12) 56-60 ... ...

13) 61-65 ... ...

14) 66-70 ... ...

15) 71-75 ... ...

16) 76-80 ... ...

17) 81-85 ... ...

18) 86-90 ... ...

19) 91-95 ... ...

20) 96-100 .. ..

5.- Now depending on the level of shortage and how many times per year this shortage occurs, the reliability on the reservoir maybe affected. Please, in your opinion (On a scale 0 - 10, 10 means 100%) how much RELIABLE is being the reservoir to meet municipal and industrial water demands?

Number of fails per year

1 2 3 4 5 6 7 8 9 10 11 12

Shortage

% Level of Achievement of the objective (Scale 0 -10)

1) 1 - 5 ... ...

2) 6 -10 ... ...

3) 11 -15 ... ...

4) 16 -20 ... ...

5) 21 -25 ... ...

6) 26 -30 ... ...

7) 31 -35 ... ...

8) 36 -40 ... ...

9) 41 -45 ... ...

10) 46-50 ... ...

11) 51-55 ... ...

12) 56-60 ... ...

13) 61-65 ... ...

14) 66-70 ... ...

15) 71-75 ... ...

16) 76-80 ... ...

17) 81-85 ... ...

18) 86-90 ... ...

19) 91-95 ... ...

20) 96-100 .. ..

Surplus

6.- Now, in the case of having surplus water, for instance in July (summer season), how would a surplus affect the achievement of an ADEQUATE Municipal and Industrial Water Supply objective.

Ex: A surplus of 40% may means to promote an inefficient use of water and therefore a 20% (or 2 in a scale 0 - 10) of achievement of this objective.

Surplus (%)	Achievement of this objective (Scale 0 - 10)
1) 1 - 10	....
2) 11 - 20	....
3) 21 - 30	....
4) 31 - 40	....
5) 41 - 50	....
6) 51 - 60	....
7) > 60	....

7.- A surplus can be present at any month i, especially in summer months. However, even tough the surplus at month i may be the same as the one at month j, the impact on the ADEQUATE Municipal and Industrial Water Supply objective may be different.

Do you agree with this statement?

1.- Yes ...... 2.- No........

8.- Now, following the procedure shown in question 6, please indicate the level of achievement of an ADEQUATE Municipal and Industrial Water Supply objective (in a scale 0 - 10) when a surplus is taking place at month i. (You may decide on using a pattern for each season; if you decide to do so, you should fill out only one month for each season).

FALL | WINTER | SPRING | SUMMER

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

Surplus

% Level of achievement of this objective (0 - 10)

1) 1-10 ... ...

2) 11-20 ... ...

3) 21-30 ... ...

4) 31-40 ... ...

5) 41-50 ... ...

6) 51-60 ... ...

7) >60 ... ...

9.- Now depending on the level of surplus and how many times per year surpluses are occurring, the reliability of the reservoir maybe affected. Please, on a scale 0 - 10 (10 means 100 %),in your opinion how much RELIABLE is being the reservoir when releases are greater than municipal and industrial water demands?

Number of surpluses per year

1 2 3 4 5 6 7 8 9 10 11 12

Surplus

% Level of achievement of this objective (0 - 10)

1) 1-10 ... ...

2) 11-20 ... ...

3) 21-30 ... ...

4) 31-40 ... ...

5) 41-50 ... ...

6) 51-60 ... ...

7) >60 ... ...

10.- If you were asked to assign a weight to this objective, relative to all other objectives what weight (0 - 100 %) would you assign?

1.- .....

11.- Suppose we were considering to shift the subjective attribute ADEQUATE to a VERY ADEQUATE attribute. In order to build its respective preference function, please select an option that best represents your opinion in regard to this shift.

1.- Add a percentage to the whole ......(Please, go to 12)
information gathered up to here

2.- No difference between these
two attributes .... (Please, go to 13)

12.- Please, select a percentage rate it would best represent a shifting from ADEQUATE to VERY ADEQUATE attribute.

1.- 20 % .... 2.- 30 % ......

3.- 40% .... 4.- 50 % ......

5.- >50 % .... 6.- Other .....

13.- Suppose we were considering to shift the subjective attribute RELIABLE to a VERY RELIABLE attribute. In order to build its respective preference function, please select an option that best represents your opinion in regard to this shift.

1.- Add a percentage to the whole information gathered up to here ......(Please, go to 14)

2.- No difference between these two attributes .... (End here).

14.- Please, select a percentage rate it would best represent a shifting from RELIABLE to VERY RELIABLE attribute.

1.- 20 %	2.- 30 % ......
3.- 40%	4.- 50 % ......
5.- >50 %	6.- Other .....

Thanks for your cooperation

Fort Collins, July 1992

APPENDIX B

MEMBERSHIP FUNCTIONS

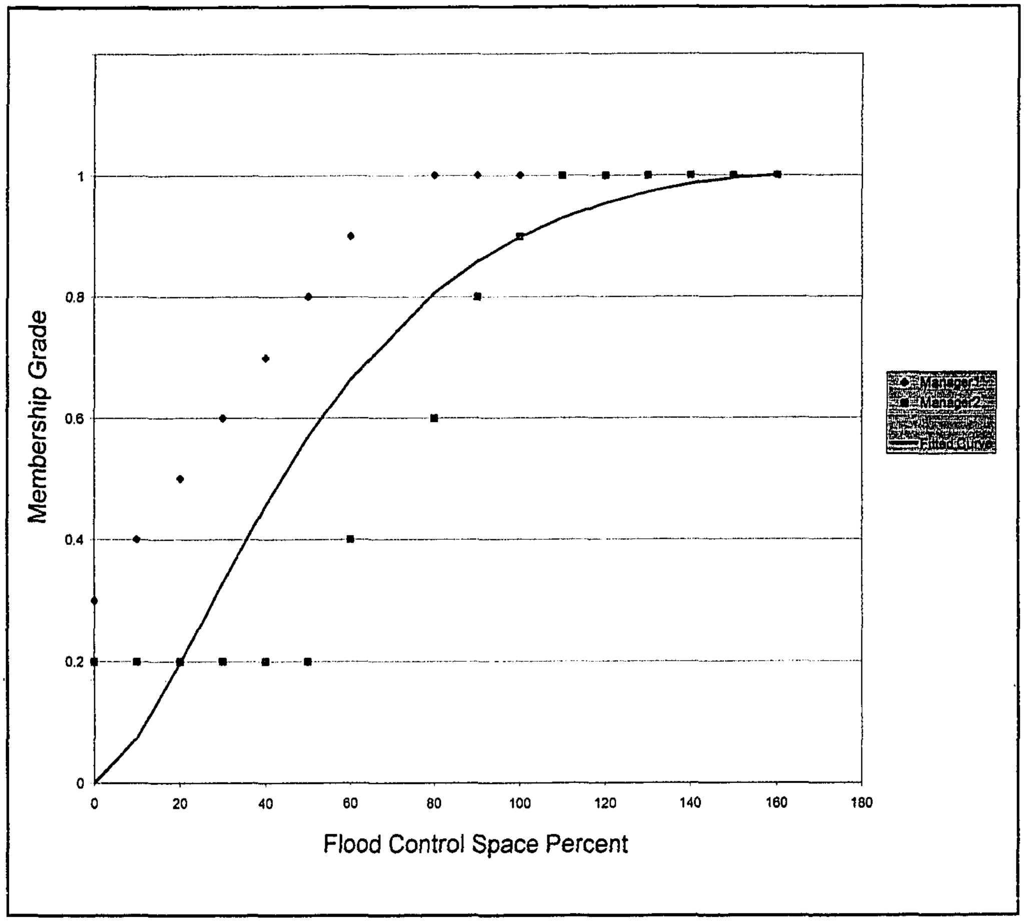


FIGURE B.1 Membership function of flood control objective (October - March).

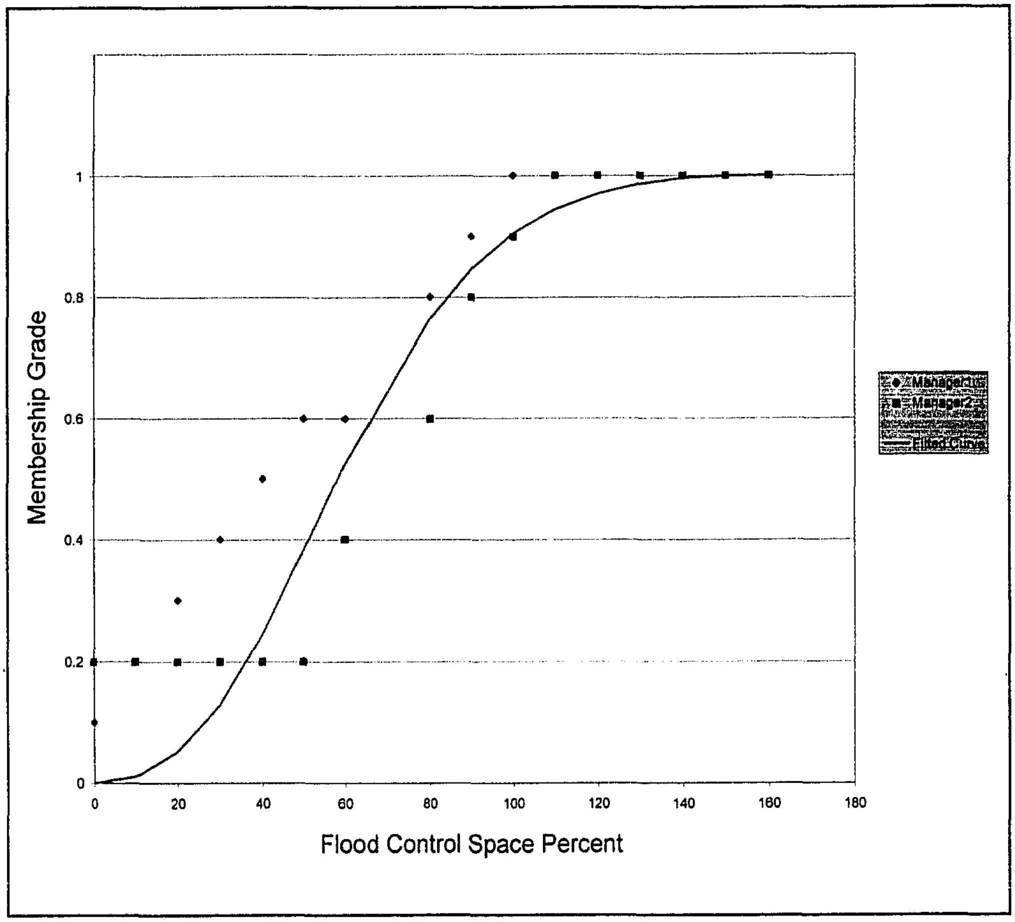


FIGURE B.2 Membership function of flood control objective (April).

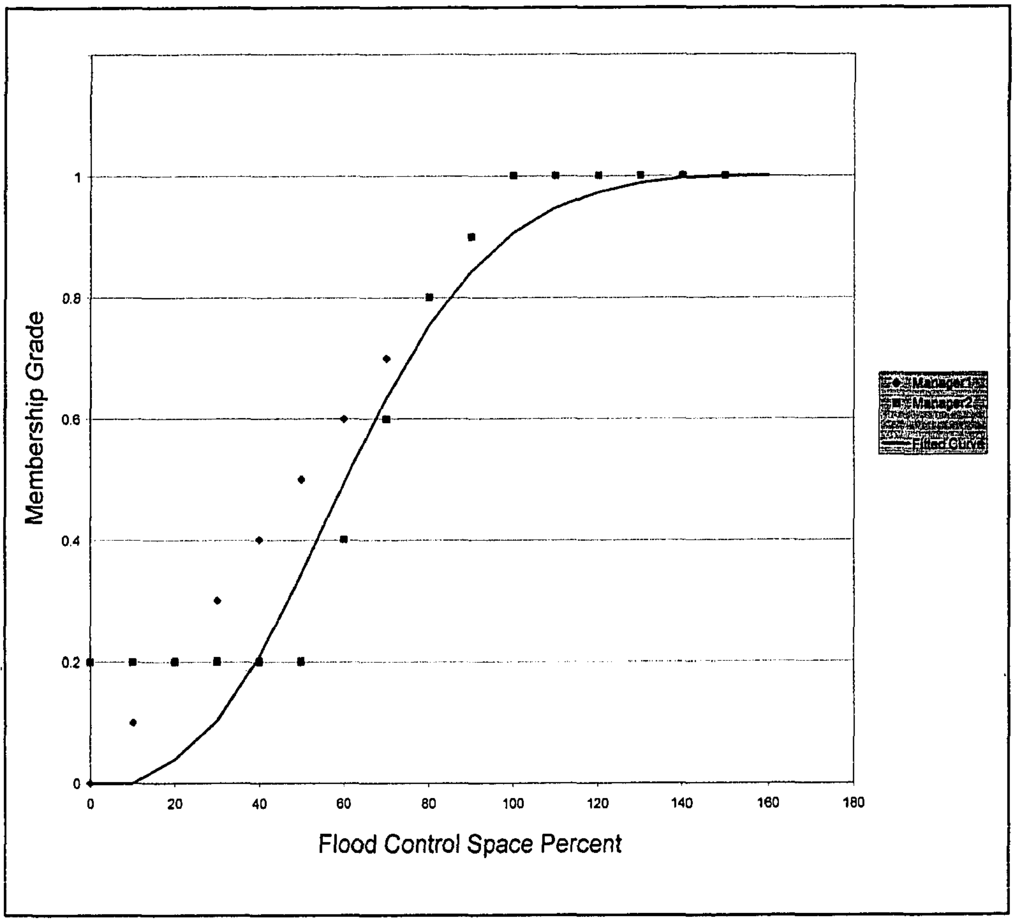


FIGURE B.3 Membership function of flood control objective (August).

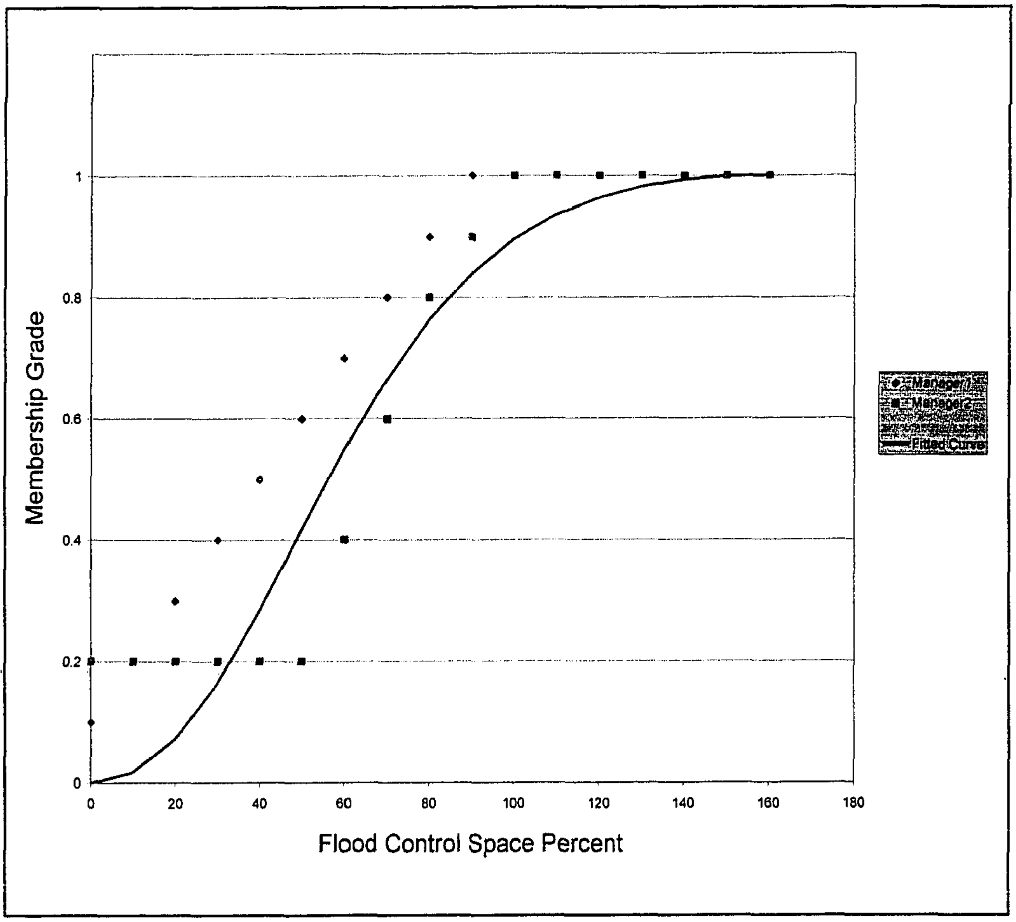


FIGURE B.4 Membership function of flood control objective (September).

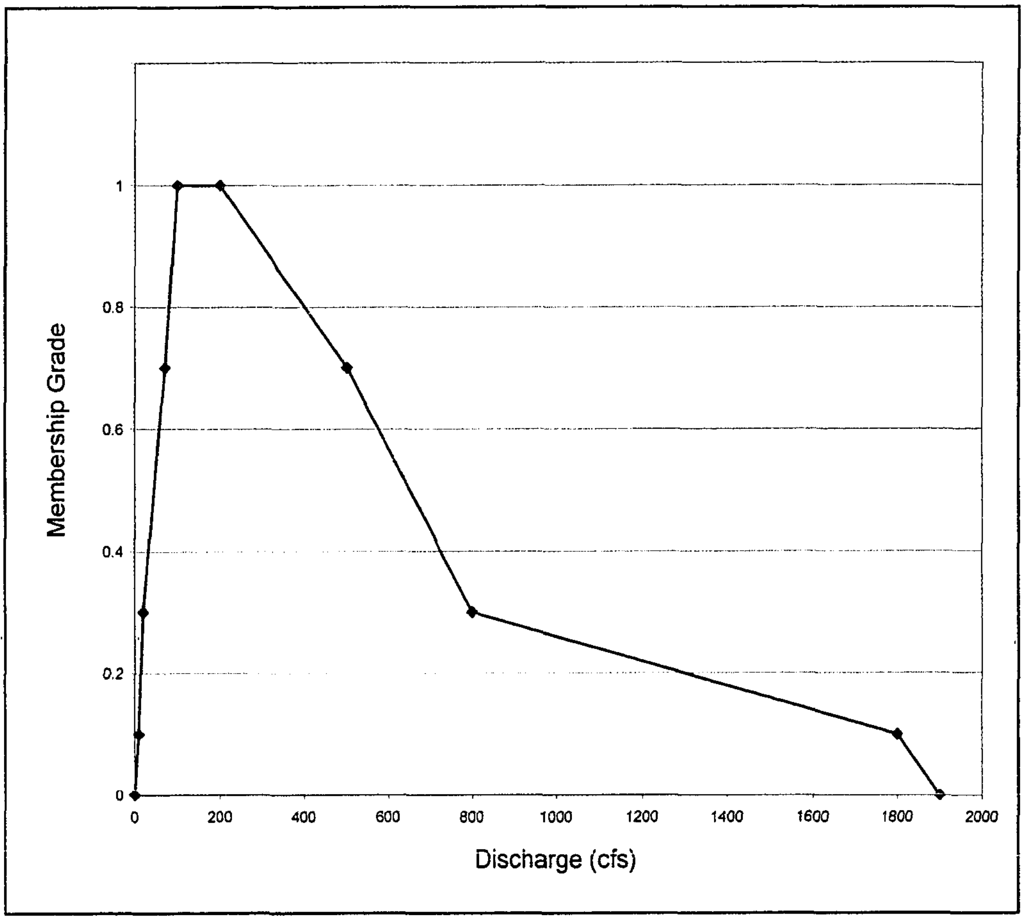


FIGURE B.5 Membership function of fish habitat objective (October - March).

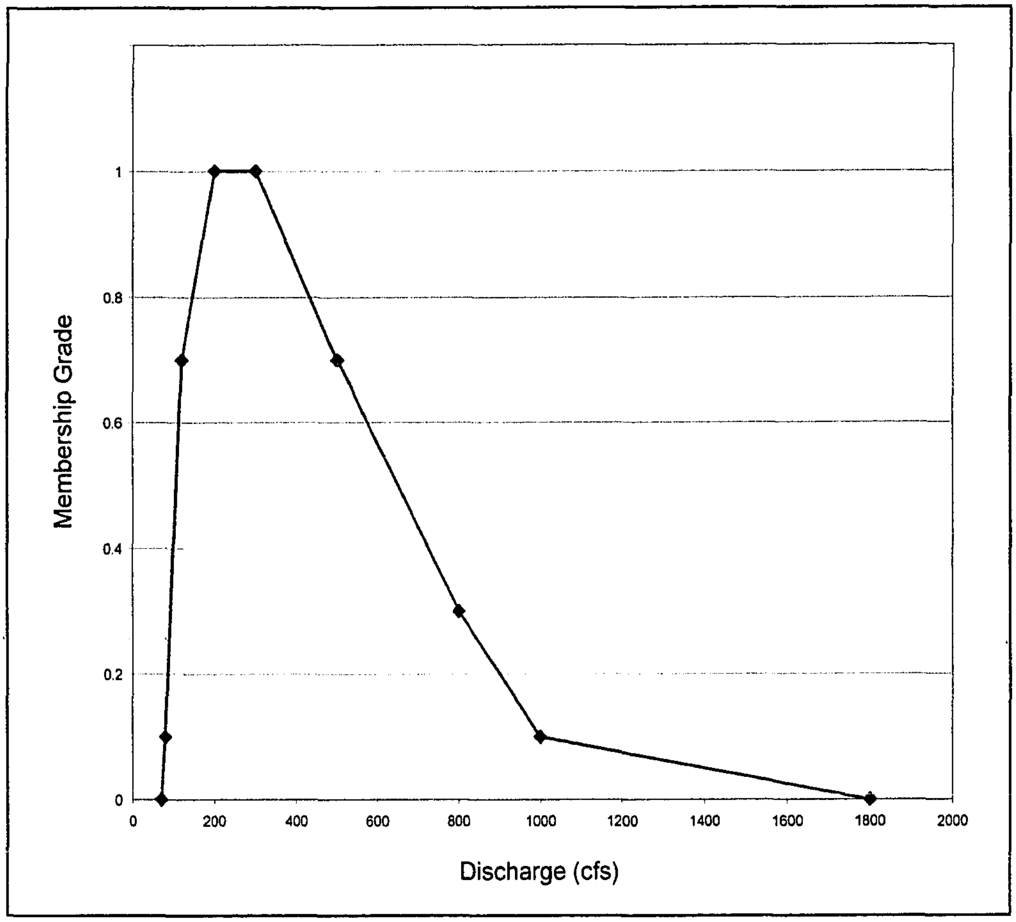


FIGURE B.6 Membership function of fish habitat objective (April).

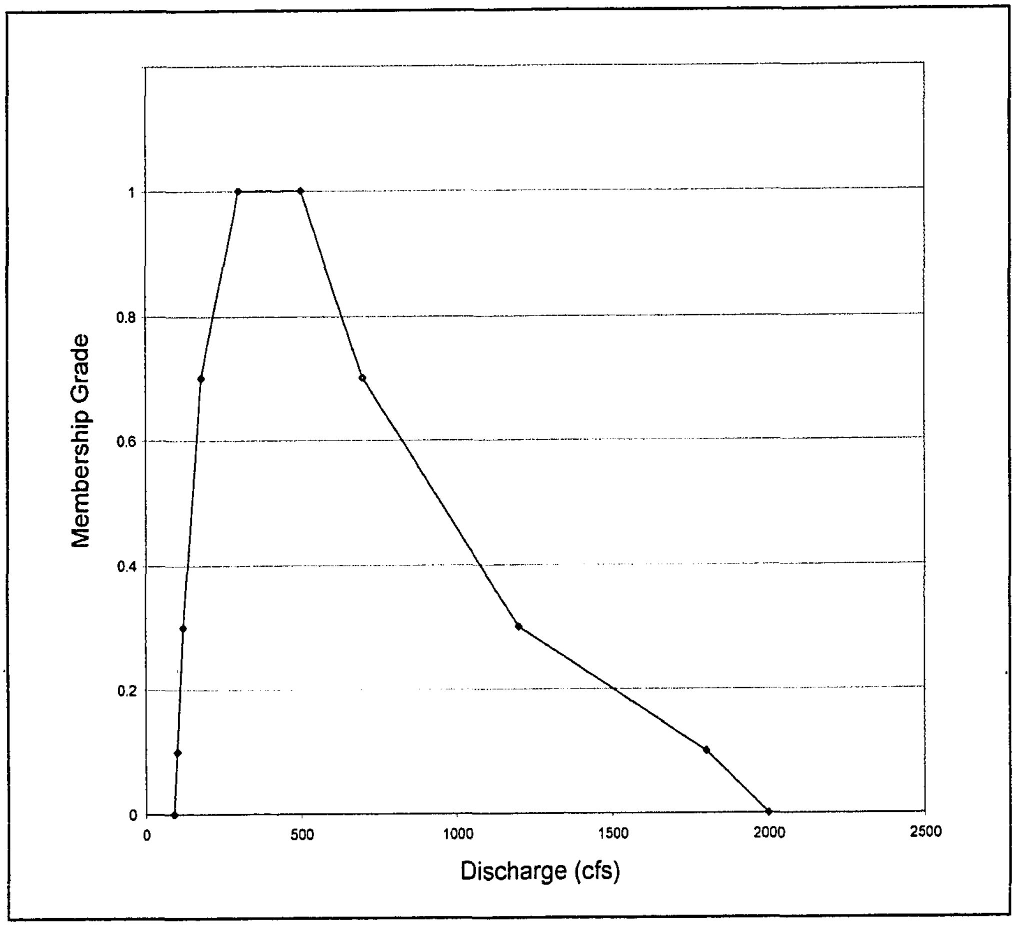


FIGURE B.7 Membership function of fish habitat objective (August).

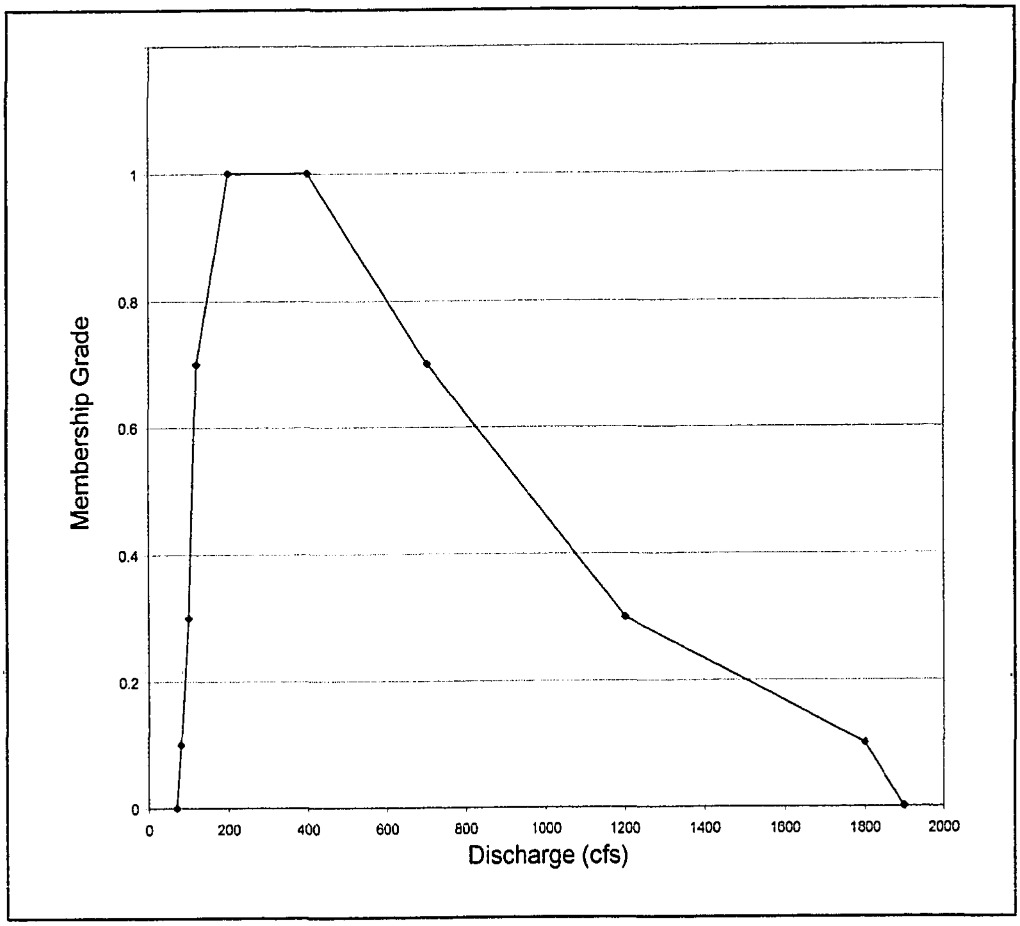


FIGURE B.8 Membership function of fish habitat objective (September).

APPENDIX C

CSUDP SUBROUTINES

```
C! ****************************************************************** !C
C!       *****      SUBROUTINE STATE     *****                         !C
C! ****************************************************************** !C
C! THIS SUBROUTINE COMPUTES THE RELEASE BASED UPON THE BEGINNING      !C
C! AND ENDING RESERVOIR STORAGES USING THE WATER BALANCE EQUATION     !C
C! ****************************************************************** !C
C!                                                                    !C
C! FOR ALL SUBROUTINES THE MAIN VARIABLES USED ARE:                   !C
C!                                                                    !C
C!  X  = BEGINNING RESERVOIR STORAGE IN MCM                           !C
C!  X1 = ENDING RESERVOIR STORAGE IN MCM                              !C
C!  U  = RESERVOIR RELEASE IN MCM                                     !C
C!  I  = STAGE OF THE ANALYSIS IN MONTHS                              !C
C!  IM = COUNTER FOR MONTHS WHERE MONTH 10 CORRESPONDS TO STAGE 1     !C
C!                                                                    !C
C! ****************************************************************** !C
      SUBROUTINE STATE
      COMMON/ONEDM/X,X1,U,F,I,J,K,L,R,PNALTY
      COMMON/RESDAT/FLOWIN(360),WDEMAN(12),EDEMAN(12),EVAPRT(12),HEAD,
     1              PWRREL,AREA,EVAP,DEPL(360),ALPHA(12),BETA(12),
     2              WATER, ENERGY, FTYPE, VACT, IM
      COMMON/COEFF/TEFF,HEADMN,HEADMX,TURMAX,HRS,A1,A2,A3,H1,H2,H3,
     *             T1,T2,T3,WGT1(4),WGT2(5),WGT3(7)
      INTEGER FTYPE
C! CALCULATE AVERAGE VOLUME FOR AREA AND HEAD CALCULATIONS
      VOLAVG = 0.5 *(X + X1)
C! CALCULATE AVERAGE AREA AS A FUNCTION OF AVERAGE VOLUME
      AREA = A1 + A2*VOLAVG**A3
C! CALCULATE AVERAGE HEAD AS A FUNCTION OF AVERAGE VOLUME
      HEAD = H1 + H2*VOLAVG**H3
C! CALCULATE EFFICIENCY AS A FUNCTION OF AVERAGE HEAD
      TEFF = T1 + T2*HEAD**T3
C! CONVERT STAGE TO MONTH FOR REQUIRED CALCULATIONS
C! NOTE THAT OCTOBER IS TREATED AS MONTH 1
      IMM = MOD(I,12)
      IF (IMM .EQ. 0) IMM = 12
      CALL MONTH(IMM, IM)
C! CALCULATE EVAPORATION FOR THE MONTH
      EVAP = EVAPRT(IM)*AREA
C! USE THE VARIABLE DEPL FOR REQUIRED DOWNSTREAM DELIVERIES
C! CALCULATE RELEASE USING THE INVERTED FORM OF THE STATE EQUATION
C! NOTE THAT X AND X1 ARE REVERSED SINCE THE PROBLEM IS BEING
C! SOLVED FORWARDS
C!
      U = X1 - X + FLOWIN(I) - EVAP - DEPL(I)
C!
      RETURN
      END
       SUBROUTINE MONTH (IMM, IM)
       IF (IMM .EQ. 12) IM = 10
       IF (IMM .EQ. 11) IM = 11
       IF (IMM .EQ. 10) IM = 12
       IF (IMM .EQ. 9) IM = 1
       IF (IMM .EQ. 8) IM = 2
       IF (IMM .EQ. 7) IM = 3
       IF (IMM .EQ. 6) IM = 4
       IF (IMM .EQ. 5) IM = 5
       IF (IMM .EQ. 4) IM = 6
       IF (IMM .EQ. 3) IM = 7
       IF (IMM .EQ. 2) IM = 8
       IF (IMM .EQ. 1) IM = 9
       RETURN
       END
```

```
C! ****************************************************************** !C
C!        *****      SUBROUTINE OBJECT     *****                      !C
C! ****************************************************************** !C
C! THIS SUBROUTINE COMPUTES THE DEGREE OF MEMBERSHIP IN THE           !C
C! VARIOUS MEMBERSHIP RELATIONSHIPS FOR EACH PURPOSE OF THE           !C
C! RESERVOIR BASED UPON THE WATER AND ENERGY DELIVERED                !C
C! BASED UPON  THE BEGINNING AND ENDING RESERVOIR                     !C
C! STORAGES AND THE RELEASE                                           !C
C! ****************************************************************** !C
C!
      SUBROUTINE OBJECT
      COMMON/ONEDM/X,X1,U,F,I,J,K,L,R,PNALTY
      COMMON/RESDAT/FLOWIN(360),WDEMAN(12),EDEMAN(12),EVAPRT(12),HEAD,
     1              PWRREL,AREA,EVAP,DEPL(360),ALPHA(12),BETA(12),
     2              WATER, ENERGY, FTYPE, VACT, IM
      COMMON/COEFF/TEFF,HEADMN,HEADMX,TURMAX,HRS,A1,A2,A3,H1,H2,H3,
     *             T1,T2,T3,WGT1(4),WGT2(5),WGT3(7)
      COMMON/MEMBER/UG, UWS, UFC, UHP, UR, UK, UA, UFH
      COMMON/TRACE/ITRACE
      INTEGER FTYPE
      LOGICAL ITRACE
C! CALCULATE DOWNSTREAM WATER SUPPLY PRODUCED IN MCM
      WATER = U + DEPL(I)
C! CALCULATE ENERGY PRODUCED IN MWH
C! DO NOT RELEASE MORE THAN THE MAXIMUM TURBINE FLOW FOR POWER
      PWRREL = AMIN1(WATER, TURMAX)
C! IF RESERVOIR IS BELOW MINIMUM HEAD DO NOT PRODUCE ENERGY
      IF ( HEAD .LT. HEADMN ) PWRREL = 0.0
C! IF RESERVOIR IS ABOVE MAXIMUM HEAD DO NOT PRODUCE ENERGY
      IF ( HEAD .GT. HEADMX ) PWRREL = 0.0
C! COMPUTE ENERGY IN MWH
      ENERGY = (HRS/730.)*2.72*PWRREL*HEAD*TEFF
C!
C!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
C!
C! COMPUTE DEGREE OF MEMBERSHIP IN THE VARIOUS FUNCTIONS
C!
C!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
C!  COMPUTE THE DEGREE OF GOAL ACHIEVEMENT OF BEING IN THE
C!  NEIGHBORHOOD OF THE TOTAL ACTIVE VOLUME (MCM)
C!
      UG = 1.0
      IF (IM .NE. 9) GO TO 110
100   CONTINUE
       IF (X .LE. 183) UG = 0.0
       IF (X .GE. 241) UG = 0.0
       IF ((X .GT. 183) .AND. (X .LE. 229)) UG = (X - 183) /
     *  (229 - 183)
       IF ((X .GT. 229) .AND. (X .LE. 234)) UG = 1.0
       IF ((X .GT. 234) .AND. (X .LT. 241)) UG = (241 - X) /
     *  (241 - 234)
C!
110   CONTINUE
C!
C!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
C!  COMPUTE THE DEGREE OF ADEQUATE WATER SUPPLY
C!
C!  COMPUTE THE PERCENT OF DEMAND ACHIEVMENT
      DAP = 100.0 * (U / WDEMAN (IM))
C!  COMPUTE THE DEGREE OF MEMBERSHIP IF FALL
      IF ((IM .GE. 10) .AND. (IM .LE. 12)) UWS = 1 /
     *   (1 + EXP(-0.116 * (DAP - 88.33)))
C!  COMPUTE THE DEGREE OF MEMBERSHIP IF WINTER
```

```
      IF ((IM .GE. 1) .AND. (IM .LE. 3)) UWS = 1 /
     *    (1 + EXP(-0.8735 * (DAP - 97.49)))
C!  COMPUTE THE DEGREE OF MEMBERSHIP IF SPRING
      IF ((IM .GE. 4) .AND. (IM .LE. 6)) UWS = 1 /
     *    (1 + EXP(-0.256 * (DAP - 90.95)))
C!  COMPUTE THE DEGREE OF MEMBERSHIP IF SUMMER
      IF ((IM .GE. 7) .AND. (IM .LE. 9)) THEN
C!
C!  SET PARAMETERS FOR THE GENERAL S- CURVE MEMBERSHIP FUNCTION
C!
       V = 0.10
       RR = 2.847
       A = 70.0
       B = 160.0
       CALL MBRSHP (DAP,V,RR,A,B,VMF)
       UWS = VMF
      ENDIF
C!
C!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
C!  COMPUTE THE DEGREE OF DEPENDABLE FLOOD CONTROL SPACE
C!
C!  COMPUTE THE % OF FLOOD CONTROL SPACE
C!
      FCSP = 100 * (X1 / VACT)
C!
C!  SET THE PARAMETERS OF THE MEMBERSHIP FUNCTION BASED UPON
C!  MONTH
C!
      IF (IM .LE. 3 .OR. IM .GE. 10) THEN
        V = 0.043
        RR = 1.46
        A = 0.0
        B = 160.0
      ELSEIF (IM .EQ. 4) THEN
        V = 0.256
        RR = 2.1
        A = 0.0
        B = 160.0
      ELSEIF (IM .EQ. 5) THEN
        V = 0.191
        RR = 2.3
        A = 20.0
        B = 160.0
      ELSEIF (IM .EQ. 6) THEN
        V = 0.275
        RR = 2.6
        A = 10.0
        B = 160.0
      ELSEIF (IM .EQ. 7) THEN
        V = 0.336
        RR = 2.43
        A = 0.0
        B = 160.0
      ELSEIF (IM .EQ. 8) THEN
        V = 0.289
        RR = 2.24
        A = 0.0
        B = 160.0
      ELSEIF (IM .EQ. 9) THEN
        V = 0.216
        RR = 1.91
        A = 0.0
        B = 160.0
```

```
      ENDIF
C!  COMPUTE MEMBERSHIP FUNCTION VALUE
        CALL MBRSHP (FCSP,V,RR,A,B,VMF)
        UFC = VMF
C!
C!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
C!  COMPUTE THE DEGREE OF EFFICIENT HYDROPOWER GENERATION
C!
C!  COMPUTE THE % OF ENERGY DEMAND
C!
          EDP = 100 * (ENERGY / EDEMAN(IM))
C!
C!  SET THE PARAMETERS OF THE MEMBERSHIP FUNCTION BASED UPON
C!  MONTH
C!
          IF (((IM .GE. 4) .AND. (IM .LT. 7)) .OR.
     *        ((IM .GE. 10) .AND. (IM .LE. 12))) THEN
          V = 0.226
          RR = 2.0
          A = 0.0
          B = 160.0
          ELSEIF (((IM .GE. 7) .AND. (IM .LT. 10)) .OR.
     *        ((IM .GE. 1) .AND. (IM .LT. 4))) THEN
           V = 0.328
           RR = 2.49
           A = 0.0
           B = 160.0
           ENDIF
           CALL MBRSHP (EDP,V,RR,A,B,VMF)
           UHP = VMF
C!
C!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
C!  COMPUTE THE DEGREE OF ENJOYABLE RAFTING
C!
C!  THE DISCHARGE FOR RAFTING IS USED AS MCM
C!
          RDCH = WATER
C!
          UR = 1.0
         IF ((IM .GE. 5) .AND. (IM .LE. 7)) UR = 1 /
     *    (1 + EXP(-0.05 * (RDCH - 78.29)))
C!
C!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
C!  COMPUTE THE DEGREE OF ENJOYABLE KAYAKING BASED ON FLOW IN MCM
C!
          KDCH = RDCH
C!
          UK = 1.0
         IF ((IM .GE. 5) .AND. (IM .LE. 7)) UK = 1 /
     *    (1 + EXP(-0.05 * (RDCH - 84.70)))
C!
C!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
C!  COMPUTE THE DEGREE OF ADEQUATE ANGLING BASED ON FLOW IN MCM
C!
       UA = 1.0
       CALL ANGLING (RDCH, IM, UA)
C!
C!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
C!  COMPUTE THE DEGREE OF SUITABLE FISH HABITAT
C!  BASED ON FLOW IN CFS
C!
C!  CONVERT FLOW FROM MCM TO CFS
C!
```

```
      DCH = (WATER / 2.628) * 35.315
      CALL FHABIT (DCH, IM, UFH)
C!
C!
C!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
C!  DEPENDING UPON THE VALUE OF FTYPE COMPUTE THE STAGE
C!  RETURN FUNCTION AS EITHER A MAX(MIN) OR
C!  MAX WEIGHTED SUMMATION
C!
      IF (FTYPE .EQ. 1) F = MIN (UWS, UFC, UHP, UR, UK, UA, UFH)
      IF ((IM .LE. 2) .AND. (IM .GE. 11)) THEN
        IF (FTYPE .EQ. 2) F = WGT1(1)*UWS + WGT1(2)*UFC
     *                         + WGT1(3)*UHP + WGT1(4)*UFH
      ELSEIF ((IM .LE. 4) .AND. (IM .GE. 8)) THEN
        IF (FTYPE .EQ. 2) F = WGT2(1)*UWS + WGT2(2)*UFC
     *               + WGT2(3)*UHP + WGT2(4)*UA + WGT2(5)*UFH
      ELSE
        IF (FTYPE .EQ. 2) F = WGT3(1)*UWS + WGT3(2)*UFC
     *               + WGT3(3)*UHP + WGT3(4)*UR + WGT3(5)*UK
     *               + WGT3(6)*UA + WGT3(7)*UFH
      ENDIF
        IF (IM .EQ. 9) F = MIN (F, UG)
C!
      IF (ITRACE) CALL RESULT
      RETURN
      END
C
C! ****************************************************************** !C
C!       *****      SUBROUTINE MBRSHP     *****                         !C
C! ****************************************************************** !C
C! THIS SUBROUTINE COMPUTES A COMMON MATHEMATICAL S-CURVE SHAPE USED  !C
C! FOR SEVERAL OF THE MEMBERSHIP FUNCTIONS                            !C
C! ****************************************************************** !C

        SUBROUTINE MBRSHP (XX,V,RR,A,B,VMF)
C!
C!  COMPUTE THE COMPONENTS OF THE EQUATION
C!
C!  TEST FOR INCOMPATIBLE VALUES OF V AND XX
C!
        IF ((V .GT. 1) .OR. (A .GT. XX)) THEN
            VMF = 0.0
            RETURN
        ELSEIF (B .LT. XX) THEN
            VMF = 1.0
            RETURN
        ENDIF
        C1 = (1 - V)**(RR-1)
        C2 = (XX - A)**RR
        C3 = V**(RR-1)
        C4 = (B - XX)**RR
C!
C!  COMPUTE THE VALUE OF THE EQUATION
C!
        VMF = (C1 * C2) / ((C1*C2) + (C3 * C4))
        RETURN
        END
C!
C! ****************************************************************** !C
C!       *****      SUBROUTINE ANGLING    *****                         !C
C! ****************************************************************** !C
C! THIS SUBROUTINE COMPUTES THE MEMBERSHIP FUNCTION FOR ANGLING       !C
C! ****************************************************************** !C
```

```
      SUBROUTINE ANGLING (RDCH, IM, UA)

      IF ((IM .GE. 11) .OR. (IM .LE. 2)) UA = 0.0
      IF ((IM .GE. 3) .AND. (IM .LE. 8)) THEN
         IF (RDCH .LE. 14.87) UA = (RDCH/14.87) * 0.5
         IF ((RDCH .GT. 14.87) .AND. (RDCH .LE. 22.34)) UA =
     *        ((RDCH - 14.87)/(22.34 - 14.87)) * (0.7 - 0.5) + 0.5
         IF ((RDCH .GT. 22.34) .AND. (RDCH .LE. 29.78)) UA =
     *        ((RDCH - 22.34)/(29.78 - 22.34)) * (0.8 - 0.7) + 0.7
         IF ((RDCH .GT. 29.78) .AND. (RDCH .LE. 37.24)) UA =
     *        ((RDCH - 29.78)/(37.24 - 29.78)) * (1.0 - 0.8) + 0.8
         IF ((RDCH .GT. 37.24) .AND. (RDCH .LE. 44.68)) UA = 1.0
         IF ((RDCH .GT. 44.68) .AND. (RDCH .LE. 52.11)) UA = 1.0 -
     *        ((RDCH - 44.68)/(52.11 - 44.68)) * (1.0 - 0.7)
         IF ((RDCH .GT. 52.11) .AND. (RDCH .LE. 59.58)) UA = 0.7 -
     *        ((RDCH - 52.11)/(59.58 - 52.11)) * (0.7 - 0.4)
         IF ((RDCH .GT. 59.58) .AND. (RDCH .LE. 67.01)) UA = 0.4 -
     *        ((RDCH - 59.58)/(67.01 - 59.58)) * (0.4 - 0.0)
         IF (RDCH .GT. 67.01) UA = 0.0
      ELSEIF ((IM .GE. 9) .AND. (IM .LE. 10)) THEN
         IF (RDCH .LE. 7.44) UA = (RDCH/7.44) * 0.3
         IF ((RDCH .GT. 7.44) .AND. (RDCH .LE. 14.88)) UA =
     *        ((RDCH - 7.44)/(14.88 - 7.44)) * (0.5 - 0.3) + 0.3
         IF ((RDCH .GT. 14.88) .AND. (RDCH .LE. 22.33)) UA =
     *        ((RDCH - 14.88)/(22.33 - 14.88)) * (0.8 - 0.5) + 0.5
         IF ((RDCH .GT. 22.33) .AND. (RDCH .LE. 37.21)) UA =
     *        ((RDCH - 22.33)/(37.21 - 22.33)) * (1.0 - 0.8) + 0.8
         IF ((RDCH .GT. 37.21) .AND. (RDCH .LE. 44.65)) UA = 1.0 -
     *        ((RDCH - 37.21)/(44.65 - 37.21)) * (1.0 - 0.8)
         IF ((RDCH .GT. 44.65) .AND. (RDCH .LE. 52.09)) UA = 0.8 -
     *        ((RDCH - 44.65)/(52.09 - 44.65)) * (0.8 - 0.5)
         IF ((RDCH .GT. 52.09) .AND. (RDCH .LE. 59.53)) UA = 0.5 -
     *        ((RDCH - 52.09)/(59.53 - 52.09)) * (0.5 - 0.3)
         IF ((RDCH .GT. 59.53) .AND. (RDCH .LE. 66.98)) UA = 0.3 -
     *        ((RDCH - 59.53)/(66.98 - 59.53)) * (0.3 - 0.0)
         IF (RDCH .GT. 66.98) UA = 0.0
      ENDIF
      RETURN
      END
C!
C! ****************************************************************** !C
C!       *****      SUBROUTINE FHABIT     *****                         !C
C! ****************************************************************** !C
C! THIS SUBROUTINE COMPUTES THE MEMBERSHIP FUNCTION FOR FISH           !C
C! HABITAT                                                             !C
C! ****************************************************************** !C
      SUBROUTINE FHABIT (RDCH, IM, UFH)

      IF ((IM .LE. 3) .OR. (IM .GE. 10)) THEN
         IF (RDCH .LE. 20.0) UFH = (RDCH/20.0) * 0.1
         IF ((RDCH .GT. 20.0) .AND. (RDCH .LE. 30.0)) UFH =
     *        ((RDCH - 20.0)/(30.0 - 20.0)) * (0.3 - 0.1) + 0.1
         IF ((RDCH .GT. 30.0) .AND. (RDCH .LE. 70.0)) UFH =
     *        ((RDCH - 30.0)/(70.0 - 30.0)) * (0.7 - 0.3) + 0.3
         IF ((RDCH .GT. 70.0) .AND. (RDCH .LE. 100.0)) UFH =
     *        ((RDCH - 70.0)/(100.0 - 70.0)) * (1.0 - 0.7) + 0.7
         IF ((RDCH .GT. 100.0) .AND. (RDCH .LE. 200.0)) UFH = 1.0
         IF ((RDCH .GT. 200.0) .AND. (RDCH .LE. 500.0)) UFH = 1.0 -
     *        ((RDCH - 200.0)/(500.0 - 200.0)) * (1.0 - 0.7)
         IF ((RDCH .GT. 500.0) .AND. (RDCH .LE. 800.0)) UFH = 0.7 -
     *        ((RDCH - 500.0)/(800.0 - 500.0)) * (0.7 - 0.3)
         IF ((RDCH .GT. 800.0) .AND. (RDCH .LE. 1800.0)) UFH = 0.3 -
     *        ((RDCH - 800.0)/(1800.0 - 800.0)) * (0.3 - 0.1)
```

```
      IF ((RDCH .GT. 1800.0) .AND. (RDCH .LE. 1900.0)) UFH = 0.1 -
*         ((RDCH - 1800.0)/(1900.0 - 1800.0)) * (0.1 - 0.0)
      IF (RDCH .GT. 1900.0) UFH = 0.0
   ELSEIF (IM .EQ. 4) THEN
      IF (RDCH .LE. 80.0) UFH = (RDCH/80.0) * 0.1
      IF ((RDCH .GT. 80.0) .AND. (RDCH .LE. 120.0)) UFH =
*         ((RDCH - 80.0)/(120.0 - 80.0)) * (0.7 - 0.1) + 0.1
      IF ((RDCH .GT. 120.0) .AND. (RDCH .LE. 200.0)) UFH =
*         ((RDCH - 120.0)/(200.0 - 120.0)) * (1.0 - 0.7) + 0.7
      IF ((RDCH .GT. 200.0) .AND. (RDCH .LE. 300.0)) UFH = 1.0
      IF ((RDCH .GT. 300.0) .AND. (RDCH .LE. 500.0)) UFH = 1.0 -
*         ((RDCH - 300.0)/(500.0 - 300.0)) * (1.0 - 0.7)
      IF ((RDCH .GT. 500.0) .AND. (RDCH .LE. 800.0)) UFH = 0.7 -
*         ((RDCH - 500.0)/(800.0 - 500.0)) * (0.7 - 0.3)
      IF ((RDCH .GT. 800.0) .AND. (RDCH .LE. 1000.0)) UFH = 0.3 -
*         ((RDCH - 800.0)/(1000.0 - 800.0)) * (0.3 - 0.1)
      IF ((RDCH .GT. 1000.0) .AND. (RDCH .LE. 1100.0)) UFH = 0.1 -
*         ((RDCH - 1000.0)/(1100.0 - 1000.0)) * (0.1 - 0.0)
      IF (RDCH .GT. 1100.0) UFH = 0.0
   ELSEIF (IM .EQ. 5) THEN
      IF (RDCH .LE. 100.0) UFH = (RDCH/100.0) * 0.1
      IF ((RDCH .GT. 100.0) .AND. (RDCH .LE. 120.0)) UFH =
*         ((RDCH - 100.0)/(120.0 - 100.0)) * (0.3 - 0.1) + 0.1
      IF ((RDCH .GT. 120.0) .AND. (RDCH .LE. 180.0)) UFH =
*         ((RDCH - 120.0)/(180.0 - 120.0)) * (0.7 - 0.3) + 0.3
      IF ((RDCH .GT. 180.0) .AND. (RDCH .LE. 300.0)) UFH =
*         ((RDCH - 180.0)/(300.0 - 180.0)) * (1.0 - 0.7) + 0.7
      IF ((RDCH .GT. 300.0) .AND. (RDCH .LE. 500.0)) UFH = 1.0
      IF ((RDCH .GT. 500.0) .AND. (RDCH .LE. 700.0)) UFH = 1.0 -
*         ((RDCH - 500.0)/(700.0 - 500.0)) * (1.0 - 0.7)
      IF ((RDCH .GT. 700.0) .AND. (RDCH .LE. 800.0)) UFH = 0.7 -
*         ((RDCH - 700.0)/(800.0 - 700.0)) * (0.7 - 0.3)
      IF ((RDCH .GT. 800.0) .AND. (RDCH .LE. 1000.0)) UFH = 0.3 -
*         ((RDCH - 800.0)/(1000.0 - 800.0)) * (0.3 - 0.1)
      IF ((RDCH .GT. 1000.0) .AND. (RDCH .LE. 1100.0)) UFH = 0.1 -
*         ((RDCH - 1000.0)/(1100.0 - 1000.0)) * (0.1 - 0.0)
      IF (RDCH .GT. 1100.0) UFH = 0.0
   ELSEIF ((IM .EQ. 6) .OR. (IM .EQ. 7)) THEN
      IF (RDCH .LE. 100.0) UFH = (RDCH/100.0) * 0.1
      IF ((RDCH .GT. 100.0) .AND. (RDCH .LE. 120.0)) UFH =
*         ((RDCH - 100.0)/(120.0 - 100.0)) * (0.3 - 0.1) + 0.1
      IF ((RDCH .GT. 120.0) .AND. (RDCH .LE. 180.0)) UFH =
*         ((RDCH - 120.0)/(180.0 - 120.0)) * (0.7 - 0.3) + 0.3
      IF ((RDCH .GT. 180.0) .AND. (RDCH .LE. 300.0)) UFH =
*         ((RDCH - 180.0)/(300.0 - 180.0)) * (1.0 - 0.7) + 0.7
      IF ((RDCH .GT. 300.0) .AND. (RDCH .LE. 500.0)) UFH = 1.0
      IF ((RDCH .GT. 500.0) .AND. (RDCH .LE. 700.0)) UFH = 1.0 -
*         ((RDCH - 500.0)/(700.0 - 500.0)) * (1.0 - 0.7)
      IF ((RDCH .GT. 700.0) .AND. (RDCH .LE. 1200.0)) UFH = 0.7 -
*         ((RDCH - 700.0)/(1200.0 - 700.0)) * (0.7 - 0.3)
      IF ((RDCH .GT. 1200.0) .AND. (RDCH .LE. 1800.0)) UFH = 0.3 -
*         ((RDCH - 1200.0)/(1800.0 - 1200.0)) * (0.3 - 0.1)
      IF ((RDCH .GT. 1800.0) .AND. (RDCH .LE. 1900.0)) UFH = 0.1 -
*         ((RDCH - 1800.0)/(1900.0 - 1800.0)) * (0.1 - 0.0)
      IF (RDCH .GT. 1900.0) UFH = 0.0
   ELSEIF (IM .EQ. 8) THEN
      IF (RDCH .LE. 100.0) UFH = (RDCH/100.0) * 0.1
      IF ((RDCH .GT. 100.0) .AND. (RDCH .LE. 120.0)) UFH =
*         ((RDCH - 100.0)/(120.0 - 100.0)) * (0.3 - 0.1) + 0.1
      IF ((RDCH .GT. 120.0) .AND. (RDCH .LE. 180.0)) UFH =
*         ((RDCH - 120.0)/(180.0 - 120.0)) * (0.7 - 0.3) + 0.3
      IF ((RDCH .GT. 180.0) .AND. (RDCH .LE. 300.0)) UFH =
*         ((RDCH - 180.0)/(300.0 - 180.0)) * (1.0 - 0.7) + 0.7
```

```
          IF ((RDCH .GT. 300.0) .AND. (RDCH .LE. 500.0)) UFH = 1.0
          IF ((RDCH .GT. 500.0) .AND. (RDCH .LE. 700.0)) UFH = 1.0 -
     *        ((RDCH - 500.0)/(700.0 - 500.0)) * (1.0 - 0.7)
          IF ((RDCH .GT. 700.0) .AND. (RDCH .LE. 1200.0)) UFH = 0.7 -
     *        ((RDCH - 700.0)/(1200.0 - 700.0)) * (0.7 - 0.3)
          IF ((RDCH .GT. 1200.0) .AND. (RDCH .LE. 1800.0)) UFH = 0.3 -
     *        ((RDCH - 1200.0)/(1800.0 - 1200.0)) * (0.3 - 0.1)
          IF ((RDCH .GT. 1800.0) .AND. (RDCH .LE. 1900.0)) UFH = 0.1 -
     *        ((RDCH - 1800.0)/(1900.0 - 1800.0)) * (0.1 - 0.0)
          IF (RDCH .GT. 1900.0) UFH = 0.0
       ELSEIF (IM .EQ. 9) THEN
          IF (RDCH .LE. 80.0) UFH = (RDCH/80.0) * 0.1
          IF ((RDCH .GT. 80.0) .AND. (RDCH .LE. 100.0)) UFH =
     *        ((RDCH - 80.0)/(100.0 - 80.0)) * (0.3 - 0.1) + 0.1
          IF ((RDCH .GT. 100.0) .AND. (RDCH .LE. 120.0)) UFH =
     *        ((RDCH - 100.0)/(120.0 - 100.0)) * (0.7 - 0.3) + 0.3
          IF ((RDCH .GT. 120.0) .AND. (RDCH .LE. 200.0)) UFH =
     *        ((RDCH - 120.0)/(200.0 - 120.0)) * (1.0 - 0.7) + 0.7
          IF ((RDCH .GT. 200.0) .AND. (RDCH .LE. 400.0)) UFH = 1.0
          IF ((RDCH .GT. 400.0) .AND. (RDCH .LE. 700.0)) UFH = 1.0 -
     *        ((RDCH - 400.0)/(700.0 - 400.0)) * (1.0 - 0.7)
          IF ((RDCH .GT. 700.0) .AND. (RDCH .LE. 1200.0)) UFH = 0.7 -
     *        ((RDCH - 700.0)/(1200.0 - 700.0)) * (0.7 - 0.3)
          IF ((RDCH .GT. 1200.0) .AND. (RDCH .LE. 1800.0)) UFH = 0.3 -
     *        ((RDCH - 1200.0)/(1800.0 - 1200.0)) * (0.3 - 0.1)
          IF ((RDCH .GT. 1800.0) .AND. (RDCH .LE. 1900.0)) UFH = 0.1 -
     *        ((RDCH - 1800.0)/(1900.0 - 1800.0)) * (0.1 - 0.0)
          IF (RDCH .GT. 1900.0) UFH = 0.0
       ENDIF
       RETURN
       END
C!
C! *************************************************************** !C
C!        *****       SUBROUTINE READIN      *****                   !C
C! *************************************************************** !C
C! THIS SUBROUTINE READS THE INPUT DATA REQUIRED TO DESCRIBE THE      !C
C! RESERVOIR PHYSCIAL AND OPERATIONAL CHARACTERISTICS AND THE INFLOW  !C
C! *************************************************************** !C
       SUBROUTINE READIN
       COMMON/RESDAT/FLOWIN(360),WDEMAN(12),EDEMAN(12),EVAPRT(12),HEAD,
     1              PWRREL,AREA,EVAP,DEPL(360),ALPHA(12),BETA(12),
     2              WATER, ENERGY, FTYPE, VACT, IM

       COMMON/COEFF/TEFF,HEADMN,HEADMX,TURMAX,HRS,A1,A2,A3,H1,H2,H3,
     *             T1,T2,T3,WGT1(4),WGT2(5),WGT3(7)
       COMMON/STGE/NSTGES
       INTEGER FTYPE
       CHARACTER TEXT
       DIMENSION FLOWINB(360), DEPLB(360)
C! UNIT=12 IS USED FOR THE RESVR.ADD INPUT DATA FILE
       OPEN(12,FILE='FUZDP3.ADD')
C! FIRST LINE IS A DATA FILE TITLE
       READ (12, 100) TEXT
C! READ THE TYPE OF OBJECTIVE FUNCTION TO BE ANALYZED
       READ (12,*) FTYPE
C! READ WEIGHTS FOR CONSTRAINTS
       READ (12,*) (WGT1(IJ),IJ=1,4)
       READ (12,*) (WGT2(IJ),IJ=1,5)
       READ (12,*) (WGT3(IJ),IJ=1,7)
C! READ ANNUAL WATER AND ENERGY DEMANDS
       READ (12,*) WANDEM, EANDEM, VACT
C! READ MONTHLY WATER USE COEFFICIENTS
       READ (12,*) (ALPHA(IJ),IJ=1,12)
```

```
C! READ MONTHLY ENERGY USE COEFFICIENTS
      READ (12,*) (BETA(IJ),IJ=1,12)
C! READ MONTHLY EVAPORATION RATES IN M
      READ (12,*) (EVAPRT(IJ),IJ=1,12)
C! READ POWER GENERATION PARAMETERS; MINIMUM HEAD = HEADMN,
C!  MAXIMUM TURBINE FLOW = TURMAX,
C!  HOURS PER MONTH OF POWER GENERATION = HRS.
      READ (12,*) HEADMN, HEADMX, TURMAX, HRS

C! READ THE COEFFICIENTS FOR THE AREA - STORAGE RELATIONSHIP
      READ (12,*) A1, A2, A3
C! READ THE COEFFICIENTS FOR THE HEAD - STORAGE RELATIONSHIP
      READ (12,*) H1, H2, H3
C! READ THE COEFFICIENTS FOR TURBINE EFFICIENCY - HEAD RELATIONSHIP
      READ (12,*) T1, T2, T3
C! READ THE NUMBER OF STAGES TO BE ANALYZED
      READ (12,*) NSTGES
C! READ A SEPARATOR LINE FOR THE INFLOWS
      READ (12,100) TEXT
C! READ THE INFLOWS FOR THE NUMBER OF STAGES TO BE ANALYZED
      READ (12,*) (FLOWINB(IJ),IJ=1,NSTGES)
C! READ A SEPARATOR LINE FOR THE DOWNSTREAM DELIVERIES
      READ (12,100) TEXT
C! READ REQUIRED DOWNSTREAM DELIVERIES IN MCM
      READ (12,*) (DEPLB(IJ),IJ=1,NSTGES)
C! END OF READING INPUT DATA
C!
C! CALCULATE MONTHLY DEMAND VALUES
C!
      DO 10 IJ = 1,12
      WDEMAN(IJ) = WANDEM * ALPHA(IJ)
      EDEMAN(IJ) = EANDEM * BETA(IJ)
10    CONTINUE
C!
C! REVERSE INFLOW AND DEPL VALUES DUE TO THE FORWARDS SOLUTION

C!
        DO 20 IJ = 1, NSTGES
         JI = NSTGES - IJ + 1
         FLOWIN(JI) = FLOWINB(IJ)
         DEPL(JI) = DEPLB(IJ)
  20    CONTINUE
C!
 100  FORMAT (A1)
      RETURN
      END
C! ***************************************************************** !C
C!        *****      SUBROUTINE RESULT     *****                      !C
C! ***************************************************************** !C
C! THIS SUBROUTINE WRITES THE USER DESIRED SPECIAL OUTPUT TO A FILE   !C
C! FOR GRAPHICAL OR OTHER DISPLAY PURPOSES.  THIS SUBROUTINE IS       !C
C! CALLED FROM SUBOUTINE OBJECT FOR EACH STAGE DURING THE TRACEBACK   !C
C! PROCESS                                                            !C
C! ***************************************************************** !C
      SUBROUTINE RESULT
      COMMON/ONEDM/X,X1,U,F,I,J,K,L,R,PNALTY
      COMMON/RESDAT/FLOWIN(360),WDEMAN(12),EDEMAN(12),EVAPRT(12),HEAD,
     1              PWRREL,AREA,EVAP,DEPL(360),ALPHA(12),BETA(12),
     2              WATER, ENERGY, FTYPE, VACT, IM

      COMMON/COEFF/TEFF,HEADMN,HEADMX,TURMAX,HRS,A1,A2,A3,H1,H2,H3,
     *             T1,T2,T3,WGT1(4),WGT2(5),WGT3(7)
      COMMON/MEMBER/UG, UWS, UFC, UHP, UR, UK, UA, UFH
```

```
      COMMON/STGE/NSTGES
      INTEGER FTYPE
      LOGICAL FIRST
      DATA FIRST /.FALSE./
C! UNIT=13 IS USED FOR THE RESVR.RES OUTPUT RESULTS FILE
      OPEN(13,FILE='FUZDP3.RES')
C! REWIND THE FILE FOR THE BEGINNING OF A TRACEBACK
      IF (I .EQ. 1) THEN
C!        REWIND(13)
        FIRST = .TRUE.
      ENDIF
C! THE FIRST TIME THIS SUBROUTINE IS CALLED WRITE A HEADING
      IF (FIRST) WRITE (13,100)
      FIRST = .FALSE.
C! WRITE THE DESIRED OUTPUT TO A FILE
      N = NSTGES - I + 1
      WRITE(13,110) N,IM,X1,X,U,FLOWIN(I),DEPL(I),UG,UWS,UFC,UHP,UR,UK,
     1              UA,UFH,F,WDEMAN(IM),EDEMAN(IM),WATER,HEAD,ENERGY
100   FORMAT (1X,48H"STAGE" "MTH" "VOL(t)" "VOL(t+1)" "REL" "INFLOW",
     1    7H "DEPL",
     1    44H "UG" "UWS" "UFC" "UHP" "UR" "UK" "UA" "UFH",
     2    56H "RETURN FUNC" "WDEMAN" "EDEMAN" "WATER" "HEAD" "ENERGY")
110   FORMAT (2I9,19F9.2)
      RETURN
      END
```

EXAMPLE INPUT DATA SET FOR CSUDP

File FUZDP.DAT

```
GREY MOUNTAIN RESERVOIR OPERATION - GENERATED DATA
Index,Jtype,N,Nd,Md,Jtie,Invert:       -1    2  360    1    1    1    1
Istoch,Istatn,Ntrans,Ispl,Itset,Iprint,Itmax:    0    0    0    0    0    1    1
DELXi,DELXf,DELUi/f:  1.0000      1.0000      .100000E-03 .100000E-03
Splice,Xmult:        5.00000     3.00000      .100000E-02  0  0
RiskLoHi;Misc:        .000000     .000000      0  0  0  0  0  0
Xmin     1           230.000
Xmax     1           230.000
Xmin     2           151.000
Xmax     2           241.000
........................................
.......................................
Xmin   359           151.000
Xmax   359           241.000
Xmin   360           151.000
Xmax   360           241.000
Xmin   361           238.000
Xmax   361           238.000
Umin     1           .000000
Umax     1           650.000
Umin     2           .000000
Umax     2           650.000
..........................................
..........................................
Umin   359           .000000
Umax   359           650.000
Umin   360           .000000
Umax   360           650.000
```

File FUZDP.ADD

```
 GENERATED HYDROLOGIC SERIES SITE  1   SAMPLE   6
        1
  0.3125   0.1875   0.1875   0.3125
   0.278    0.167    0.167    0.111    0.278
    0.25     0.15     0.15     0.05     0.05      0.1     0.25
      51    52000      229
    0.02     0.03     0.03     0.06     0.09     0.15      0.2     0.18     0.12     0.07     0.03     0.02
   0.083    0.083    0.083    0.083    0.083    0.083    0.083    0.083    0.083    0.083    0.083    0.083
       0        0        0        0        0        0        0        0        0        0        0        0
      47      118   100000      730
       0        1        1
       0  14.3797  0.38287
  0.2375        0        0
     360
```

INFLOWS

3.80	2.08	2.25	1.51	1.80	2.16	3.70	33.77	59.81	17.55	7.59	3.79
3.33	2.30	1.36	1.41	1.42	2.82	9.81	87.00	224.27	91.79	13.63	8.57
2.51	2.48	2.24	1.98	2.06	2.20	4.59	26.59	80.21	62.39	15.32	7.48
2.77	1.64	1.41	1.08	1.01	1.17	3.04	39.91	82.52	29.06	11.36	4.31
2.81	2.22	1.46	1.42	1.13	1.68	5.85	106.67	157.10	75.73	18.03	8.84
5.91	2.57	2.29	2.25	1.33	1.74	2.86	36.63	80.65	65.61	10.63	3.87
2.45	2.59	1.85	1.14	1.07	1.79	2.48	46.32	101.83	45.64	20.20	6.67
2.68	1.60	0.75	1.02	0.80	1.12	2.51	17.03	168.90	81.21	42.19	12.15
4.02	3.68	2.24	1.29	1.65	1.62	4.66	36.96	73.61	22.07	12.22	9.04
2.71	1.41	2.04	2.46	2.93	3.16	5.24	32.23	79.64	27.57	6.85	3.51
2.50	2.66	4.15	5.66	5.58	5.42	12.29	64.00	146.59	90.44	34.73	11.51
4.72	2.25	1.68	1.52	1.59	3.70	4.87	120.65	104.25	12.05	10.87	3.47
2.21	1.28	1.41	1.41	1.43	6.54	29.12	195.30	460.93	263.44	49.35	13.25
9.23	1.77	1.01	1.08	0.86	1.27	3.82	32.22	121.23	61.85	19.14	6.02
3.61	1.84	1.59	1.66	1.28	2.26	2.87	25.08	95.42	43.07	26.31	13.04
8.79	3.47	2.72	2.06	1.57	2.54	4.08	43.02	130.34	50.05	22.14	6.87
3.25	1.57	2.58	2.57	1.66	6.89	6.53	102.67	264.86	102.15	34.15	4.83
5.40	3.93	3.44	2.21	1.94	6.61	29.06	149.06	344.03	190.57	33.44	7.19
7.56	2.52	2.11	1.81	4.09	1.15	3.02	36.67	59.68	37.74	6.36	6.11
4.93	3.71	3.03	3.36	3.42	4.80	11.54	82.37	80.10	25.06	19.08	3.18
3.67	1.80	1.07	0.97	0.75	1.55	2.71	24.84	52.60	17.86	7.80	5.07
3.17	12.89	6.46	7.41	7.21	12.55	8.31	65.47	83.74	29.07	9.51	3.72
2.69	1.39	1.52	1.30	1.67	2.11	24.16	48.81	131.48	37.26	16.22	5.27
2.88	1.42	1.23	1.01	1.00	1.24	6.34	27.62	123.08	58.55	28.69	13.30
14.02	8.68	4.91	5.22	5.57	2.38	4.91	82.73	134.73	49.01	14.30	4.83
4.25	3.96	3.19	1.89	1.78	2.02	8.77	46.00	84.11	29.22	7.43	9.13
5.44	2.52	1.76	1.74	1.24	3.04	5.56	58.88	105.77	58.79	23.39	4.42
2.36	1.19	1.65	1.84	1.77	2.00	3.43	35.85	85.68	29.56	14.36	4.84
3.67	3.20	4.96	7.38	14.13	5.84	9.34	68.20	74.93	38.39	19.11	6.59
3.23	3.37	2.33	2.63	2.68	2.28	3.26	29.63	68.83	25.27	8.72	4.72

DEMANDS

3.80	2.08	2.25	1.51	1.80	2.16	3.70	33.77	59.81	17.55	7.59	3.79
3.33	2.30	1.36	1.41	1.42	2.82	9.81	54.78	170.66	91.79	13.63	8.57
2.51	2.48	2.24	1.98	2.06	2.20	4.59	7.03	58.92	62.39	15.32	7.48
2.77	1.64	1.41	1.08	1.01	1.17	3.04	33.51	82.52	29.06	11.36	4.31
2.81	2.22	1.46	1.42	1.13	1.68	5.85	81.54	49.95	23.99	18.03	8.84
5.91	2.57	2.29	2.25	1.33	1.74	2.86	18.81	51.14	65.61	10.63	3.87
2.45	2.59	1.85	1.14	1.07	1.79	2.48	46.32	100.19	45.64	20.20	6.67
2.68	1.60	0.75	1.02	0.80	1.12	2.51	14.90	61.76	81.21	42.19	12.15
4.02	3.68	2.24	1.29	1.65	1.62	4.66	36.96	73.61	22.07	12.22	9.04
2.71	1.41	2.04	2.46	2.93	3.16	5.24	13.79	79.64	27.57	6.85	3.51
2.50	2.66	4.15	5.66	5.58	5.42	2.20	26.62	58.94	39.61	34.73	11.51
4.72	2.25	1.68	1.52	1.59	3.70	4.87	64.39	81.88	12.05	10.87	3.47
2.21	1.28	1.41	1.41	1.43	2.71	4.55	26.82	184.08	57.64	16.86	13.25
9.23	1.77	1.01	1.08	0.86	1.27	3.82	32.22	121.23	61.85	19.14	6.02
3.61	1.84	1.59	1.66	1.28	2.26	2.87	13.60	95.42	43.07	26.31	13.04
8.79	3.47	2.72	2.06	1.57	2.54	4.08	7.67	8.34	50.05	22.14	6.87
3.25	1.57	2.58	2.57	1.66	6.89	1.24	14.09	46.58	30.57	34.15	4.83
5.40	3.93	3.44	2.21	1.94	1.45	5.76	43.14	73.96	38.61	33.44	7.19
7.56	2.52	2.11	1.81	4.09	1.15	3.02	12.40	44.33	37.74	6.36	6.11
4.93	3.71	3.03	3.36	3.42	4.80	3.48	29.64	54.48	25.06	19.08	3.18
3.67	1.80	1.07	0.97	0.75	1.55	2.71	24.84	52.60	17.86	7.80	5.07
3.17	6.32	4.58	3.87	3.81	1.71	1.38	3.85	49.14	29.07	9.51	3.72
2.69	1.39	1.52	1.30	1.67	2.11	6.32	48.81	105.35	37.26	16.22	5.27
2.88	1.42	1.23	1.01	1.00	1.24	6.34	27.62	93.77	58.55	28.69	13.30
6.55	5.69	4.91	5.22	5.57	2.38	4.91	33.73	58.62	49.01	14.30	4.83
4.25	3.96	3.19	1.89	1.78	2.02	8.77	46.00	53.34	29.22	7.43	9.13
5.44	2.52	1.76	1.74	1.24	3.04	5.56	20.76	36.52	58.79	23.39	4.42
2.36	1.19	1.65	1.84	1.77	2.00	3.43	35.85	85.68	29.56	14.36	4.84
3.67	3.20	4.96	7.38	11.20	5.84	0.21	-2.08	71.65	38.39	19.11	6.59
3.23	3.37	2.33	2.63	2.68	2.28	3.26	29.63	68.83	25.27	8.72	4.72

APPENDIX D

RESULTS FROM HYDROLOGIC TIME SERIES MODELING

```
***************************************************************************
               INPUT DATA FOR PROGRAM CSU003
***************************************************************************
THIS IS AN  EXAMPLE OF AN INPUT FILE TO RUN PROGRAM CSU003.  IT BRIEFLY
DESCRIBES ALL  INPUT VARIABLES  NEEDED TO RUN  THE PROGRAM.  IDENTIFIER
INDEXES  ARE INCLUDED  AT EACH  DATA LINE IN  COLUMNS 77-80.
LINE 0001 DESCRIBES: NYRS=NUMBER OF YEARS, NSES=NUMBER OF SEASONS, NSER=
NUMBER OF SERIES, IRE=INDEX FOR FOURIER FITTING ( 0 - FOURIER FITTING IS
NOT WANTED, 1 - FOURIER FITTING IS WANTED ), IFE=INDEX FOR RESIDUAL SERIES
(0-RESIDUALS SERIES MUST BE COMPUTED, 1-RESIDUALS SERIES ARE GIVEN),(5I8).
    NYRS    NSES    NSER     IRE     IFE
      30      12       2       0       0                                    0001
LINE 0002 DESCRIBES INDEX FOR TRANSFORMATION FOR EACH SERIES IDE(L),L=1,NSER
IF IFE=0 (12I6).IDE(K)=0 MEANS NO TRANSFORMATION, IDE(K) BETWEEN 1 AND 9
MEANS DIFFERENT TRANSFORMATION. FOR TRANSFORMATION TYPE REFER TO THE MANUAL.
     2     2     2     0     0     0     0     0     0     0     0     0    0002
LINE 0003 DESCRIBES NUMBER OF FOURIER HARMONICS TO FIT THE PERIODIC MEAN
NHM(L),L=1,NSER IF IRE = 1 (12I6).
     0     0     0     0     0     0     0     0     0     0     0     0    0003
LINE 0004 DESCRIBES NUMBER OF FOURIER HARMONICS TO FIT THE PERIODIC
STANDARD DEVIATION NHS(L),L=1,NSER IF IRE = 1 (12I6).
     0     0     0     0     0     0     0     0     0     0     0     0    0004
LINE 0005 DESCRIBES TYPE OF MODEL FOR DETERMINIG THE RESIDUALS FOR EACH
SERIES INE(K),K=1,NSER IF IFE = 0 (12I6).
     1     1     1     0     0     0     0     0     0     0     0     0    0005
***************************************************************************
                   SERIES NUMBER: 1
***************************************************************************
LINES 0101 THROUGH 0105 DESCRIBE PROY=NAME OF PROJECT, BASIN=NAME OF RIVER
BASIN, STAC=NAME OF GAGING STATION, SERIE=TYPE OF HYDROLOGIC DATA AND
UNIT=UNITS OF HYDROLOGIC DATA.
PROY  (60A)...:Fuzzy Reservoir Planning                                     0101
BASIN (20A)...:Cache La Poudre River                                        0102
STAC  (30A)...:Grey Mountain Reservoir                                      0103
SERIE (30A)...:Monthly Inflow Volume                                        0104
UNIT  (10A)...:Acre Feet                                                    0105
```

```
LINES 0106 THROUGH 0107 DESCRIBE: NFYR=FIRST AND NLYR=LAST YEAR OF DATA.
NFYR   (I4)...:1954                                                    0106
NLYR   (I4)...:1983                                                    0107
LINE 0108 GIVES A FORMAT TO READ SAMP.SER. (IFE=0) OR RESID.SER. (IFE=1)
(12F9.0)                                                               0108
LINES 0109 CORRESPOND TO SAMPLE SERIES (IFE=0) OR RESIDUAL SERIES (IFE=1)
```

3386	1940	2010	1940	1554	1554	2921	25403	34125	15040	3722	5693
4970	1634	1049	1208	911	1228	1960	21859	60321	27908	15484	4316
3049	2287	2435	1693	1396	1911	3455	72052	86477	24295	11553	3198
2020	1208	1584	1277	1346	1426	6989	35174	134937	103554	20127	9623
5000	2693	2614	2089	2059	2663	10821	91872	95169	16097	4029	3227
3148	1861	2000	1634	1980	3039	11999	43709	102862	24562	10712	4029
4485	3713	1139	1059	764	3000	5495	49688	95783	27631	6475	4188
2990	1697	1542	2249	1643	2800	7865	70100	116622	31914	18735	11670
16178	6724	3211	3595	5698	5413	19215	68809	84752	45892	11290	2216
3778	2095	1760	1095	1034	756	3992	27255	37729	12205	11684	7368
3707	2115	982	830	853	1546	2297	35757	65720	31409	10799	4439
1851	1024	776	832	861	863	2526	32272	129475	77075	25457	7556
4008	1051	1309	1166	1220	1667	2814	29781	33300	9708	6233	5861
2841	1441	798	737	566	1093	1857	26255	75731	43314	7138	4172
1679	3271	2823	2210	2525	1936	2982	28793	102644	40849	20251	6706
2566	2152	1677	1168	1036	1635	6279	50427	74151	35585	6884	7465
4186	1881	889	871	616	1437	5560	59037	108563	55826	17200	6249
4758	4202	1867	1851	1352	1954	11614	62231	141541	56400	13319	9540
2477	4505	2176	1632	1820	2172	3966	35941	85857	25336	5170	6233
3887	2625	1590	1459	1443	2051	3459	89254	123196	65406	22851	3742
5200	6506	3085	2398	2935	5687	7256	78705	107682	36893	6562	4681
4736	2738	1378	810	739	1148	2099	18757	86675	78778	17222	5936
3231	1695	1671	1535	1408	1513	2293	27682	64924	27284	18945	3522
4584	1598	1004	915	847	1348	2964	12525	39105	10484	14137	3734
2455	2222	1632	1416	1275	1616	3903	36097	127571	65982	19650	5839
2841	1786	1293	1152	931	1461	5013	51161	122859	59314	34547	8760
3315	1810	2643	5554	4368	9122	32698	158438	142085	41340	16814	6203
5120	4328	3089	1764	1093	1287	4469	22501	55363	20794	12294	5790
2156	1519	1546	1208	2996	1190	1956	23000	87236	80277	37788	9589
4291	2711	3412	2772	3879	5871	36521	108484	283199	136573	43531	12458

```
LINE 0110 GIVES THE FORMAT FOR PRINTING SEASONAL STATISTICAL PROPERTIES OF
HYDROLOGICAL SERIES (IN PARENTHESIS).
(6X,12F10.2)                                                                0110
LINE 0111 GIVES THE WRITING FORMAT OF THE TITLE OF THE OUTPUT HYDROLOGICAL
SERIES (IN PARENTHESIS).
(1X,  4HYEAR,1X,12(5X,A3))                                                 0111
LINE 0112 GIVES THE WRITING FORMAT OF THE OUTPUT HYDROLOGICAL SERIES.
(IN PARENTHESIS).
(1X,I4,1X,12F11.2)                                                          0112
LINE 0113 DESCRIBES PERIODIC POWER TRANSFORMATION EE(K,L), FOR EACH K=1,NSER
AND L=1,NSES, IF IDE(K)=2 (12F6.0).
     0     0     0     0     0     0     0     0     0     0     0     0    0113
LINE 0114 DESCRIBES CONSTANTS OF TRANSFORMATION C(K,L), FOR EACH K=1,NSER
AND L=1,NSES, IF IDE(K)>0 AND IDE(K)<7 (12F6.0).
     0     0     0     0     0     0     0     0     0     0     0     0    0114
LINE 0115 AND 0116 DESCRIBE FI COEFFICIENTS (12F6.0).
  .501  .646  .642  .709  .838  .804  .856  .793  .609  .804  .770  .608    0115
     0     0     0     0     0     0     0     0     0     0     0     0    0116
LINE 0117 DESCRIBES THETA COEFFICIENTS (12F6.0).
     0     0     0     0     0     0     0     0     0     0     0     0    0117
**************************************************************************
                   SERIES NUMBER: 2
**************************************************************************
LINES 0201 THROUGH 0205 DESCRIBE PROY=NAME OF PROJECT, BASIN=NAME OF RIVER
BASIN, STAC=NAME OF GAGING STATION, SERIE=TYPE OF HYDROLOGIC DATA AND
UNIT=UNITS OF HYDROLOGIC DATA.
PROY  (60A)...:Fuzzy Reservoir Planning                                     0201
BASIN (20A)...:Cache La Poudre River                                        0202
STAC  (30A)...:Grey Mountain Reservoir                                      0203
SERIE (30A)...:Monthly Diversion Volume                                     0204
UNIT  (10A)...:Acre Feet                                                    0205
LINES 0206 THROUGH 0207 DESCRIBE: NFYR=FIRST AND NLYR=LAST YEAR OF DATA.
NFYR   (I4)...:1954                                                         0206
NLYR   (I4)...:1983                                                         0207
LINE 0208 GIVES A FORMAT OF SAMPLE SERIES (IFE=0) OR RESIDUAL SERIES (IFE=1)
(12F9.0)                                                                    0208
```

LINES 0209 CORRESPOND TO SAMPLE SERIES (IFE=0), OR RESIDUAL SERIES (IFE=1)

3386	1940	2010	1940	1554	1554	2921	25403	34125	15040	3722	5693
4970	1634	1049	1208	911	1228	1960	21859	60321	27908	15484	4316
3049	2287	2435	1693	1396	1911	3455	67389	83004	24295	11553	3198
2020	1208	1584	1277	1346	1426	6989	28967	96078	103554	20127	9623
5000	2693	2614	2089	2059	2663	576	24760	79717	16097	4029	3227
3148	1861	2000	1634	1980	3039	3998	32512	98095	24562	10712	4029
4485	3713	1139	1059	764	3000	5495	49688	95783	27631	6475	4188
2990	1697	1542	2249	1643	2800	3798	35864	50007	31914	18735	11670
5106	669	673	558	451	491	11211	64859	62614	45892	11290	2216
3778	2095	1760	1095	1034	756	3992	27255	37729	12205	11684	7368
3707	2115	982	830	853	1546	2297	33844	65720	31409	10799	4439
1851	1024	776	832	861	863	2526	30409	59069	77075	25457	7556
4008	1051	1309	1166	1220	1667	2814	29781	33300	9708	6233	5861
2841	1441	798	737	566	1093	1857	24788	48746	32650	7138	4172
1679	3271	2823	2210	2525	1936	2982	27104	92516	40849	20251	6706
2566	2152	1677	1168	1036	1635	6279	49702	55394	35585	6884	7465
4186	1881	889	871	616	1437	5560	55412	69153	55826	17200	6249
4758	4202	1867	1851	1352	1954	5223	5904	105894	47353	13319	9540
2477	4505	2176	1632	1820	2172	3966	34745	70427	25336	5170	6233
3887	2625	1590	1459	1443	2051	3459	31090	94276	58236	22851	3742
1020	701	1107	669	614	2610	4811	73121	76685	36893	6562	4681
4736	2738	1378	810	739	1148	2099	18757	59115	72260	17222	5936
3231	1695	1671	1535	1408	1513	2293	27682	62366	27284	18945	3522
4584	1598	1004	915	847	1348	2964	12525	39105	10484	14137	3734
2455	2222	1632	1416	1275	1616	3903	33765	87108	65982	19650	5839
2841	1786	1293	1152	931	1461	5013	14628	45221	55301	34547	8760
3315	1810	2643	5554	4368	820	806	10000	89823	41340	16814	6203
5120	4328	3089	1764	1093	1287	4469	22501	40004	20794	12294	5790
2156	1519	1546	1208	2996	1190	1956	23000	55105	52551	37788	9589
4291	2711	3412	2772	3879	5871	881	1744	6045	55567	27352	12458

LINE 0210 GIVES THE FORMAT FOR PRINTING SEASONAL STATISTICAL PROPERTIES OF HYDROLOGICAL SERIES (IN PARENTHESIS).

(6X,12F10.2)   0210

LINE 0211 GIVES THE WRITING FORMAT OF THE TITLE OF THE OUTPUT HYDROLOGICAL SERIES (IN PARENTHESIS).

```
(1X,  4HYEAR,1X,12(5X,A3))                                                  0211
LINE 0212 GIVES THE WRITING FORMAT OF THE OUTPUT HYDROLOGICAL SERIES.
(IN PARENTHESIS).
(1X,I4,1X,12F11.2)                                                           0212
LINE 0213 DESCRIBES PERIODIC POWER TRANSFORMATION EE(K,L), FOR EACH K=1,NSER
AND L=1,NSES, IF IDE(K)=2 (12F6.0).
     0     0     0     0     0     0     0     0     0     0     0     0    0213
LINE 0214 DESCRIBES CONSTANTS OF TRANSFORMATION C(K,L), FOR EACH K=1,NSER
AND L=1,NSES, IF IDE(K)>0 AND IDE(K)<7 (12F6.0).
     0     0     0     0     0     0     0     0     0     0     0     0    0214
LINES 0215 AND 0216 DESCRIBE FI COEFFICIENTS (12F6.0).
  .385  .293  .557  .684  .847  .409 -.225  .555  .264  .275  .599  .534    0215
     0     0     0     0     0     0     0     0     0     0     0     0    0216
LINE 0217 DESCRIBES THETA COEFFICIENTS (12F6.0).
     0     0     0     0     0     0     0     0     0     0     0     0    0217
```

```
*************************************************************************
               INPUT DATA FOR PROGRAM CSU004
*************************************************************************
THIS IS AN EXAMPLE OF AN INPUT FILE TO RUN PROGRAM CSU004. IT BRIEFLY
DESCRIBES ALL INPUT VARIABLES NEEDED TO RUN THE PROGRAM. IDENTIFIER INDEXES
ARE INCLUDED AT EACH DATA LINE IN COLUMNS 77-80. THERE ARE 05 IDENTIFIER
INDEXES 0001 THROUGH 0005 CORRESPONDING TO EACH INPUT DATA LINE. THE INDEX
0004 IS REPEATED FOR ALL LINES OF SEASONAL PARAMETER MATRICES B. THE INDEX
0005 IS REPEATED FOR ALL LINES OF SEASONAL PARAMETER MATRICES M0. THE INDEX
0I18 IS REPEATED FOR ALL YEARS OF DATA OF SERIES Y(L,J) AT SITE I. TO RUN
THE PROGRAM WITH ANY OTHER DATA SET, THE USER NEEDS TO EDIT THIS FILE AND
INSERT CORRESPONDING DATA ONLY ON THOSE LINES HAVING IDENTIFIERS.
*************************************************************************
LINE 0001 DESCRIBES NSER=NUMBER OF SITES TO BE ANALYZED (I5):
    2                                                                        0001
LINE 0002 DESCRIBES IDE(K)=INDEX OF TRANSFORMATION FOR EACH SITE K (16I5):
    3     3                                                                 0002
LINE 0003 DESCRIBES NSAM=NUMBER OF SAMPLES TO BE GENERATED, NYRS=NUMBER
OF YEARS OF HISTORIC SERIES, NSES=NUMBER OF SEASONS, NGEN=NUMBER OF YEARS
OF GENERATED SERIES, ND=PROGRAM GENERATES NYRS+ND YEARS AND DROPS FIRST
ND YEARS, ILE=INDICATOR FOR PRINTING(ILE=0,PRINT SERIES WITHOUT TRANSFORMATION
ONLY,ILE=1,PRINT ORIGINAL AND TRANSFORMED SERIES IF IDE.NE.0,ILE=2,PRINT
TRANSFORMED SERIES ONLY IF IDE.NE.0) (6I5):
    1   30   12   30    0    1                                              0003
LINES 0004 DESCRIBE PARAMETER MATRICES B FOR EACH SEASON
SEASON 1
 1.000  .000                                                                 0004
  .573  .819                                                                 0004
SEASON 2
 1.000  .000                                                                 0004
  .599  .801                                                                 0004
SEASON 3
 1.000  .000                                                                 0004
  .924  .386                                                                 0004
SEASON 4
 1.000  .000                                                                 0004
  .883  .469                                                                 0004
```

```
SEASON 5
 1.000  .000                                                                     0004
   .420  .908                                                                    0004
SEASON 6
 1.000  .000                                                                     0004
   .411  .912                                                                    0004
SEASON 7
 1.000  .000                                                                     0004
   .170  .985                                                                    0004
SEASON 8
 1.000  .000                                                                     0004
   .373  .928                                                                    0004
SEASON 9
 1.000  .000                                                                     0004
   .140  .990                                                                    0004
SEASON 10
 1.000  .000                                                                     0004
   .442  .897                                                                    0004
SEASON 11
 1.000  .000                                                                     0004
   .672  .741                                                                    0004
SEASON 12
 1.000  .000                                                                     0004
   .791  .611                                                                    0004
LINES 0005 DESCRIBE PARAMETER MATRICES M0 FOR EACH SEASON
SEASON 1
 1.000  .573                                                                     0005
   .573 1.000                                                                    0005
SEASON 2
 1.000  .599                                                                     0005
   .599 1.000                                                                    0005
SEASON 3
 1.000  .924                                                                     0005
   .924 1.000                                                                    0005
SEASON 4
 1.000  .883                                                                     0005
   .883 1.000                                                                    0005
```

```
SEASON 5
 1.000  .420                                                                  0005
  .420 1.000                                                                  0005
SEASON 6
 1.000  .411                                                                  0005
  .411 1.000                                                                  0005
SEASON 7
 1.000  .170                                                                  0005
  .170 1.000                                                                  0005
SEASON 8
 1.000  .373                                                                  0005
  .373 1.000                                                                  0005
SEASON 9
 1.000  .140                                                                  0005
  .140 1.000                                                                  0005
SEASON 10
 1.000  .442                                                                  0005
  .442 1.000                                                                  0005
SEASON 11
 1.000  .672                                                                  0005
  .672 1.000                                                                  0005
SEASON 12
 1.000  .791                                                                  0005
  .791 1.000                                                                  0005
************************************************************************
LINES 0101 THROUGH 0105 DESCRIBE PROY=NAME OF PROJECT, BASIN=NAME OF RIVER
BASIN, STAC=NAME OF GAGING STATION, SERIE=TYPE OF HYDROLOGIC DATA AND
UNIT=UNITS OF HYDROLOGIC DATA
PROY  (60A)...:Fuzzy Reservoir Planning                                       0101
BASIN (20A)...:Cache La Poudre River                                          0102
STAC  (30A)...:Grey Mountain Reservoir                                        0103
SERIE (30A)...:Monthly Inflow Volume                                          0104
UNIT  (10A)...:Acre Feet                                                      0105
LINES 0106 THROUGH 0107 DESCRIBE:NFYR=FIRST AND NLYR=LAST YEAR OF DATA
NFYR   (I4)...:1954                                                           0106
NLYR   (I4)...:1983                                                           0107
LINE 0108 DESCRIBES PERIODIC MEAN USED IN THE MODEL EVY(L),L=1,NSES)
```

```
(NSES IS LESS OR EQUAL 12) (12F6.2)
  8.18  7.73  7.43  7.30  7.26  7.56  8.50 10.64 11.38 10.49  9.48  8.64    0108
LINE 0109 DESCRIBES PERIODIC STANDARD DEVIATION USED IN THE MODEL
SDY(L),L=1,NSES (12F6.2)
   .43   .48   .43   .47   .58   .58   .80   .59   .48   .67   .63   .42    0109
LINE 0110 DESCRIBES PERIODIC EXPONENT IN TRANSFORMATION EE(L),L=1,NSES
IF IDE=2 (12F6.2)
   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00    0110
LINE 0111 DESCRIBES PERIODIC ADDED CONSTANT FOR TRANSFORMATION C(L),
L=1,NSES IF IDE = 1,2,3,4,5 OR 6 (12F6.2)
   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00    0111
LINE 0112 DESCRIBES INDICATOR NAR WHICH DEFINES WHAT TYPE OF PERIODIC
AR OR ARMA MODEL IS USED: NAR=0 FOR PAR(0), NAR=1 FOR PAR(1), NAR=2 FOR
PAR(2) AND NAR=3 FOR PARMA(1,1) (I6)
   NAR
     2                                                                      0112
LINES 0113 AND 0114 DESCRIBE MATRIX OF PERIODIC AR PARAMETERS PHIP(IL,L,M),
IL=1,NAR, L=1,NSES, M=1,NSER. EACH COLUMN CORRESPONDS TO DIFFERENT SEASON,
THE FIRST LINE CORRESPONDS TO FIRST ORDER AR PARAMETERS (NAR=1, 2, OR 3),
THE SECOND LINE CORRESPONDS TO SECOND ORDER AR PARAMETERS (NAR=2) (12F6.3)
 0.501 0.646 0.642 0.709 0.838 0.804 0.856 0.793 0.609 0.804 0.770 0.608    0113
  .161  .311  .373  .360  .743  .901  .734  .837  .704  .216  .643  .588    0114
LINE 0115 DESCRIBES VECTOR OF PERIODIC MA PARAMETERS THTP(L), L=1,NSES
(FOR NAR=3) (12F6.3)
  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000    0115
LINE 0116 DESCRIBES PERIODIC RESIDUAL STANDARD DEVIATION WNSTD(L),L=1,NSES
(12F6.3)
 0.928 0.875 0.882 0.652 0.780 0.999 0.927 0.923 0.949 0.678 1.030 1.050    0116
***************************************************************************
SEASONAL HYDROLOGIC SERIES
***************************************************************************
LINE 0117 GIVES THE FORMAT MFO (IN PARENTHESIS) TO READ THE SEASONAL
HYDROLOGIC SERIES Y(I,J)
(12F9.0)                                                                    0117
LINES 0118 CORRESPOND TO SEASONAL HYDROLOGIC SERIES Y(I,J)
     3386     1940     2010     1940     1554     1554     2921    25403    34125    15040     3722     5693
     4970     1634     1049     1208      911     1228     1960    21859    60321    27908    15484     4316
```

3049	2287	2435	1693	1396	1911	3455	72052	86477	24295	11553	3198
2020	1208	1584	1277	1346	1426	6989	35174	134937	103554	20127	9623
5000	2693	2614	2089	2059	2663	10821	91872	95169	16097	4029	3227
3148	1861	2000	1634	1980	3039	11999	43709	102762	24562	10712	4029
4485	3713	1139	1059	764	3000	5495	49688	95783	27631	6475	4188
2990	1697	1542	2249	1643	2800	7865	70100	116622	31914	18735	11670
16178	6724	3211	3595	5698	5413	19215	68809	84752	45892	11290	2216
3778	2095	1760	1095	1034	756	3992	27255	37729	12205	11684	7368
3707	2115	982	830	853	1546	2297	35757	65720	31409	10799	4439
1851	1024	776	832	861	863	2526	32272	129472	77075	25457	7556
4008	1051	1309	1166	1220	1667	2814	29781	33300	9708	6233	5861
2841	1441	798	737	566	1093	1857	26255	75731	43314	7138	4172
1679	3271	2823	2210	2525	1936	2982	28793	102644	40849	20251	6706
2566	2152	1677	1168	1036	1635	6279	50427	74151	35585	6884	7465
4186	1881	889	871	616	1437	5560	59037	108563	55826	17200	6249
4758	4202	1867	1851	1352	1954	11614	62231	141451	56400	13319	9540
2477	4505	2176	1632	1820	2172	3966	35941	85857	25336	5170	6233
3887	2625	1590	1459	1443	2051	3459	89254	123196	65406	22851	3742
5200	6506	3085	2398	2935	5687	7256	78705	107862	36893	6562	4681
4736	2738	1378	810	739	1148	2099	18757	86675	78778	17222	5936
3231	1695	1671	1535	1408	1513	2293	27682	64924	27284	18945	3522
4584	1598	1004	915	847	1348	2964	12525	39105	10484	14137	3734
2455	2222	1632	1416	1275	1616	3903	36097	127571	65982	19650	5839
2841	1786	1293	1152	931	1461	5013	51161	122859	59314	34547	8760
3315	1810	2643	5554	4368	9122	32698	158438	142085	41340	16814	6203
5120	4328	3089	1764	1093	1287	4469	22501	55363	20794	12294	5790
2156	1519	1546	1208	2996	1190	1956	23000	87236	80277	37788	9589
4291	2711	3412	2772	3879	5871	36521	108484	283199	136573	43531	12458

```
LINE 0119 GIVES THE FORMAT MF1 (IN PARENTHESIS) TO WRITE THE SEASONAL
HYDROLOGIC SERIES Y(I,J) TO THE OUTPUT FILE
(12F10.0)                                                                0119
LINE 0120 GIVES THE FORMAT MF2 (IN PARENTHESIS) TO WRITE THE SEASONAL
STATISTICS OF THE SEASONAL HYDROLOGIC SERIES Y(I,J) TO THE OUTPUT FILE
(4X,12F10.2)                                                             0120
LINE 0121 GIVES THE FORMAT MF3 (IN PARENTHESIS) TO WRITE THE HEADINGS FOR
SEASONS Y(I,J) IN THE TABLE OF SEASONAL DATA, TO THE OUTPUT FILE
(1X,13I10/)                                                              0121
***************************************************************************
```

```
LINES 0201 THROUGH 0205 DESCRIBE PROY=NAME OF PROJECT, BASIN=NAME OF RIVER
BASIN, STAC=NAME OF GAGING STATION, SERIE=TYPE OF HYDROLOGIC DATA AND
UNIT=UNITS OF HYDROLOGIC DATA
PROY  (60A)...:Fuzzy Reservoir Planning                                    0201
BASIN (20A)...:Cache La Poudre River                                       0202
STAC  (30A)...:Grey Mountain Reservoir                                     0203
SERIE (30A)...:Monthly Diversion Volume                                    0204
UNIT  (10A)...:Acre Feet                                                   0205
LINES 0206 THROUGH 0207 DESCRIBE:NFYR=FIRST AND NLYR=LAST YEAR OF DATA
NFYR   (I4)...:1954                                                        0206
NLYR   (I4)...:1983                                                        0207
LINE 0208 DESCRIBES PERIODIC MEAN USED IN THE MODEL EVY(L),L=1,NSES)
(NSES IS LESS OR EQUAL 12) (12F6.2)
  8.08  7.58  7.34  7.20  7.12  7.38  8.04 10.16 10.98 10.42  9.46  8.63   0208
LINE 0209 DESCRIBES PERIODIC STANDARD DEVIATION USED IN THE MODEL
SDY(L),L=1,NSES (12F6.2)
  0.38  0.48  0.43  0.48  0.55  0.49  0.64  0.75  0.55  0.60  0.61  0.42   0209
LINE 0200 DESCRIBES PERIODIC EXPONENT IN TRANSFORMATION EE(L),L=1,NSES
IF IDE=2 (12F6.2)
   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   0210
LINE 0211 DESCRIBES PERIODIC ADDED CONSTANT FOR TRANSFORMATION C(L),
L=1,NSES IF IDE = 1,2,3,4,5 OR 6 (12F6.2)
   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   0211
LINE 0212 DESCRIBES INDICATOR NAR WHICH DEFINES WHAT TYPE OF PERIODIC
AR OR ARMA MODEL IS USED: NAR=0 FOR PAR(0), NAR=1 FOR PAR(1), NAR=2 FOR
PAR(2) AND NAR=3 FOR PARMA(1,1) (I6)
   NAR
     1                                                                     0212
LINES 0213 AND 0214 DESCRIBE MATRIX OF PERIODIC AR PARAMETERS PHIP(IL,L,M),
IL=1,NAR, L=1,NSES, M=1,NSER. EACH COLUMN CORRESPONDS TO DIFFERENT SEASON,
THE FIRST LINE CORRESPONDS TO FIRST ORDER AR PARAMETERS (NAR=1, 2, OR 3),
THE SECOND LINE CORRESPONDS TO SECOND ORDER AR PARAMETERS (NAR=2) (12F6.3)
 0.385 0.293 0.557 0.684 0.847 0.409 -.225 0.555  .264 0.275 0.599 0.534   0213
  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000   0214
LINE 0215 DESCRIBES VECTOR OF PERIODIC MA PARAMETERS THTP(L), L=1,NSES
(FOR NAR=3) (12F6.3)
  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000   0215
```

```
LINE 0216 DESCRIBES PERIODIC RESIDUAL STANDARD DEVIATION WNSTD(L),L=1,NSES
(12F6.3)
 0.918 0.925 0.775 0.557 0.463 0.904 0.965 0.840 0.862 0.967 0.767 0.897    0216
***************************************************************************
SEASONAL HYDROLOGIC SERIES
***************************************************************************
LINE 0217 GIVES THE FORMAT MFO (IN PARENTHESIS) TO READ THE SEASONAL
HYDROLOGIC SERIES Y(I,J)
(12F9.0)                                                                    0217
LINES 0218 CORRESPOND TO SEASONAL HYDROLOGIC SERIES Y(I,J)
```

3386	1940	2010	1940	1554	1554	2921	25403	34125	15040	3722	5693
4970	1634	1049	1208	911	1228	1960	21859	60321	27908	15484	4316
3049	2287	2435	1693	1396	1911	3455	67389	83004	24295	11553	3198
2020	1208	1584	1277	1346	1426	6989	28967	96078	103554	20127	9623
5000	2693	2614	2089	2059	2663	576	24760	79717	16097	4029	3227
3148	1861	2000	1634	1980	3039	3998	32512	98095	24562	10712	4029
4485	3713	1139	1059	764	3000	5495	49688	95783	27631	6475	4188
2990	1697	1542	2249	1643	2800	3798	35864	50007	31914	18735	11670
5106	669	673	558	451	491	11211	64859	62614	45892	11290	2216
3778	2095	1760	1095	1034	756	3992	27255	37729	12205	11684	7368
3707	2115	982	830	853	1546	2297	33844	65720	31409	10799	4439
1851	1024	776	832	861	863	2526	30409	59069	77075	25457	7556
4008	1051	1309	1166	1220	1667	2814	29781	33300	9708	6233	5861
2841	1441	798	737	566	1093	1857	24788	48746	32650	7138	4172
1679	3271	2823	2210	2525	1936	2982	27104	92516	40849	20251	6706
2566	2152	1677	1168	1036	1635	6279	49702	55394	35585	6884	7465
4186	1881	889	871	616	1437	5560	55412	69153	55826	17200	6249
4758	4202	1867	1851	1352	1954	5223	5904	105894	47353	13319	9540
2477	4505	2176	1632	1820	2172	3966	34745	70427	25336	5170	6233
3887	2625	1590	1459	1443	2051	3459	31090	94276	58236	22851	3742
1020	701	1107	669	614	2610	4811	73121	76685	36893	6562	4681
4736	2738	1378	810	739	1148	2099	18757	59115	72260	17222	5936
3231	1695	1671	1535	1408	1513	2293	27682	62366	27284	18945	3522
4584	1598	1004	915	847	1348	2964	12525	39105	10484	14137	3734
2455	2222	1632	1416	1275	1616	3903	33765	87108	65982	19650	5839
2841	1786	1293	1152	931	1461	5013	14628	45221	55301	34547	8760

3315	1810	2643	5554	4368	820	806	10000	89823	41340	16814	6203
5120	4328	3089	1764	1093	1287	4469	22501	40004	20794	12294	5790
2156	1519	1546	1208	2996	1190	1956	23000	55105	52551	37788	9589
4291	2711	3412	2772	3879	5871	881	1744	6045	55567	27352	12458

```
LINE 0219 GIVES THE FORMAT MF1 (IN PARENTHESIS) TO WRITE THE SEASONAL
HYDROLOGIC SERIES Y(I,J) TO THE OUTPUT FILE
(12F10.0)                                                           0219
LINE 0220 GIVES THE FORMAT MF2 (IN PARENTHESIS) TO WRITE THE SEASONAL
STATISTICS OF THE SEASONAL HYDROLOGIC SERIES Y(I,J) TO THE OUTPUT FILE
(4X,12F10.2)                                                         0220
LINE 0221 GIVES THE FORMAT MF3 (IN PARENTHESIS) TO WRITE THE HEADINGS FOR
SEASONS Y(I,J) IN THE TABLE OF SEASONAL DATA, TO THE OUTPUT FILE
(1X,13I10/)                                                         0221
***************************************************************************
```

```
**************************************************************************
               INPUT DATA FOR PROGRAM CSU004
**************************************************************************
THIS IS AN EXAMPLE OF AN INPUT FILE TO RUN PROGRAM CSU004. IT BRIEFLY
DESCRIBES ALL INPUT VARIABLES NEEDED TO RUN THE PROGRAM. IDENTIFIER INDEXES
ARE INCLUDED AT EACH DATA LINE IN COLUMNS 77-80. THERE ARE 05 IDENTIFIER
INDEXES 0001 THROUGH 0005 CORRESPONDING TO EACH INPUT DATA LINE. THE INDEX
0004 IS REPEATED FOR ALL LINES OF SEASONAL PARAMETER MATRICES B. THE INDEX
0005 IS REPEATED FOR ALL LINES OF SEASONAL PARAMETER MATRICES M0. THE INDEX
0I18 IS REPEATED FOR ALL YEARS OF DATA OF SERIES Y(L,J) AT SITE I. TO RUN
THE PROGRAM WITH ANY OTHER DATA SET, THE USER NEEDS TO EDIT THIS FILE AND
INSERT CORRESPONDING DATA ONLY ON THOSE LINES HAVING IDENTIFIERS.
**************************************************************************
LINE 0001 DESCRIBES NSER=NUMBER OF SITES TO BE ANALYZED (I5):
    2                                                                        0001
LINE 0002 DESCRIBES IDE(K)=INDEX OF TRANSFORMATION FOR EACH SITE K (16I5):
    0    0                                                                    0002
LINE 0003 DESCRIBES NSAM=NUMBER OF SAMPLES TO BE GENERATED, NYRS=NUMBER
OF YEARS OF HISTORIC SERIES, NSES=NUMBER OF SEASONS, NGEN=NUMBER OF YEARS
OF GENERATED SERIES, ND=PROGRAM GENERATES NYRS+ND YEARS AND DROPS FIRST
ND YEARS, ILE=INDICATOR FOR PRINTING(ILE=0,PRINT SERIES WITHOUT TRANSFORMATION
ONLY,ILE=1,PRINT ORIGINAL AND TRANSFORMED SERIES IF IDE.NE.0,ILE=2,PRINT
TRANSFORMED SERIES ONLY IF IDE.NE.0) (6I5):
   20   30   12   30   10    0                                                0003
LINES 0004 DESCRIBE PARAMETER MATRICES B FOR EACH SEASON
SEASON 1
  .861  .000
  .396  .824
SEASON 2
  .763  .000
  .612  .734
SEASON 3
  .765  .000
  .812  .129
SEASON 4
  .695  .000
  .653  .260
```

```
SEASON 5
  .503  .000
  .376  .323
SEASON 6
  .425  .000
  .485  .735
SEASON 7
  .511  .000
  .042  .869
SEASON 8
  .527  .000
  .204  .806
SEASON 9
  .705  .000
  .173  .945
SEASON10
  .485  .000
  .608  .731
SEASON11
  .637  .000
  .686  .304
SEASON12
  .771  .000
  .799  .251
LINES OOO5 DESCRIBE PARAMETER MATRICES M0 FOR EACH SEASON
SEASON 1
 1.000  .545                                                          0005
  .545 1.000                                                          0005
SEASON 2
 1.000  .280                                                          0005
  .280 1.000                                                          0005
SEASON 3
 1.000  .698                                                          0005
  .698 1.000                                                          0005
SEASON 4
 1.000  .785                                                          0005
  .785 1.000                                                          0005
```

```
SEASON 5
 1.000  .554                                                                0005
  .554 1.000                                                                0005
SEASON 6
 1.000  .323                                                                0005
  .323 1.000                                                                0005
SEASON 7
 1.000  -.029                                                               0005
 -.029 1.000                                                                0005
SEASON 8
 1.000  .040                                                                0005
  .040 1.000                                                                0005
SEASON 9
 1.000  .087                                                                0005
  .087 1.000                                                                0005
SEASON 10
 1.000  .858                                                                0005
  .858 1.000                                                                0005
SEASON 11
 1.000  .957                                                                0005
  .957 1.000                                                                0005
SEASON 12
 1.000 1.000                                                                0005
 1.000 1.000                                                                0005
*************************************************************************
LINES 0101 THROUGH 0105 DESCRIBE PROY=NAME OF PROJECT, BASIN=NAME OF RIVER
BASIN, STAC=NAME OF GAGING STATION, SERIE=TYPE OF HYDROLOGIC DATA AND
UNIT=UNITS OF HYDROLOGIC DATA
PROY  (60A)...:Fuzzy Reservoir Planning                                     0101
BASIN (20A)...:Cache La Poudre River                                        0102
STAC  (30A)...:Grey Mountain Reservoir                                      0103
SERIE (30A)...:Monthly Inflow Volume                                        0104
UNIT  (10A)...:Acre Feet                                                    0105
LINES 0106 THROUGH 0107 DESCRIBE:NFYR=FIRST AND NLYR=LAST YEAR OF DATA
NFYR    (I4)...:1954                                                        0106
NLYR    (I4)...:1983                                                        0107
LINE 0108 DESCRIBES PERIODIC MEAN USED IN THE MODEL EVY(L),L=1,NSES)
```

```
(NSES IS LESS OR EQUAL 12) (12F6.2)
3963.100  2567.733  1832.800  1670.633  1704.933  2346.233  7241.267 49767.300 96855.130 44257.500 15686.770
6133.433
LINE 0109 DESCRIBES PERIODIC STANDARD DEVIATION USED IN THE MODEL
SDY(L),L=1,NSES (12F6.2)
2438.114  1411.447   754.292   963.827  1179.813  1817.547  8249.022 31432.750 46796.250 28889.000  9603.303
2520.017
LINE 0110 DESCRIBES PERIODIC EXPONENT IN TRANSFORMATION EE(L),L=1,NSES
IF IDE=2 (12F6.2)
   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00    0110
LINE 0111 DESCRIBES PERIODIC ADDED CONSTANT FOR TRANSFORMATION C(L),
L=1,NSES IF IDE = 1,2,3,4,5 OR 6 (12F6.2)
   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00
LINE 0112 DESCRIBES INDICATOR NAR WHICH DEFINES WHAT TYPE OF PERIODIC
AR OR ARMA MODEL IS USED: NAR=0 FOR PAR(0), NAR=1 FOR PAR(1), NAR=2 FOR
PAR(2) AND NAR=3 FOR PARMA(1,1) (I6)
   NAR
     2                                                                      0112
LINES 0113 AND 0114 DESCRIBE MATRIX OF PERIODIC AR PARAMETERS PHIP(IL,L,M),
IL=1,NAR, L=1,NSES, M=1,NSER. EACH COLUMN CORRESPONDS TO DIFFERENT SEASON,
THE FIRST LINE CORRESPONDS TO FIRST ORDER AR PARAMETERS (NAR=1, 2, OR 3),
THE SECOND LINE CORRESPONDS TO SECOND ORDER AR PARAMETERS (NAR=2) (12F6.3)
  .618  .655  .687  .812  .626  .164  .751  .289  .135 1.068  .716  .381
 -.126 -.022 -.070 -.161  .299  .764  .131  .589  .597 -.434  .067  .295
LINE 0115 DESCRIBES VECTOR OF PERIODIC MA PARAMETERS THTP(L), L=1,NSES
(FOR NAR=3) (12F6.3)
  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000    0115
LINE 0116 DESCRIBES PERIODIC RESIDUAL STANDARD DEVIATION WNSTD(L),L=1,NSES
(12F6.3)
.861      .763      .765      .695      .503      .425      .511      .527      .705      .485      .637
.771
***************************************************************************
SEASONAL HYDROLOGIC SERIES
***************************************************************************
LINE 0117 GIVES THE FORMAT MFO (IN PARENTHESIS) TO READ THE SEASONAL
HYDROLOGIC SERIES Y(I,J)
(12F9.0)                                                                    0117
```

LINES 0118 CORRESPOND TO SEASONAL HYDROLOGIC SERIES Y(I,J)

3386	1940	2010	1940	1554	1554	2921	25403	34125	15040	3722	5693
4970	1634	1049	1208	911	1228	1960	21859	60321	27908	15484	4316
3049	2287	2435	1693	1396	1911	3455	72052	86477	24295	11553	3198
2020	1208	1584	1277	1346	1426	6989	35174	134937	103554	20127	9623
5000	2693	2614	2089	2059	2663	10821	91872	95169	16097	4029	3227
3148	1861	2000	1634	1980	3039	11999	43709	102762	24562	10712	4029
4485	3713	1139	1059	764	3000	5495	49688	95783	27631	6475	4188
2990	1697	1542	2249	1643	2800	7865	70100	116622	31914	18735	11670
16178	6724	3211	3595	5698	5413	19215	68809	84752	45892	11290	2216
3778	2095	1760	1095	1034	756	3992	27255	37729	12205	11684	7368
3707	2115	982	830	853	1546	2297	35757	65720	31409	10799	4439
1851	1024	776	832	861	863	2526	32272	129472	77075	25457	7556
4008	1051	1309	1166	1220	1667	2814	29781	33300	9708	6233	5861
2841	1441	798	737	566	1093	1857	26255	75731	43314	7138	4172
1679	3271	2823	2210	2525	1936	2982	28793	102644	40849	20251	6706
2566	2152	1677	1168	1036	1635	6279	50427	74151	35585	6884	7465
4186	1881	889	871	616	1437	5560	59037	108563	55826	17200	6249
4758	4202	1867	1851	1352	1954	11614	62231	141451	56400	13319	9540
2477	4505	2176	1632	1820	2172	3966	35941	85857	25336	5170	6233
3887	2625	1590	1459	1443	2051	3459	89254	123196	65406	22851	3742
5200	6506	3085	2398	2935	5687	7256	78705	107862	36893	6562	4681
4736	2738	1378	810	739	1148	2099	18757	86675	78778	17222	5936
3231	1695	1671	1535	1408	1513	2293	27682	64924	27284	18945	3522
4584	1598	1004	915	847	1348	2964	12525	39105	10484	14137	3734
2455	2222	1632	1416	1275	1616	3903	36097	127571	65982	19650	5839
2841	1786	1293	1152	931	1461	5013	51161	122859	59314	34547	8760
3315	1810	2643	5554	4368	9122	32698	158438	142085	41340	16814	6203
5120	4328	3089	1764	1093	1287	4469	22501	55363	20794	12294	5790
2156	1519	1546	1208	2996	1190	1956	23000	87236	80277	37788	9589
4291	2711	3412	2772	3879	5871	36521	108484	283199	136573	43531	12458

LINE 0119 GIVES THE FORMAT MF1 (IN PARENTHESIS) TO WRITE THE SEASONAL HYDROLOGIC SERIES Y(I,J) TO THE OUTPUT FILE

(12F10.0) 0119

LINE 0120 GIVES THE FORMAT MF2 (IN PARENTHESIS) TO WRITE THE SEASONAL STATISTICS OF THE SEASONAL HYDROLOGIC SERIES Y(I,J) TO THE OUTPUT FILE

```
(4X,12F10.2)                                                              0120
LINE 0121 GIVES THE FORMAT MF3 (IN PARENTHESIS) TO WRITE THE HEADINGS FOR
SEASONS Y(I,J) IN THE TABLE OF SEASONAL DATA, TO THE OUTPUT FILE
(1X,13I10/)                                                               0121
***************************************************************************
LINES 0201 THROUGH 0205 DESCRIBE PROY=NAME OF PROJECT, BASIN=NAME OF RIVER
BASIN, STAC=NAME OF GAGING STATION, SERIE=TYPE OF HYDROLOGIC DATA AND
UNIT=UNITS OF HYDROLOGIC DATA
PROY  (60A)...:Fuzzy Reservoir Planning                                   0201
BASIN (20A)...:Cache La Poudre River                                      0202
STAC  (30A)...:Grey Mountain Reservoir                                    0203
SERIE (30A)...:Monthly Diversion Volume                                   0204
UNIT  (10A)...:Acre Feet                                                  0205
LINES 0206 THROUGH 0207 DESCRIBE:NFYR=FIRST AND NLYR=LAST YEAR OF DATA
NFYR   (I4)...:1954                                                       0206
NLYR   (I4)...:1983                                                       0207
LINE 0208 DESCRIBES PERIODIC MEAN USED IN THE MODEL EVY(L),L=1,NSES)
(NSES IS LESS OR EQUAL 12) (12F6.2)
3454.700  2172.400  1682.267  1511.767  1452.667  1802.867  3685.100 31301.930 65084.830 39386.040 15147.470
6133.433
LINE 0209 DESCRIBES PERIODIC STANDARD DEVIATION USED IN THE MODEL
SDY(L),L=1,NSES (12F6.2)
1113.577   989.650   702.219   915.071   915.687   993.494  2103.391 16983.830 23644.650 21551.710  8403.876
2520.017
LINE 0200 DESCRIBES PERIODIC EXPONENT IN TRANSFORMATION EE(L),L=1,NSES
IF IDE=2 (12F6.2)
   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00    0210
LINE 0211 DESCRIBES PERIODIC ADDED CONSTANT FOR TRANSFORMATION C(L),
L=1,NSES IF IDE = 1,2,3,4,5 OR 6 (12F6.2)
   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00
LINE 0212 DESCRIBES INDICATOR NAR WHICH DEFINES WHAT TYPE OF PERIODIC
AR OR ARMA MODEL IS USED: NAR=0 FOR PAR(0), NAR=1 FOR PAR(1), NAR=2 FOR
PAR(2) AND NAR=3 FOR PARMA(1,1) (I6)
   NAR
     2                                                                    0212
LINES 0213 AND 0214 DESCRIBE MATRIX OF PERIODIC AR PARAMETERS PHIP(IL,L,M),
IL=1,NAR, L=1,NSES, M=1,NSER. EACH COLUMN CORRESPONDS TO DIFFERENT SEASON,
```

THE FIRST LINE CORRESPONDS TO FIRST ORDER AR PARAMETERS (NAR=1, 2, OR 3),
THE SECOND LINE CORRESPONDS TO SECOND ORDER AR PARAMETERS (NAR=2) (12F6.3)

```
  .512  .297  .594  .815  .666  .789 -.029  .562  .208  .314  .679  .445
 -.155 -.010 -.125 -.236  .264 -.450 -.480  .030  .100 -.149 -.291  .147
```

LINE 0215 DESCRIBES VECTOR OF PERIODIC MA PARAMETERS THTP(L), L=1,NSES
(FOR NAR=3) (12F6.3)

```
  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000  .000    0215
```

LINE 0216 DESCRIBES PERIODIC RESIDUAL STANDARD DEVIATION WNSTD(L),L=1,NSES
(12F6.3)

```
.914      .956      .822      .703      .496      .881      .870      .831      .961      .951      .750
.838
```

****
SEASONAL HYDROLOGIC SERIES
****

LINE 0217 GIVES THE FORMAT MFO (IN PARENTHESIS) TO READ THE SEASONAL
HYDROLOGIC SERIES Y(I,J)
(12F9.0)   0217
LINES 0218 CORRESPOND TO SEASONAL HYDROLOGIC SERIES Y(I,J)

3386	1940	2010	1940	1554	1554	2921	25403	34125	15040	3722	5693
4970	1634	1049	1208	911	1228	1960	21859	60321	27908	15484	4316
3049	2287	2435	1693	1396	1911	3455	67389	83004	24295	11553	3198
2020	1208	1584	1277	1346	1426	6989	28967	96078	103554	20127	9623
5000	2693	2614	2089	2059	2663	576	24760	79717	16097	4029	3227
3148	1861	2000	1634	1980	3039	3998	32512	98095	24562	10712	4029
4485	3713	1139	1059	764	3000	5495	49688	95783	27631	6475	4188
2990	1697	1542	2249	1643	2800	3798	35864	50007	31914	18735	11670
5106	669	673	558	451	491	11211	64859	62614	45892	11290	2216
3778	2095	1760	1095	1034	756	3992	27255	37729	12205	11684	7368
3707	2115	982	830	853	1546	2297	33844	65720	31409	10799	4439
1851	1024	776	832	861	863	2526	30409	59069	77075	25457	7556
4008	1051	1309	1166	1220	1667	2814	29781	33300	9708	6233	5861
2841	1441	798	737	566	1093	1857	24788	48746	32650	7138	4172
1679	3271	2823	2210	2525	1936	2982	27104	92516	40849	20251	6706
2566	2152	1677	1168	1036	1635	6279	49702	55394	35585	6884	7465
4186	1881	889	871	616	1437	5560	55412	69153	55826	17200	6249
4758	4202	1867	1851	1352	1954	5223	5904	105894	47353	13319	9540
2477	4505	2176	1632	1820	2172	3966	34745	70427	25336	5170	6233

3887	2625	1590	1459	1443	2051	3459	31090	94276	58236	22851	3742
1020	701	1107	669	614	2610	4811	73121	76685	36893	6562	4681
4736	2738	1378	810	739	1148	2099	18757	59115	72260	17222	5936
3231	1695	1671	1535	1408	1513	2293	27682	62366	27284	18945	3522
4584	1598	1004	915	847	1348	2964	12525	39105	10484	14137	3734
2455	2222	1632	1416	1275	1616	3903	33765	87108	65982	19650	5839
2841	1786	1293	1152	931	1461	5013	14628	45221	55301	34547	8760
3315	1810	2643	5554	4368	820	806	10000	89823	41340	16814	6203
5120	4328	3089	1764	1093	1287	4469	22501	40004	20794	12294	5790
2156	1519	1546	1208	2996	1190	1956	23000	55105	52551	37788	9589
4291	2711	3412	2772	3879	5871	881	1744	6045	55567	27352	12458

```
LINE 0219 GIVES THE FORMAT MF1 (IN PARENTHESIS) TO WRITE THE SEASONAL
HYDROLOGIC SERIES Y(I,J) TO THE OUTPUT FILE
(12F10.0)                                                              0219
LINE 0220 GIVES THE FORMAT MF2 (IN PARENTHESIS) TO WRITE THE SEASONAL
STATISTICS OF THE SEASONAL HYDROLOGIC SERIES Y(I,J) TO THE OUTPUT FILE
(4X,12F10.2)                                                            0220
LINE 0221 GIVES THE FORMAT MF3 (IN PARENTHESIS) TO WRITE THE HEADINGS FOR
SEASONS Y(I,J) IN THE TABLE OF SEASONAL DATA, TO THE OUTPUT FILE
(1X,13I10/)                                                            0221
***************************************************************************
```

Example of generated data

1

GENERATED HYDROLOGIC SERIES SITE 1 SAMPLE 1

	1	2	3	4	5	6	7	8	9	10	11	12
1	209.	2933.	3462.	2548.	4318.	4612.	12948.	98440.	147829.	75269.	16635.	6340.
2	2675.	2723.	2680.	2956.	3103.	4480.	21415.	106358.	142418.	79066.	28286.	6871.
3	809.	332.	-22.	774.	273.	1106.	2457.	44735.	91517.	37901.	18853.	6496.
4	5476.	4198.	2254.	1901.	2441.	4229.	11553.	56149.	58319.	20845.	8493.	1133.
5	1109.	866.	1730.	1984.	1040.	2523.	9223.	50665.	66912.	26530.	7375.	5360.
6	3946.	2502.	1242.	1040.	433.	-226.	-2102.	29688.	55694.	32225.	3537.	8353.
7	8453.	2520.	2006.	1446.	2232.	1570.	11348.	57873.	118791.	41884.	5074.	6215.
8	1399.	2540.	1895.	1051.	600.	759.	9545.	52004.	107100.	31533.	17767.	5865.
9	1961.	759.	1510.	1830.	1625.	3560.	5933.	85161.	68708.	16043.	13416.	6613.
10	7258.	2754.	2070.	2368.	2296.	2549.	15388.	49018.	149074.	108772.	40406.	10331.
11	4995.	4330.	3005.	1990.	2752.	3011.	13265.	86784.	165890.	83201.	19569.	4800.
12	1395.	1159.	1155.	492.	1388.	97.	405.	15281.	51482.	4838.	8949.	6077.
13	4568.	2491.	1537.	2039.	1280.	2164.	11025.	39559.	136684.	99450.	25712.	8798.
14	7806.	4222.	2019.	1434.	1651.	1232.	5336.	9508.	94880.	59650.	18510.	5346.
15	4199.	3023.	2160.	2751.	2272.	3887.	17569.	79899.	175571.	87280.	14627.	2823.
16	4563.	2885.	1910.	2247.	3261.	3577.	11801.	79056.	155831.	74426.	22830.	8304.
17	5037.	2725.	2084.	1784.	1928.	2331.	-3117.	30690.	68142.	35427.	13827.	8114.
18	5323.	4371.	2121.	1347.	2950.	1616.	-3374.	29778.	108060.	63370.	21185.	5033.
19	5920.	3658.	2387.	986.	2104.	976.	3082.	16385.	78003.	38271.	15646.	5230.
20	558.	268.	964.	816.	328.	844.	18.	6928.	19219.	51442.	14116.	9329.
21	5129.	2754.	2346.	2070.	2002.	1996.	11446.	71177.	140904.	61888.	21448.	6737.
22	6261.	2806.	2297.	2863.	3477.	4026.	20017.	111280.	198485.	97055.	28607.	9878.
23	2966.	2079.	815.	1036.	44.	-329.	-2275.	9756.	15355.	17064.	16480.	3430.
24	2309.	1343.	1159.	2155.	2532.	2616.	13381.	55360.	62439.	18458.	20162.	6030.
25	2632.	1468.	2020.	2845.	1014.	4285.	12766.	83746.	147892.	84341.	31652.	12853.
26	10796.	6246.	2272.	2366.	1227.	3550.	12107.	58713.	93209.	24880.	2537.	5866.
27	7581.	4543.	1877.	1096.	1497.	2191.	11383.	38417.	149088.	81824.	22811.	8150.
28	5264.	3213.	1870.	2269.	1450.	4734.	32301.	101023.	204551.	94577.	25394.	8872.
29	8603.	3921.	1576.	-69.	-27.	-595.	-2327.	-21813.	73131.	58323.	14135.	7207.
30	3862.	2652.	1805.	3312.	2816.	4966.	17880.	73575.	118948.	23442.	13965.	3947.

1

GENERATED HYDROLOGIC SERIES SITE 2 SAMPLE 1

	1	2	3	4	5	6	7	8	9	10	11	12
1	3800.	3145.	3395.	2303.	3397.	2350.	2858.	14250.	81392.	68031.	16004.	6261.
2	3539.	2015.	2223.	2360.	2390.	2867.	2159.	23244.	52396.	64123.	28034.	6318.
3	4997.	1212.	167.	777.	127.	707.	6864.	49985.	55642.	40969.	20779.	6787.
4	3860.	3829.	2065.	1444.	1297.	1345.	3374.	9261.	71108.	42472.	18706.	2882.
5	3865.	2212.	2307.	2104.	1462.	1766.	8955.	59348.	45588.	70220.	21833.	6929.
6	2825.	1363.	761.	708.	43.	-903.	4239.	32835.	41074.	1321.	411.	7256.
7	2723.	1634.	1818.	1530.	1775.	1940.	3030.	33402.	73146.	21161.	1223.	4917.
8	2876.	3063.	2236.	1173.	1166.	-193.	5575.	50489.	73800.	13376.	14047.	5786.
9	2627.	1086.	1583.	1986.	1923.	2080.	6937.	48356.	84511.	77309.	27197.	9940.
10	6460.	1646.	1344.	1471.	1378.	1971.	94.	11626.	65531.	49597.	24659.	8026.
11	2383.	1762.	2220.	1392.	1346.	452.	4562.	3606.	73792.	48571.	14040.	2948.
12	3015.	2622.	1743.	758.	1762.	1820.	3219.	37547.	93277.	30854.	11397.	8249.
13	4437.	2312.	1392.	1709.	1726.	1910.	2445.	23049.	67746.	89929.	23092.	9487.
14	5461.	2255.	1199.	1195.	1599.	2088.	3145.	27150.	8552.	-183.	11105.	3875.
15	2821.	1843.	1725.	2061.	1547.	2766.	3877.	19142.	69765.	32530.	722.	-138.
16	2286.	1643.	1623.	1679.	2200.	1485.	3324.	30656.	72494.	54712.	19163.	8071.
17	4537.	2904.	2104.	1924.	1308.	109.	4122.	33868.	45730.	37806.	13358.	8401.
18	4084.	2335.	1346.	393.	1180.	2406.	675.	45647.	47880.	18592.	9759.	2336.
19	4096.	3116.	2352.	901.	2310.	2553.	1256.	29417.	67414.	24916.	7585.	4137.
20	3343.	88.	724.	507.	821.	2068.	5645.	41066.	62417.	95056.	30190.	13647.
21	5006.	1477.	1786.	1844.	1644.	849.	2383.	26398.	48658.	77701.	27511.	8173.
22	4705.	1248.	1433.	2291.	2335.	2141.	943.	23244.	87428.	54523.	14373.	8739.
23	6133.	2727.	851.	790.	239.	-292.	5465.	28407.	67721.	66216.	28808.	5308.
24	2595.	352.	673.	1432.	1603.	1896.	3965.	45877.	101462.	33236.	23210.	7505.
25	2535.	895.	1817.	2540.	980.	1439.	7105.	55943.	88360.	60985.	24784.	12228.
26	5617.	2716.	960.	1309.	412.	-52.	2798.	25445.	27296.	24482.	4425.	5648.
27	5225.	3115.	1434.	593.	781.	2555.	2490.	17960.	67435.	37016.	8842.	5347.
28	2683.	2189.	1493.	2208.	1319.	2853.	4286.	17128.	80998.	40085.	9904.	5337.
29	1331.	530.	623.	105.	-39.	1412.	6227.	59163.	87301.	27879.	5591.	5746.
30	3078.	1033.	1222.	2386.	1617.	397.	4766.	22529.	50160.	12152.	14269.	3709.

1

APPENDIX E

STOCHASTIC RESULTS

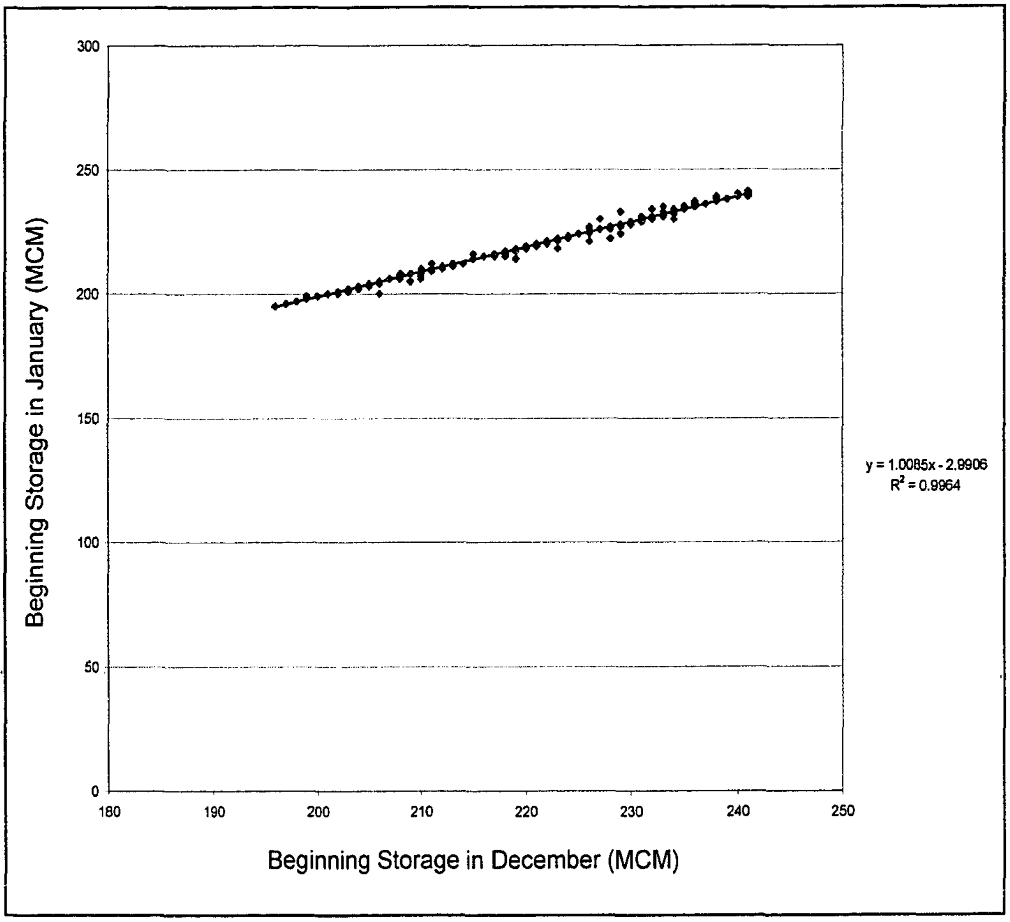


FIGURE E.1 Reservoir operating rule - January.

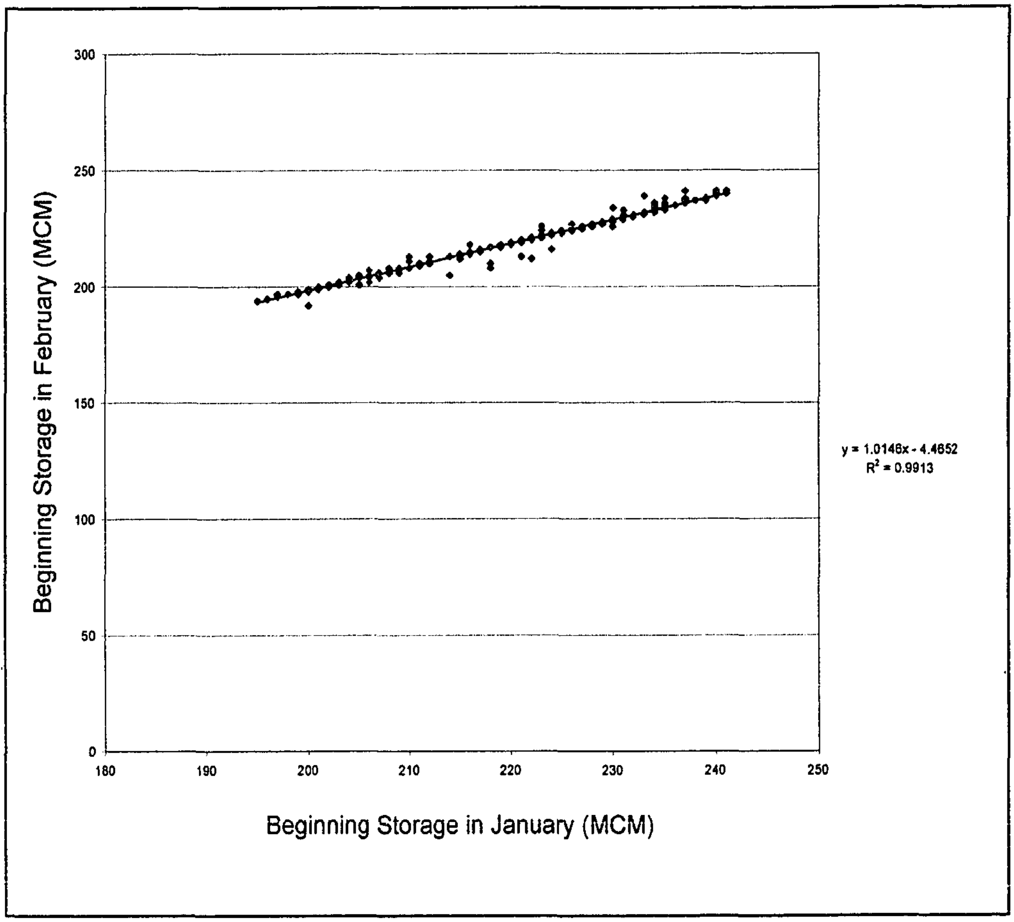


FIGURE E.2 Reservoir operating rule - February.

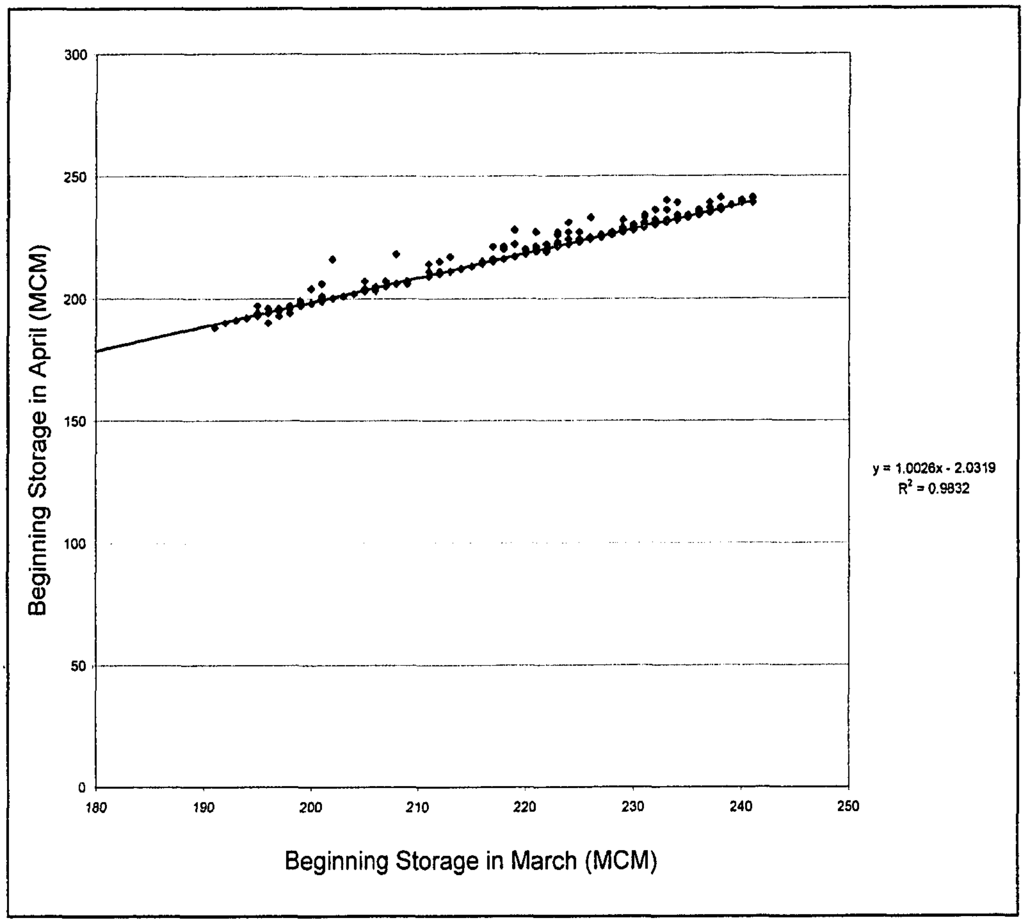


FIGURE E.3 Reservoir operating rule - April.

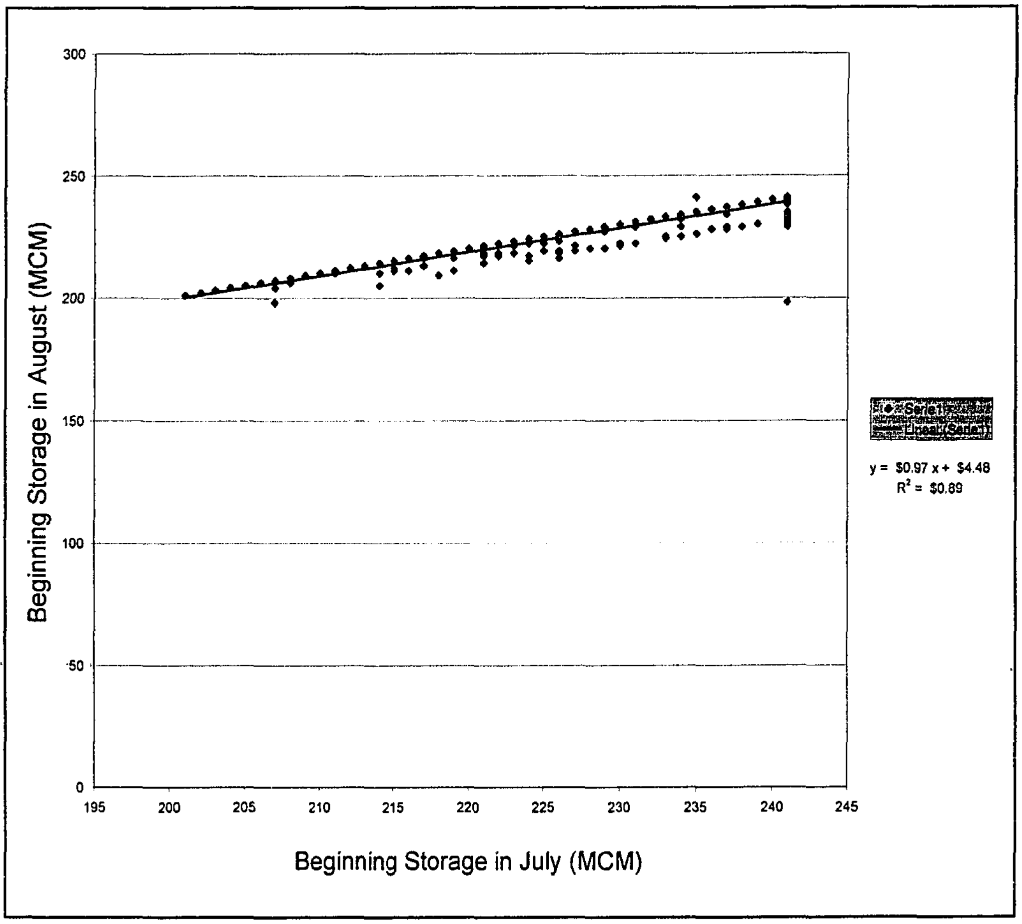


FIGURE E.4 Reservoir operating rule - August.

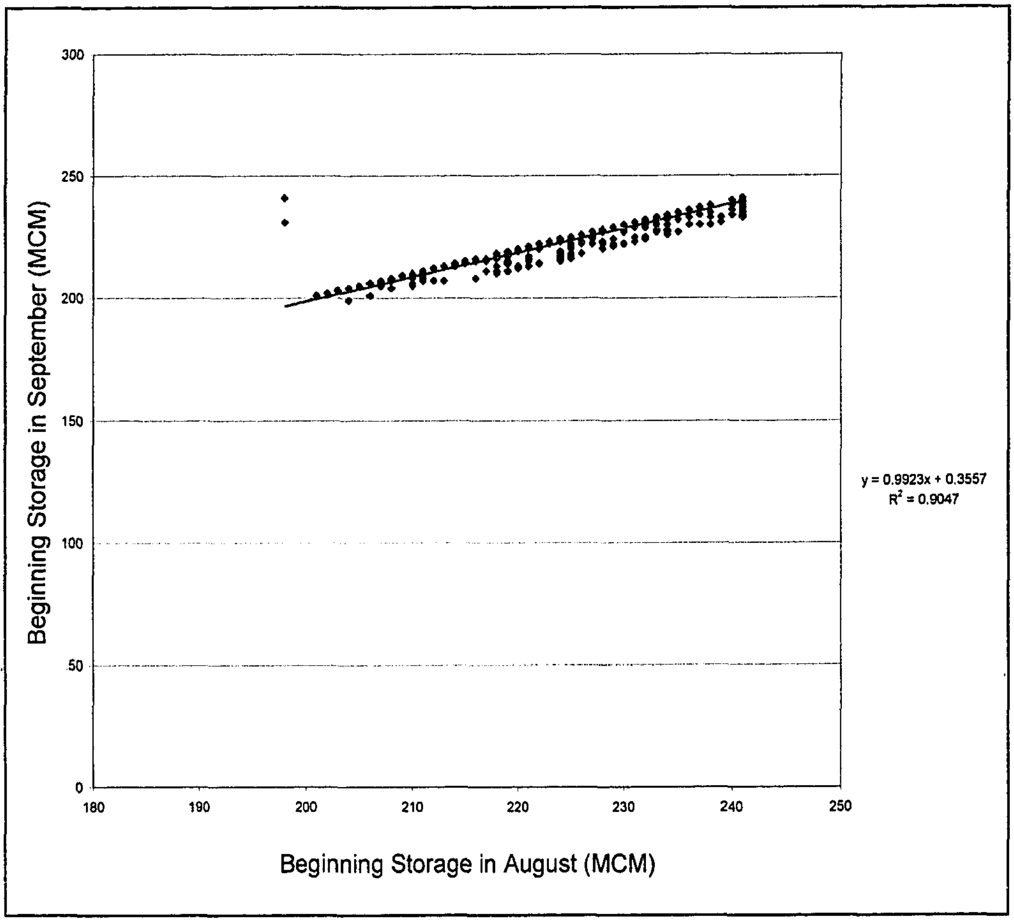


FIGURE E.5 Reservoir operating rule - September.

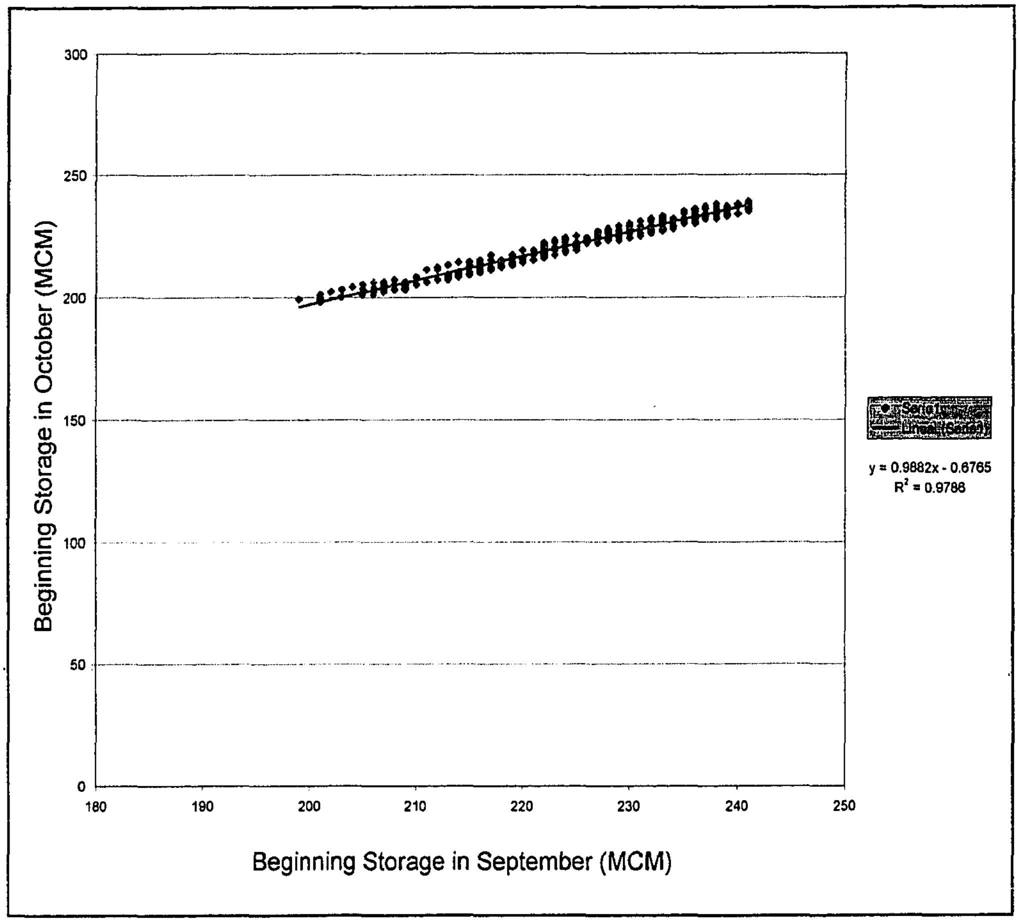


FIGURE E.6 Reservoir operating rule - October.

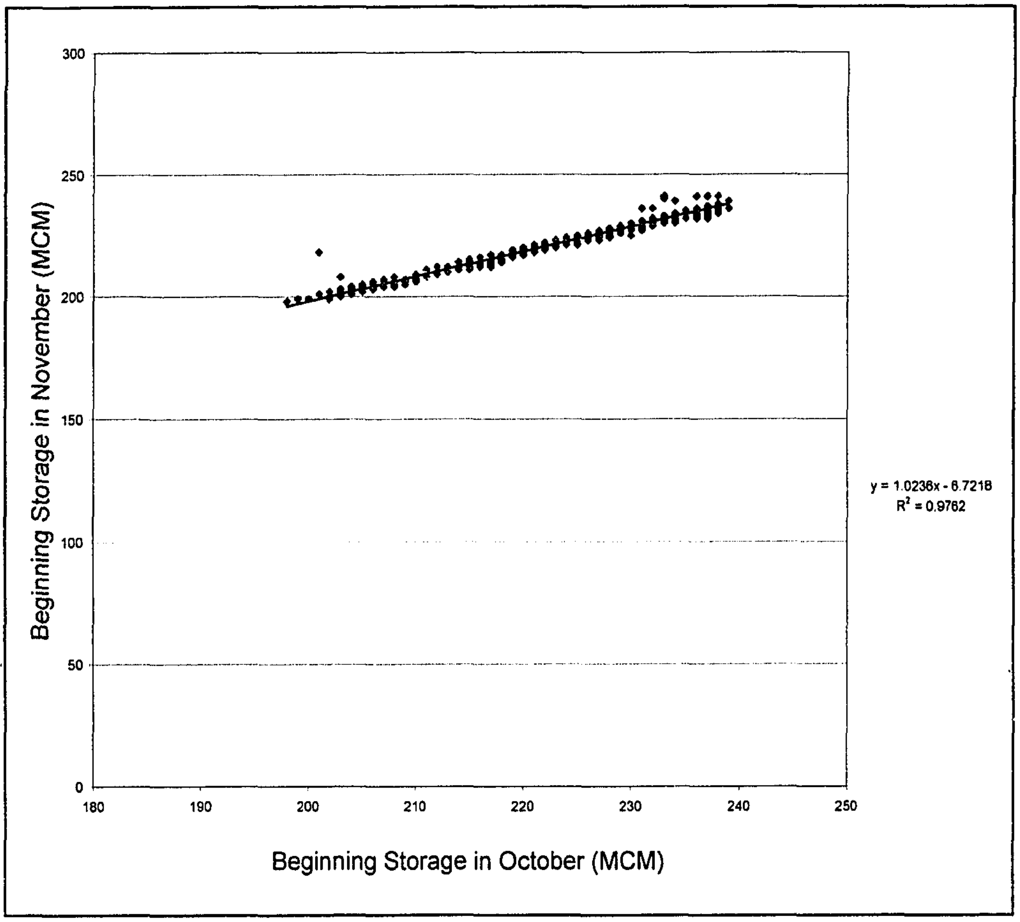


FIGURE E.7 Reservoir operating rule - November.

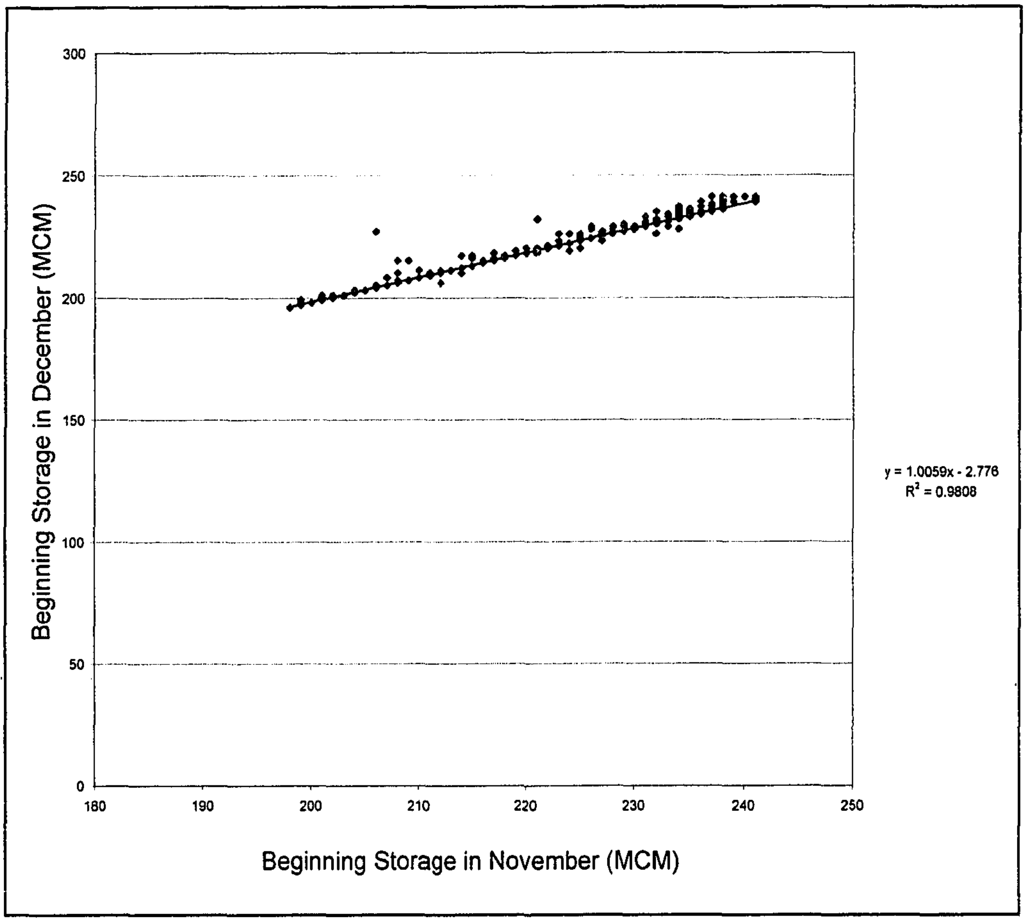


FIGURE E.8 Reservoir operating rule - December.

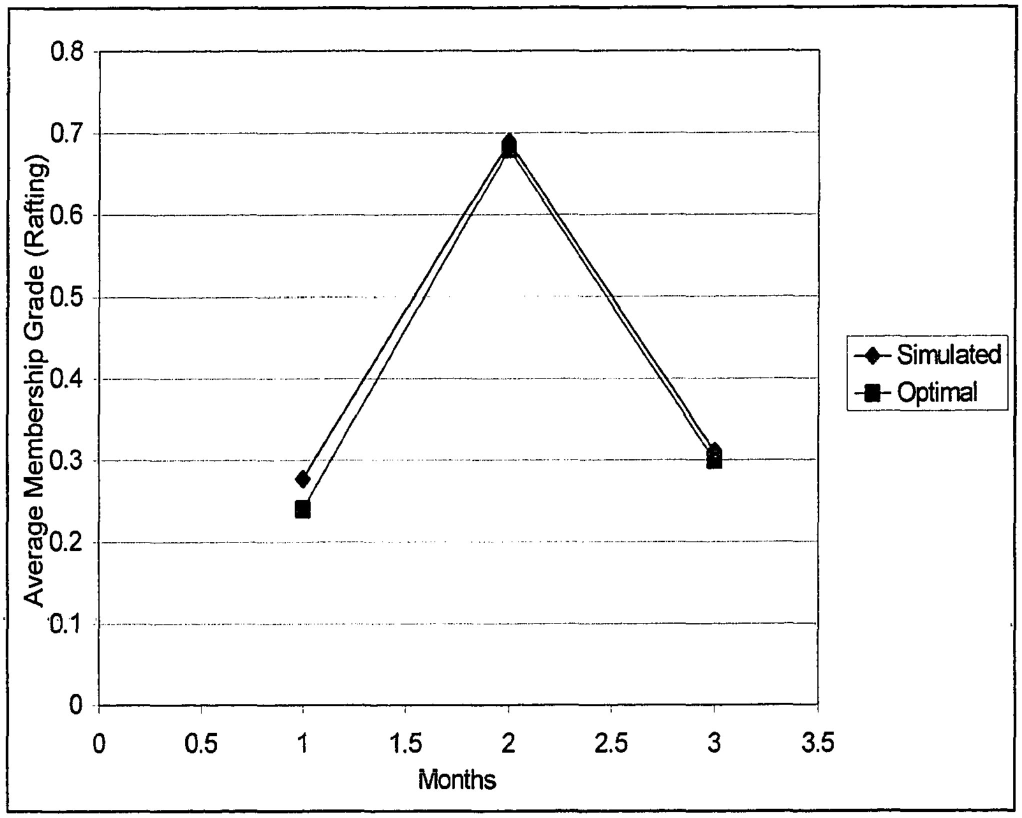


FIGURE E.9 Average membership grades for rafting (simulated and optimal).

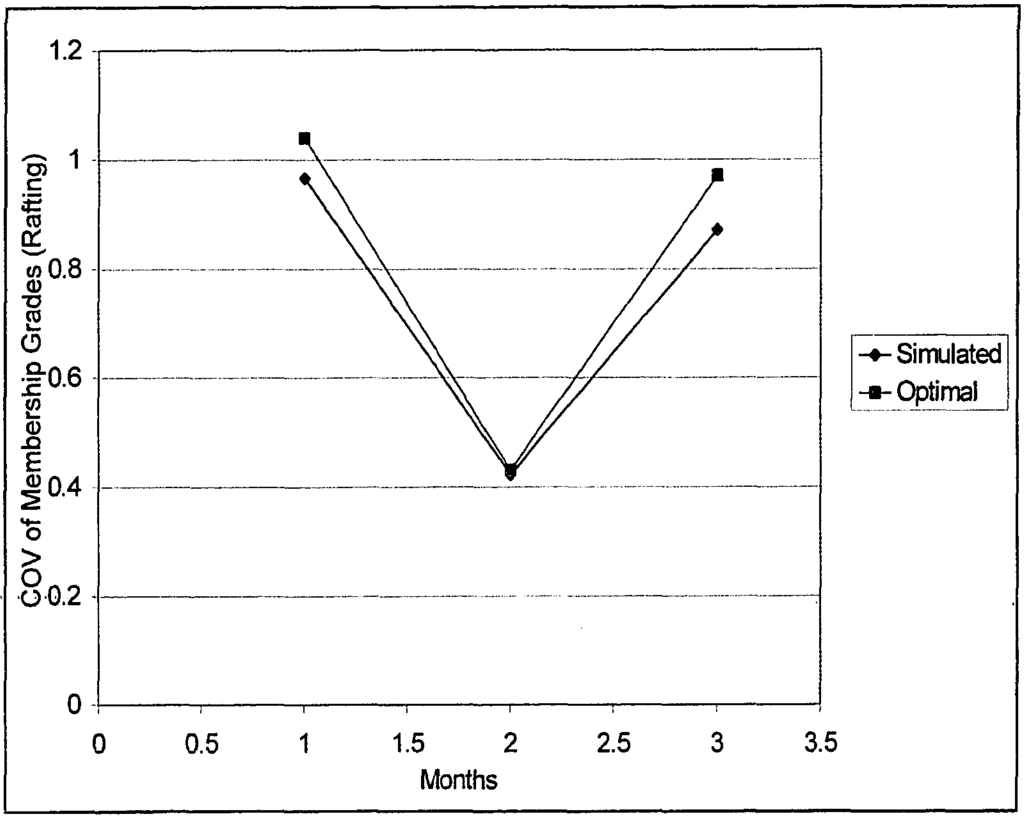


FIGURE E.10 COV for rafting objective (simulated and optimal).

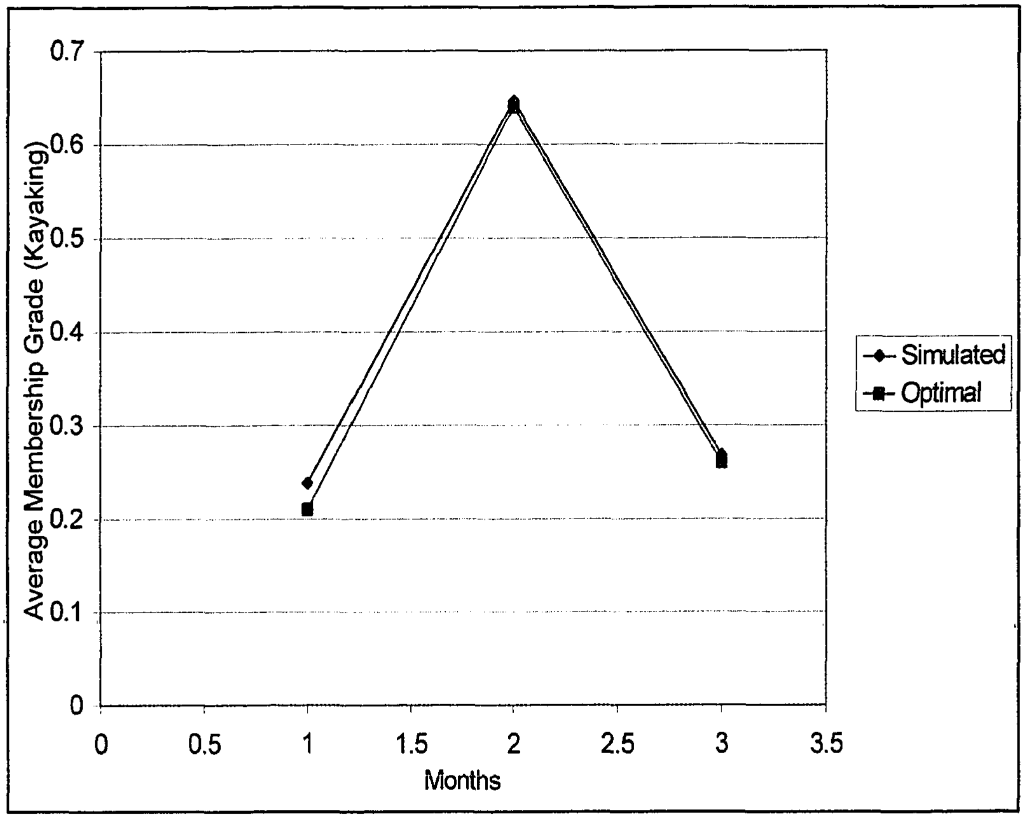


FIGURE E.11 Average membership grades for kayaking (simulated and optimal).

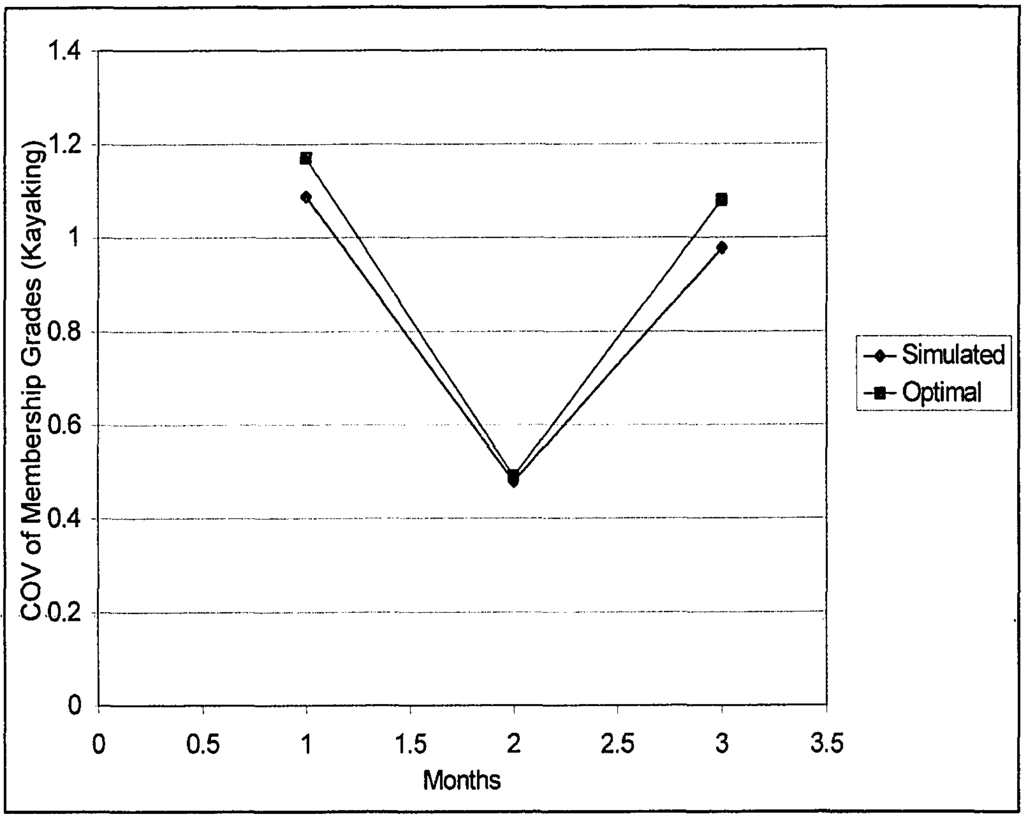


FIGURE E.12 COV for kayaking objective (simulated and optimal).

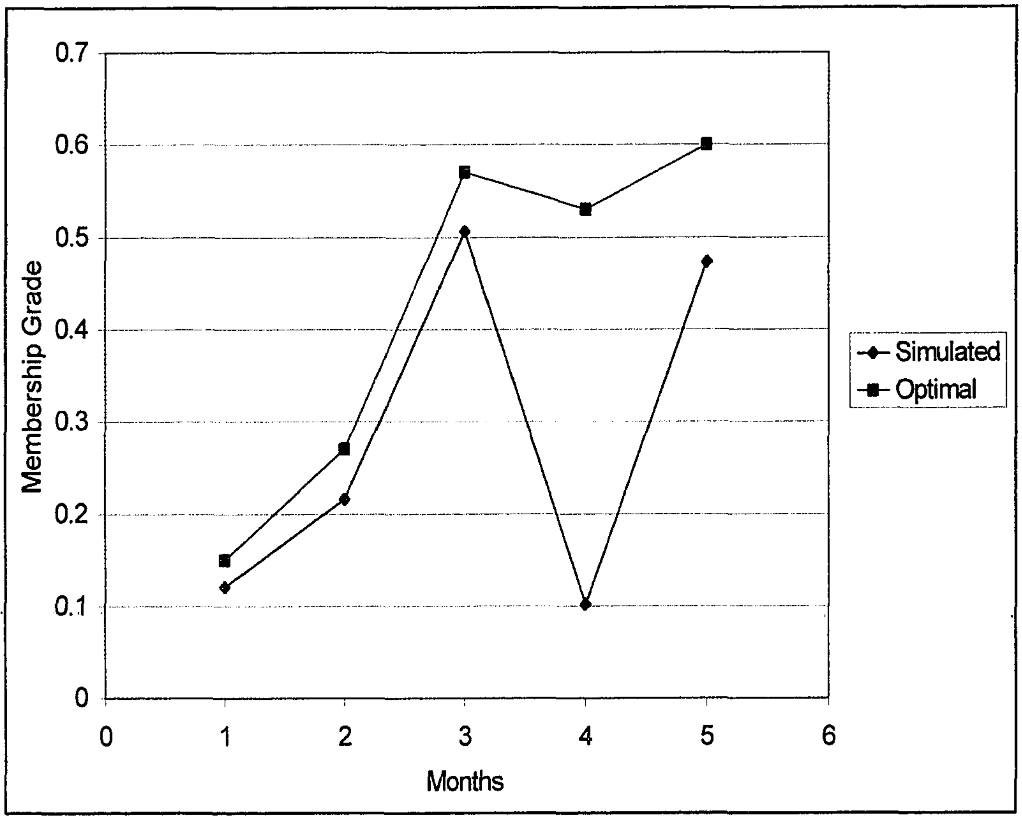


FIGURE E.13 Average membership grades for angling (simulated and optimal).

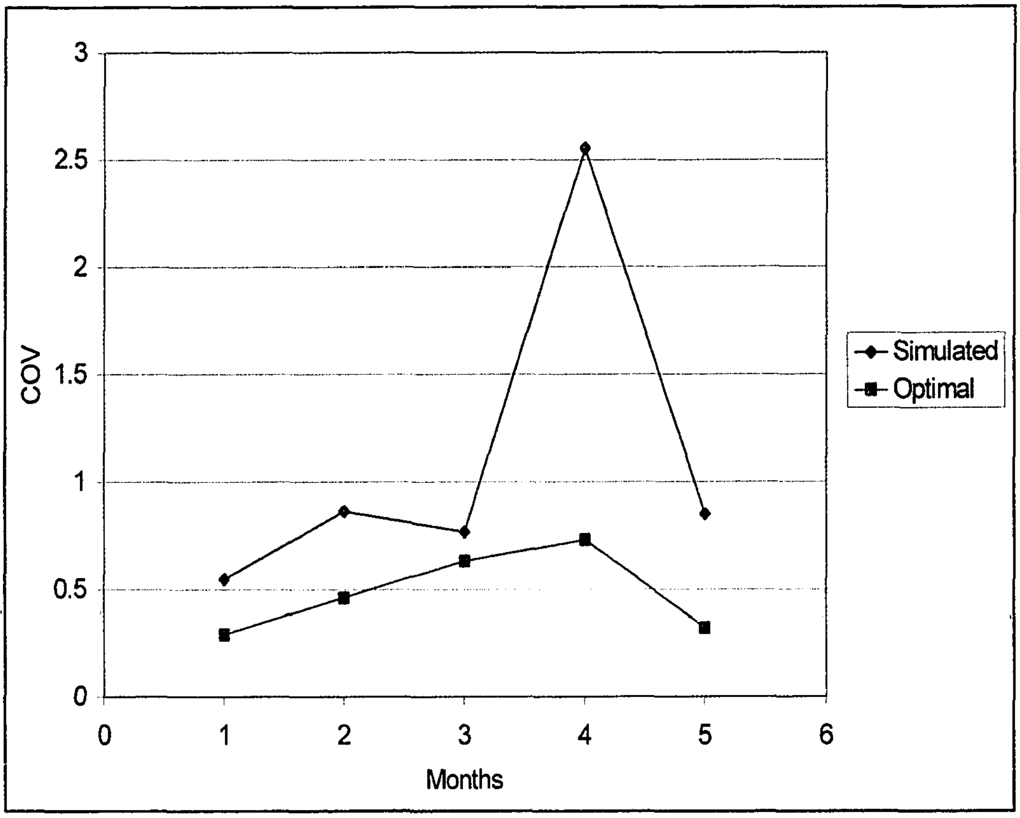


FIGURE E.14 COV of angling objective (simulated and optimal).

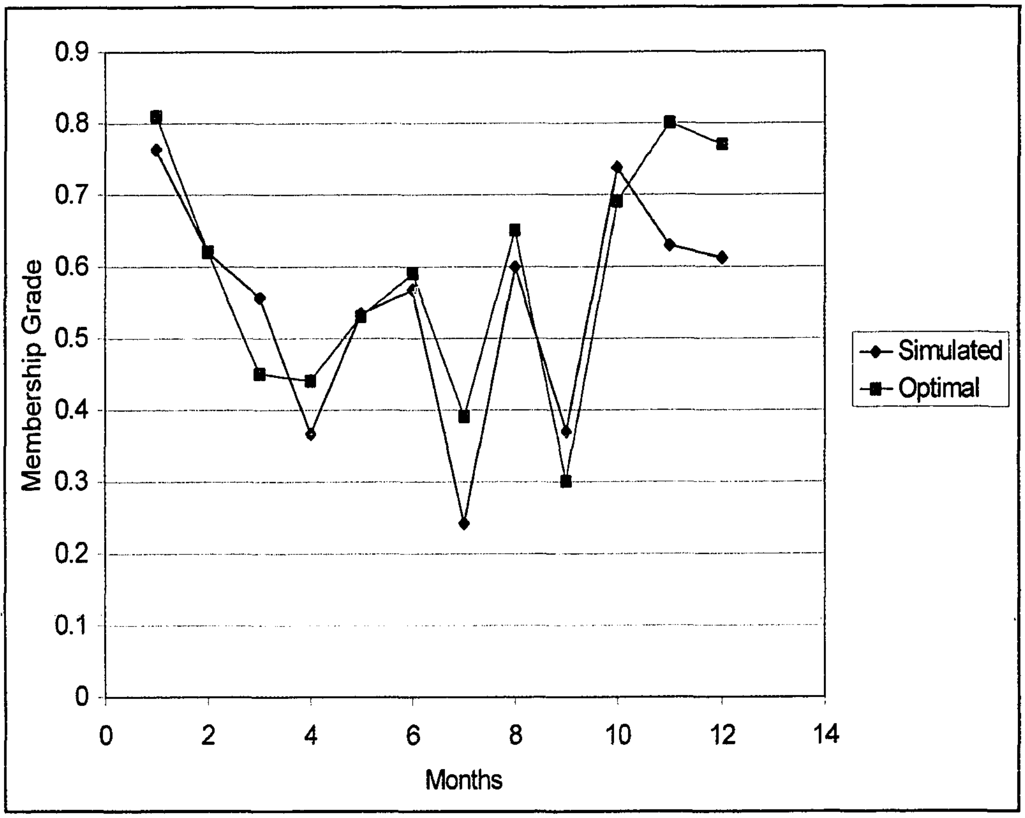


Figure E.15 Average membership grades for fish habitat (simulated and optimal).

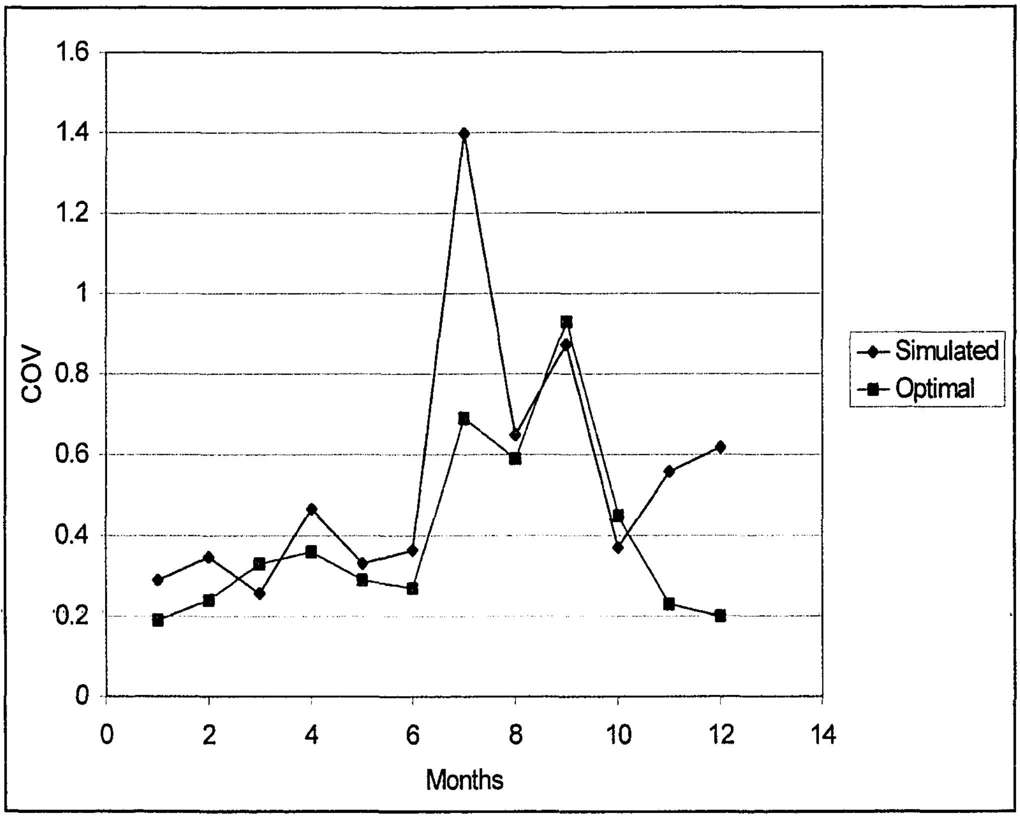


FIGURE E.16 COV of fish habitat objective (simulated and optimal).