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Rule-based reservoir operation considering long range forecast

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Abstract

A model for long range and real time reservoir operations is developed, considering the medium and long range weather forecast provided by the meteorological agency. The reasoning employed by the reservoir operator to make the appropriate decision on the reservoir operations, in the presence of uncertainty and inevitable errors in the forecast, is modeled through a rule-based scheme. A fuzzy inference procedure is used to evaluate the rules and produce the control output. The forecast inputs are of medium and long range inflow rates and trends. The operations are conducted according to "control levels" that are related to control actions designed to keep the reservoir state as near as possible to the target one. The simulation of the operation of a single reservoir throughout the year is performed for water utilization, hydropower and river preservation purposes. The focus is on drought management, and the results show that the model behaviour is coherent with the model formulation.

1. Introduction

During exceptional hydrological situations, like floods or droughts, the decision making process does not depend only on the technical conditions but also involves political and social factors. The long range simulation models for reservoir operation usually cannot reproduce these kind of situations and the consequent errors may strongly influence the simulated scenario of the sequent periods. Considering the case of shortage of water, the authority has to decide between reducing part of the release to the users and assuming the risk of a coming collapse of the system.

In addition, there are many factors which cannot be estimated in terms of probabilities due to various uncertainties both in the whole meteorological prediction and in the hydrological processes. The human expert operator many times performs better than automatic or optimized control. It would be desirable for an operation model to incorporate the experience and judgement of the operator, such as capability of self adaption and ability to derive effective operation procedures in the presence of uncertainty. Furthermore, the knowledge from the senior operator can be kept to help younger operators.

This work presents an operation model for a single reservoir, for water utilization, hydropower and river preservation purposes. The model considers information of medium and long range weather forecast. The main hydrological and reservoir state variables considered influencing this decision are compiled in a rule based algorithm. Fuzzy theory is applied as the mathematical framework for rule evaluation, due to its capability to deal with uncertainties caused by ill-defined criteria or class of membership, combining the hydrological information and the actual experience of the user.

2. Elements of Fuzzy Theory

Classical or "crisp" sets are defined as a collection of elements that can either belong to or not belong to the set. Each element can have a characteristic function valued 0 or 1, indicating nonmembership or membership, respectively. For a fuzzy set, the characteristic function allows various degrees of membership for the elements[1]. Thus, a fuzzy set A is defined as:

$$A=\{(x,\ \mu_A(x))\,|\,x\in X\} \tag{1}$$

where,

X is the universe of discourse, x are elements defined in X, and $\mu_A(x)$ is the membership function of x in A.

The membership function values are usually defined in the [0, 1] interval.

In order to use fuzzy sets in practical applications some operational rules similar to those used in the classical set theory were defined. The membership function of the union of two fuzzy sets is defined by:

$$\mu_{(C=A\vee B)}(x)=\mu_A(x)\vee\mu_B(x)=\max\{\mu_A(x),\ \mu_B(x)\} \tag{2}$$

and the membership function of the intersection of two fuzzy sets is:

$$\mu_{(D=A\wedge B)}(x)=\mu_A(x)\wedge\mu_B(x)=\min\{\mu_A(x),\ \mu_B(x)\} \tag{3}$$

where, $x\in X$.

The max and min operators are not the only ones that can model the union and intersection of fuzzy sets, and many others have been defined in the literature[2].

A "fuzzy variable" takes fuzzy sets as its values. A fuzzy variable for water level in the reservoir, for example, could take the values "low", "normal" and "high", which are each defined one by a fuzzy set. Logical expressions relating two or more fuzzy variables may be formed by using logical operators. The operators "AND" and "OR" are defined by the intersection and union operations, respectively.

Fuzzy set theory was first applied to the control of systems by Assilan and Mamdani[3], after the work by Zadeh[4]. The control strategy is usually expressed as linguistic statements in "IF-THEN" form. Thus, given the inputs, the control output is calculated through the "compositional rule of inference". Given a rule of inference in the form

R_i: IF x_1 is $A_{i,1}$ and x_2 is $A_{i,2}$ then y is B_i,

the grade of membership for rule R_i is

$$\mu_{Bi}\ (=w_i)=\mu_{Ai,1}(x_1^0)\wedge\mu_{Ai,2}(x_2^0) \tag{4}$$

Several rules are combined by using the union operation:

$$\mu_B = \vee \mu_{Bi},\ \forall_i \tag{5}$$

Since the actual user can only produce crisp outputs, the inferred fuzzy output must be defuzzified by taking a crisp value that represents it. This may be done in many ways. The centre of gravity procedure[5] is employed in the present model.

$$y^0 = \frac{\int B^*(y)y\,dy}{\int B^*(y)dy} \tag{6}$$

The fuzzy inference procedure can be visualized in **Fig. 1**.

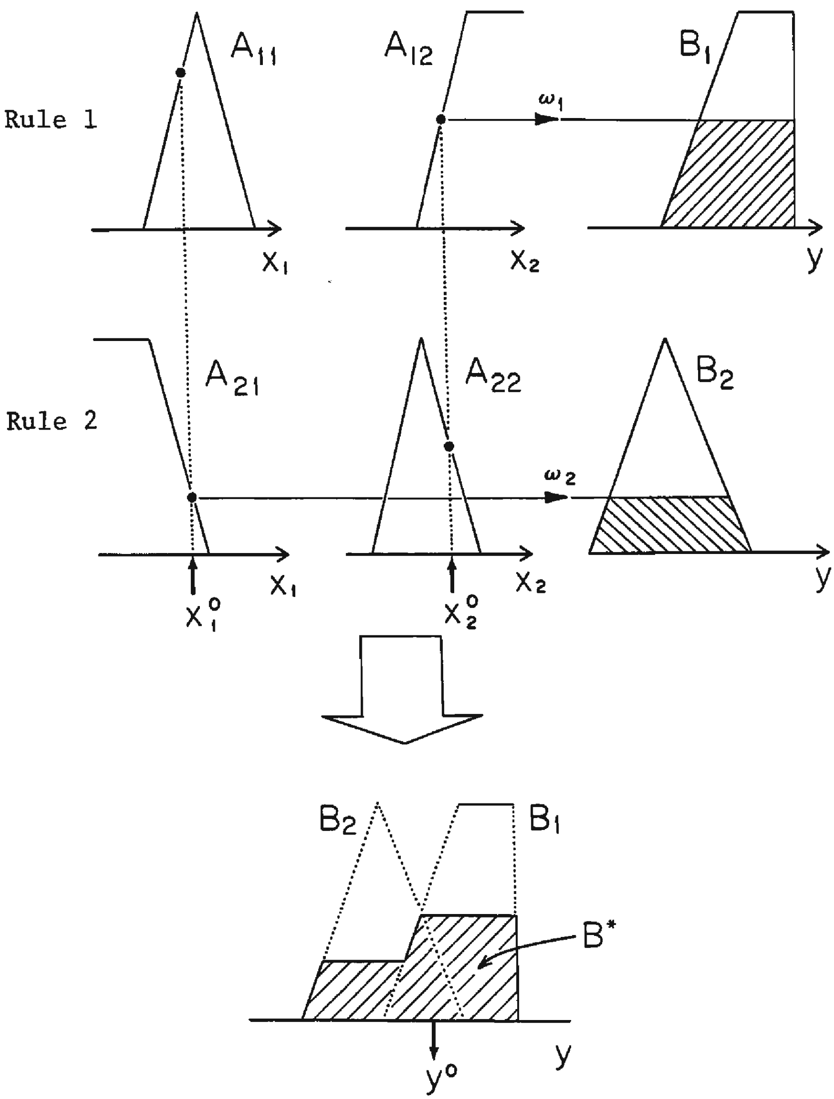


Fig. 1. Fuzzy inference procedure.

3. The reservoir operation model

The simulation of the operation of a single reservoir throughout the year is modeled for water utilization (conjunct uses), hydropower and river preservation purposes. The flood control procedure is not included. The forecast inputs are of medium and long range inflow rates and trends. In the following sections the operational policy adopted, the decision variables and rules of inference are discussed.

3.1 Operational policy

The operations are conducted according to "control levels" that regulate the supply reduction for each use. The control levels are related to control actions designed to keep the reservoir state as near as possible to the target one. In the present approach, the focus is on drought management, therefore the control actions intend to reduce the damage in times of shortage. For example, the operational actions and control levels may take the shape shown in **Table 1**.

The reservoir is operated time by time under one of these control levels. At every time interval the reservoir and forecast information is updated and new evaluation of the control level is made. The result of this evaluation presents the planned control levels in the "operating horizon". In the present discussion, the operating horizon for each time interval is considered as the coming one month, and the operational time interval is of five days. The term "operational policy" in this context is defined as the set of control levels planned to hold in the operating horizon.

The process for evaluation of the operational policy (**Fig. 2**) is made through the following steps, at the beginning of every time interval:

1. Systematization of weather forecast information as predicted inflows $\boldsymbol{Q}_i$ and long range trend index $\mathcal{J}$ (refer to section 4).
2. Monitoring current information on the storage volume S in the reservoir and control level of operation $\boldsymbol{C}_n$.
3. Evaluation of present storage level $\boldsymbol{S}_n$.
4. Estimation of the expected inflows I_i (refer to section 3.3) for the coming time

Table 1. Control levels ($\boldsymbol{C}$) of reservoir operation.

Control level	Control actions
Warning for flood (WF)	The operation is conducted by an appropriate flood control procedure.
Normal operation (N)	The release meets the target demands.
Warning for drought (WD)	There is some restriction on river preservation release.
Drought (D)	There is some restriction also on the releases for the other uses.
Abnormal drought (AD)	There is more severe restriction on the releases for the other uses.
Emergency (E)	More severe restrictions are imposed and the releases are limited to the available water.

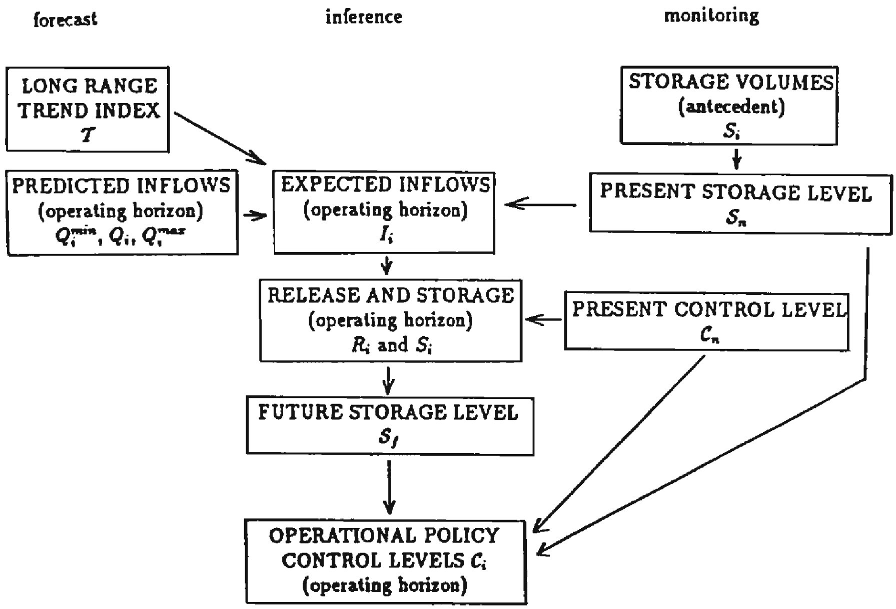


Fig. 2. Operational policy evaluation.

intervals of the operating horizon.

5. Calculation of releases R_i and storage volumes S_i for the coming time intervals of the operating horizon, considering that the present operational policy holds (refer to section 3.4).
6. Evaluation of the future storage level S_f (refer to section 3.2).
7. Decision on changes in the current operational policy (control levels to adopt in the coming time intervals of the operating horizon).
8. Recalculation of releases and storage volumes if eventual changes in the current operational policy were decided.

3.2 Storage level evaluation

The state of storage of the reservoir is expressed by the variable "storage level" ($\boldsymbol{S}$). The value of this variable is decided by fuzzy inference considering the "storage ratio" ($\boldsymbol{R}$) and the "difference in storage ratio" ($\boldsymbol{D}$) of the reservoir:

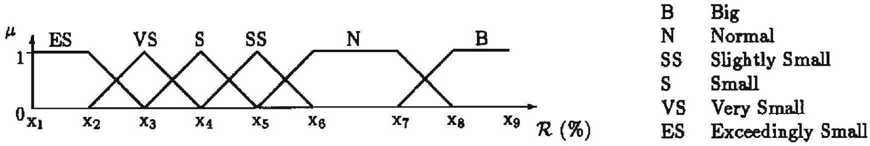
$$\boldsymbol{R}_i = 100\frac{S_i}{S_i^*} \tag{7}$$

$$\boldsymbol{D}_i = \boldsymbol{R}_i - \boldsymbol{R}_{i-1} \tag{8}$$

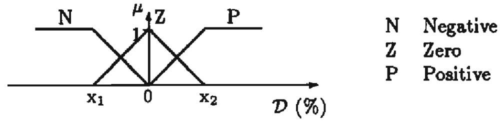
where,

S_i is the actual reservoir storage volume at time interval i, S_i^* is the target reservoir storage volume at time interval i, and $\boldsymbol{R}$ and $\boldsymbol{D}$ are expressed in %.

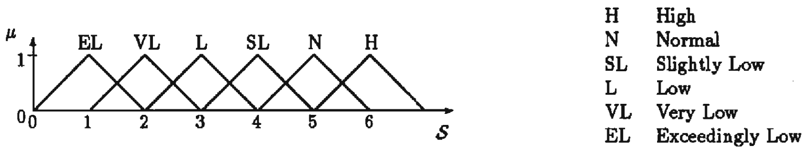
The "storage ratio" is the present stored volume expressed in relation to the target



(a)Membership functions for "storage ratio" ($\mathcal{R}$).



(b)Membership functions for "difference in storage ratio" ($\mathcal{D}$).



(c)Membership functions for "storage level" ($\mathcal{S}$).

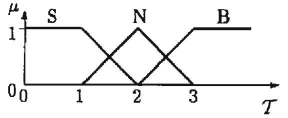
	$\mathcal{R}$					
$\mathcal{D}$	ES	VR	S	SS	N	B
N	EL	EL	VL	L	N	H
Z	EL	VL	L	SL	N	H
P	VL	L	SL	N	N	H

(d)Inference rules for evaluation of "storage level" ($\mathcal{S}$)

Fig. 3. Variables and rules for inference of "storage level" ($\mathcal{S}$).

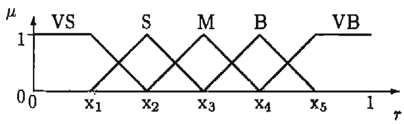
volume for the time interval under consideration. The "difference in storage ratio" expresses the relative gain or loss of water from the last to the present time interval. As fuzzy variables, they may have, for example, membership functions shown in **Fig. 3**. Possible definitions for the variable $\boldsymbol{S}$ and for the rules for inference of $\boldsymbol{S}$ from $\boldsymbol{R}$ and $\boldsymbol{D}$ are also shown at **Fig. 3**. As for $\boldsymbol{D}$, smaller values of x_1 and x_2 will emphasize the weight of this parameter on the decision of $\boldsymbol{S}$, since they will lead to a small range for the "zero" value, which has no influence on the decision (for the case of the rules of **Fig. 3**). Conversely, bigger values of x_1 and x_2 will make this parameter meaningless and sensitive only to strong variations in the storage ratio from one interval to another. On the other hand, asymmetrical values of x_1 and x_2 imply different criteria for making $\boldsymbol{S}$ higher or not.

The "present storage level" ($\boldsymbol{S}_n$) is defined as the "storage level" for the present time interval of operation; the "future storage level" ($\boldsymbol{S}_f$) is defined as the lowest "storage level" in the operating horizon, and is a measure of the scarcity in the operation horizon.



S Small
N Normal
B Big

(a)Membership functions for "long range trend index" ($\mathcal{T}$).



VS Very Small
S Small
M Medium
B Big
VB Very Big

(b)Membership functions for the coefficient r.

$\mathcal{T}$	S_n					
	EL	VL	L	SL	N	H
S	VS			S	M	
N	S			M	B	
B	M			B	VB	

(c)Inference rules for the coefficient r.

Fig. 4. Variables and rules for evaluation of coefficient r.

3.3 Estimation of expected inflows

The information on hydrological forecasting required at every time interval of operation is:

1. Predicted inflows Q_i for the time intervals i of the operating horizon, and their expected range of variation (boundary values: minimum Q_i^{min} and maximum Q_i^{max}).
2. An index expressing the weather trends for the time intervals after the operating horizon. This "long range trend index" ($\mathcal{T}$) is expressed in linguistic terms and is supposed to represent the probable amount of inflow to be expected after the operating horizon.

The estimation of a single value of inflow to expect into the predicted range, for using in the release computations and control level evaluation, is done by a fuzzy inference process. The expected inflow I_i for each time interval i is computed as the weighted mean among the predicted value Q_i and its minimum boundary value Q_i^{min}:

$$I_i = Q_i r + Q_i^{min}(1-r) \tag{9}$$

where, r is a coefficient, $0 \leq r \leq 1$.

The coefficient r is estimated by a set of rules, considering the present storage level S_n and the long range trend index $\mathcal{T}$. Possible definitions of $\mathcal{T}$ and r as fuzzy variables and the control rules may take form shown in **Fig. 4**. The expected inflows are then calculated for the coming time interval in the operating horizon.

3.4 Release

The release and storage sequences are calculated from the water balance equation in the reservoir:

$$S_{i+1}=S_i+I_i-L_i-R_i \tag{10}$$

where,

S_i and S_{i+1} are the reservoir storage volumes at the beginning of time intervals i and $i+1$, respectively, I_i is the expected inflow into the reservoir during the time interval i, L_i is the loss of water by evaporation and leakage during time interval i, and R_i is the total amount of water released in the time interval i.

The amount of water released is subjected to some criteria, designed for water conservation. Therefore, demands are attended to, while keeping any excess of water in storage, in order to use it in periods of shortage. As exemplified in **Table 1**, the current operational policy may impose restrictions on the supply. However, the river regulation release is supposed to fall not below a specified minimum amount and has priority over the others. Hydropower is not considered a conjunct use, which means that the total release is the maximum value among the hydropower release and the summation of all others.

The demand for hydropower is specified in terms of generated energy and the amount of water released to meet it is computed as:

$$R_i^{hp}=\frac{E_i}{h_i t_i e g} \tag{11}$$

where,

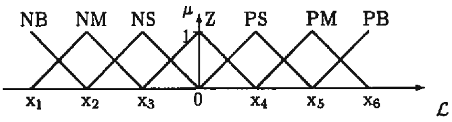
R_i^{hp} is the release for hydropower (m^3/s), E_i is the energy to be generated (KW-h), h_i is the available head in the reservoir (m), t_i, is the length of the time interval (h), e is the efficiency of the power plant, g is the gravity acceleration (m/s^2), and i is the time interval under consideration.

In the periods when a flood storage space has to be kept or when spill occurs, additional water is released to the usual demands (flood release).

3.5 Decision of control level

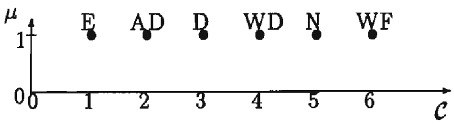
The proposed approach to model the decision making process by an expert operator considers that this decision is based on the present situation of stored volume and on the predicted values and also on the current operational policy. The decision of reinforcing or relaxing the present control level of operation is expressed by the "desirable control level parameter" ($\underset{\sim}{D}$), suggested in **Fig. 5(a)**, and depends upon the "present control level" ($\boldsymbol{C_n}$), on the "present storage level" ($\boldsymbol{S_n}$), and on the "future storage level" ($\boldsymbol{S_f}$).

The "storage levels" are evaluated following the rules and fuzzy variables described in the section **3.2**. The "control level", defined in **Table 1**, is not considered a fuzzy variable and thus has the membership functions of **Fig. 5(b)**. The inference rules of $\underset{\sim}{D}$



NB	Negative Big
NM	Negative Medium
NS	Negative Small
Z	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big

(a)Membership functions for "desirable control level parameter" ($\mathcal{L}$).



WF	Warning for Flood
N	Normal Operation
WD	Warning for Drought
D	Drought
AD	Abnormal Drought
E	Emergency

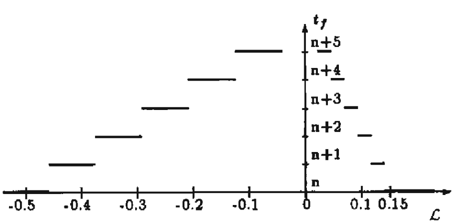
(b)Membership functions for "control level" ($\mathcal{C}$).

	$\mathcal{C}_n$					
$\mathcal{S}_n$	E	AD	D	WD	N	WF
EL	Z	PM	PM	PB	PB	PB
VL	NS	Z	PS	PM	PB	PB
L	NM	NS	Z	PS	PM	PB
SL	NB	NM	NS	Z	PS	PM
N	NB	NB	NM	NM	Z	PS
H	NB	NB	NB	NM	NS	Z

(c)Inference rules for evaluation of " desirable control level parameter"($\mathcal{L}$)–set($\mathcal{S}_n$,$\mathcal{C}_n$).

	$\mathcal{C}_n$					
$\mathcal{S}_f$	E	AD	D	WD	N	WF
EL	Z	PM	PM	PB	PB	PB
VL	NS	Z	PS	PM	PB	PB
L	NM	NS	Z	PS	PM	PB
SL	NB	NM	NS	Z	PS	PM
N	NB	NB	NM	NM	Z	PS
H	NB	NB	NB	NM	NS	Z

(d)Inference rules for evaluation of "desirable control level parameter"($\mathcal{L}$)–set($\mathcal{S}_f$,$\mathcal{C}_n$)



(e)Timing for changing the control level.

	$\mathcal{C}_n$					
$\mathcal{L}$	E	AD	D	WD	N	WF
NB	D	WD	N	WF	WF	WF
NM	AD	D	WD	N	WF	WF
NS	E	AD	D	WD	N	WF
Z	E	AD	D	WD	N	WF
PS	E	E	AD	D	WD	N
PM	E	E	AD	D	WD	N
PB	E	E	E	AD	D	WD

(f) Criteria for changes in "control level"($\mathcal{C}$).

Fig. 5. Criteria for changes in control level.

are shown in **Fig. 5(c)**. There are two sets of rules: the first one relating the "present control level" to the "present storage level" and the second one to the "future storage level". The rules may have the same formulation, as shown in those tables, or different ones, if it is desired to emphasize one of the decision variables. This conception aims to model the conflict between the wishes of changing or not the control level when considering the present state of storage or considering the predicted state in the future. Experimental simulations during the model building process showed the necessity to consider this conflict, which appeared to be very important when reverting the course of control level changes, and making the decision process smooth.

The value of $\mathcal{B}$ determines whether and when the control level should be changed:

- If $\mathcal{B} \leq d_2$, the control level is relaxed by two levels, starting in the present time interval.
- If $d_2 < \mathcal{B} \leq d_1$, the control level is relaxed by one level, starting in the present time interval.
- If $d_1 < \mathcal{B} < 0$, the control level is kept the same until the time interval t_f but, may be relaxed by one level starting at time interval t_f:

$$t_f = n + \left[T \left(1 - \frac{\mathcal{B}}{d_1} \right) \right] \tag{12}$$

- If $\mathcal{B} = 0$, the control level is kept the same and, no change is predicted in the operating horizon.
- If $0 < \mathcal{B} < u_1$, the control level is kept the same until the time interval t_f but, may be reinforced by one level starting at times interval t_f:

$$t_f = n + \left[T \left(1 - \frac{\mathcal{B}}{u_1} \right) \right] \tag{13}$$

- If $u_1 \leq \mathcal{B} < u_2$, the control level is reinforced by one level, starting in the present time interval.
- If $\mathcal{B} > u_2$, the control level is reinforced by two levels, starting in the present time interval.

where,

t_f is the time interval when control level may be changed, n is the current time interval, T is the total number of time intervals in the operating horizon (six, considering one month operating horizon and time intervals of five days), d_1, d_2, u_1 and u_2 are boundary values expressed in the same way of $\mathcal{B}$, and
[ ] denotes the Gaussian integer function.

As an illustration, the case in which the boundary values for control level change are defined as u_1='positive small', u_2='positive big', d_1='negative medium', and d_2 ='negative big', would lead to the control level change criteria and respective time interval t_f, shown in **Fig. 5(d)**.

3.6 Evaluation of the control process

"Damage indices", relating the shortage of water to the target values, are computed for each use as:

$$D=\sum_{i=1}^{t}\left(\frac{d_i^*-d_i}{d_i^*}\right)^2 \tag{14}$$

where,

D is the damage index, d_i^* is the target demand, d_i is the actually attended supply, i is the time interval of computation, and t is the total number of time intervals in the simulation period.

In order to improve the model performance, the operator may change the rules and membership functions, after evaluating the damage indices and simulation of the process. The membership functions and rules of inference are intrinsically case-dependent. A dam-site evaluation of the proper values and formulation to adopt, with the direct participation of the technical staff involved in the operation, followed by extensive simulations to check their correctness, is a proper way to tune the model.

4. The forecast model

The computation of the forecast data required by the reservoir operation model depends basically on the weather forecast information available on the region where the model will be applied. For the case of Japan, Ikebuchi et al[6]. devised a method for calculation of these data using the standard information provided by the Japanese Meteorological Agency. This method was adapted to this study and it is outlined in the following sections.

4.1 Medium and long range rainfall forecast information in Japan

In Japan, the weather forecast service information on rainfall may be classified in medium range for the week scope, and long range for the month, three month and six month scopes[7].

The weekly forecast is announced every day on weather condition for each of the next seven days and total expected amount of precipitation for the whole period. The weather condition is expressed as patterns like "fine", "cloudy", "fine sometimes cloudy", "cloudy sometimes rainy", "rainy", etc. The total expected amount of precipitation for the whole week is expressed as the patterns "small", "normal" and "big".

The monthly forecast is done at the end of every month also as weather condition and total expected amount of precipitation for each ten day period (1st to 10th, 11th to 20th, and 21st to 30th) of the next month.

At every 20th of the month the forecast for the next three months is announced. The weather condition is expressed in more general terms and the total amount of expected precipitation for each month follows the same pattern of weekly and monthly forecasts. Weather trends for the next six months are announced at the beginning of hot and cold seasons.

The terms "small", "normal" and "big" are related to occurrence probability and a

Table 2. Patterns for medium and long range rainfall forecast by the Japanese Meteorological Agency.

Scope	Range of variation f for the precipitation (% of the historical mean P)		
	Small	Normal	Big
	$R_{small,I}-R_{small,F}$	$R_{normal,I}-R_{normal,F}$	$R_{big,I}-R_{big,F}$
Month (R^t)	0–69	70–119	120–200
Ten days (R^m)	0–39	40–139	140–300
Week (R^w)	0–19	20–119	120–400
Five days (R^5)	0–19	20–119	120–400
Probability of Occurrence (%)	30	40	30

Table 3. Summary of information for rainfall prediction.

Symbol	Information	Scope
P_i^5 $R^5_{f_i^5,I}$, $R^5_{f_i^5,F}$	five days: historical mean for each time interval i initial and final values for the ranges f^5 defined in **Table 2**	time interval i of the year (starting at 1st, 6th, 11th, 16th, 20th and 26th)
W_j f_i^w P_i^w $R^w_{f_i^w,I}$, $R^w_{f_i^w,F}$	weekly forecast: weather condition for each day j of the week ('fine', 'cloudy', 'rainy', etc.) expected amount of precipitation for the whole week i ('small', 'normal', 'big') historical mean for each week i initial and final values for the ranges f^w defined in **Table 2**	seven days starting at the first day of time interval i of the year
f_k^m $R^m_{f_k^m,I}$, $R^m_{f_k^m,F}$	one month forecast: expected amount of precipitation for each ten days k ('small', 'normal', 'big') initial and final values for the ranges f^m defined in **Table 2**	ten day period k of the month
f_l^t $R^t_{f_l^t,I}$, $R^t_{f_l^t,F}$	three month forecast: expected amount of precipitation for each coming month l ('small', 'normal', 'big') initial and final values for the ranges f^t defined in **Table 2**	month l of each three month forecast period

range of variation. **Table 2** shows these values for one month (three month forecast), ten days (one month forecast), one week (one week forecast) and five days[6),8)]. The range of variation of the precipitation rates are expressed as percentages of the historical mean for the site (calculated over a 30-year series). Thus, for example, a forecasted "small" amount for the middle ten days of next month (11th to 20th) means a rainfall ranging from 0 to 39% of the historical mean for these ten days of the year.

The information particularly important for the method in question here is summarized in **Table 3**.

4.2 Prediction of precipitation rates

The above rainfall forecast information is used to calculate the amount of precipitation for each of the six coming time intervals (operating horizon). These values are estimated from the weekly forecast, for the first time interval, and from the monthly and three month forecast, for the subsequent time intervals. Three values are calculated for each time interval: the minimum, medium and maximum expected precipitation. These data are intended to be used in a rainfall-runoff model, which will calculate the inflow rates, as required by the operation model.

In order to compute the values for the current time interval, the information from the weekly forecast is used. As the meteorological agency does not provide information for five days, the information for one week is used to predict the precipitation for the first five days of the week. If we consider that the possibility of rain is related to the weather condition, it may be expressed as:

$$L_i^7 = \sum_{j=1}^{7} W_j \ and \ L_i^5 = \sum_{j=1}^{5} W_j \tag{15}$$

where,

L_i^s is a possibility index for rain, i is the time interval, s refers to the range considered (7 or 5 days), W_j is the numerical value of weather condition for the day j of the week. The weather condition, announced in qualitative terms, can be expressed numerically as shown in **Table 4**.

Table 4. Numerical values for weather condition (W).

Qualitative Expression	Value (W)
fine	0
fine sometimes cloudy and other states between fine and cloudy	0.5
cloudy	1.0
cloudy sometimes rainy and other states between cloudy and rainy	1.5
rainy	2.0
rainy sometimes heavy rain and other states between rainy and heavy rain	2.5
heavy rain	3.0

The ratio of L_i^5 to L_i^7 gives the part of the total week precipitation occurring in the first five days:

$$L_i^{5/7} = \frac{L_i^5}{L_i^7} \tag{16}$$

The total expected mean precipitation p_i^w for the week is given by the numerical value related to the forecasted amount f_i^w. This amount refers to a percentage of the historical mean for this week P_i^w, as shown in **Table 2**:

$$p_i^w = P_i^w \frac{R^w_{f_i^w,I} + R^w_{f_i^w,F}}{2} \tag{17}$$

It follows that the expected mean precipitation for five days is:

$$p_i^5 = p_i^w L_i^{5/7} \tag{18}$$

that represents v_i% of the historical mean for these five days:

$$v_i = 100 \frac{p_i^5}{P_i^5} \tag{19}$$

By **Table 2**, it is found in which range ('small', 'normal' or 'big') this value of v_i falls, thus obtaining the qualitative forecast for this five days f_i^5.

Then, the estimation of the minimum, medium and maximum expected values of precipitation can be done as:

$$p^5_{i,min} = P_i^5 R^5_{f^5_{i,I}},\ p^5_{i,med} = P_i^5 \frac{R^5_{f^5_{i,I}} + R^5_{f^5_{i,F}}}{2} \text{ and } p^5_{i,max} = P_i^5 R^5_{f^5_{i,F}} \tag{20}$$

In order to compute the expected precipitation for five sequential time intervals, the monthly and three month forecast information is used. At the beginning of the month, the values for each of the six time intervals of the month are estimated from the monthly forecast:

$$p^5_{i,min} = P_i^5 R^m_{f^m_k,I},\ p^5_{i,med} = P_i^5 \frac{R^m_{f^m_{k,I}} + R^m_{f^m_{k,F}}}{2} \text{ and } p^5_{i,max} = P_i^5 R^m_{f^m_{k,F}} \tag{21}$$

where,

k is the 'ten day' interval of the month in which the 'five day' time interval i considered is located.

For the 2nd to 4th time intervals of the month, the values estimated by eq. (21) are used within the month and the values for the 1st to 3rd time intervals of the coming month are estimated, using the three month forecast information.

$$p^5_{i,min} = P_i^5 R^t_{f^t_{l,I}},\ p^5_{i,med} = P_i^5 \frac{R^t_{f^t_{l,I}} + R^t_{f^t_{l,F}}}{2} \text{ and } p^5_{i,max} = P_i^5 R^t_{f^t_{l,F}} \tag{22}$$

where, l is the coming month.

At the 21st of the month, new information for the three month forecast is announced. Then for the 5th and 6th time intervals of the present month the values estimated by eq. (21) are used and the values for the coming month are estimated as the same as eq. (22) from the new information from the forecast of the next 3 months.

4.3 The long range trend index

The long range trend index ($\mathcal{J}$) represents the precipitation forecast for the horizon of three months ahead. It is expressed in qualitative terms ("small", "normal", "big"), and is calculated from the rainfall forecast information for the coming three months. Let's assume that the forecasted information for the amount of precipitation in the next three months can be expressed as numerical values, 1 for "small", 2 for "normal" and 3 for "big". The value of $\mathcal{J}$ is the weighted mean of the forecasted rainfall for the future three months.

At every 20th of the month, the forecast for the next three months is announced. At this time, the monthly forecast (announced at the beginning of the month) is available only until the next ten days. For these two last time intervals of the month, $\mathcal{J}$ then expresses the trend of precipitation for the next three months:
case i—for the 5th and 6th time intervals of the month:

$$\mathcal{J} = 0.5f_1^t + 0.3f_2^t + 0.2f_3^t \tag{23}$$

where,

f_l^t are the numerical values for the forecast of the next three months.

At the beginning of the month, the new monthly forecast is announced and $\mathcal{J}$ will express the trend of precipitation in the next two months, since the present month's precipitation has already been forecasted:
case ii—for the 1st to 4th time intervals of the month:

$$\mathcal{J} = 0.6f_2^t + 0.4f_3^t \tag{24}$$

$\mathcal{J}$ is a fuzzy value and can be defined following the pattern required by the reservoir operation model, as shown in **Fig. 4(a)**.

4.4 Inflow estimation

The minimum, medium and maximum estimated rainfall amounts constitute the input for a rainfall-runoff model that provides the expected inflow sequences Q_i^{min}, Q_i and Q_i^{max}, into the reservoir, for each time interval i of the operating horizon.

5. Case study

The reservoir under study attends to irrigation and power demands, and supplies water for downstream river preservation. Another main purpose is flood control. The contributing basin has an area of 471 km^2. The available historical series of daily inflow and precipitation were summarized in five-day series. The year of 1990 is chosen to perform the model simulations.

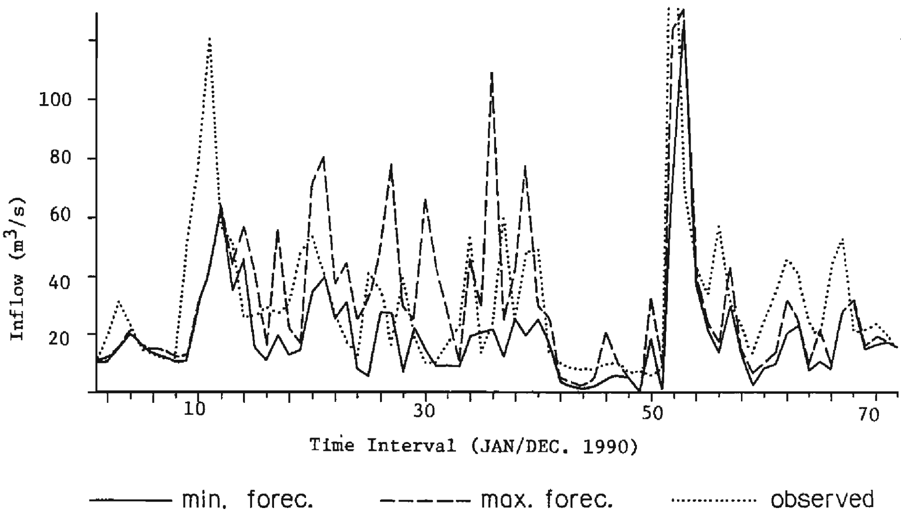


Fig. 6. Prediction of inflow.

5.1 Prediction of rainfall and inflow

As the available historical series for rainfall are not long, the five year series' mean is assumed as representative of the historical series. These data set was tested in the estimation of precipitation rates, according to the procedures described in section 4.2. The predicted rainfall series for the present time interval and for one month ahead are applied to the model for estimation of inflow. The long range index's values ($\mathcal{J}$) are also calculated.

A multiple linear regression model is fitted to the five-day series of precipitation and runoff:

$$Q_i = \alpha Q_{i-1} + \beta P_{i-1} + \gamma P_i + \theta \tag{25}$$

where,

Q is the inflow into the reservoir (m^3/s), P is the precipitation in the basin (mm), α, β, γ and θ are the model parameters, and i is the time interval under consideration.

In order to achieve a better fitting of the model to the data, a seasonal adjustment was done. **Fig. 6** shows the predicted inflow series for the present time interval (the year 1990).

5.2 Reservoir operation

5.2.1 Operational characteristics

The total gross capacity of the reservoir is 43 million m^3, with an effective capacity of 33 million m^3. The target rule curve, reservoir spaces and demand curves were compiled from available documents on the dam. The operational policy, membership functions, inference rules and related parameters were formulated by experience and tested

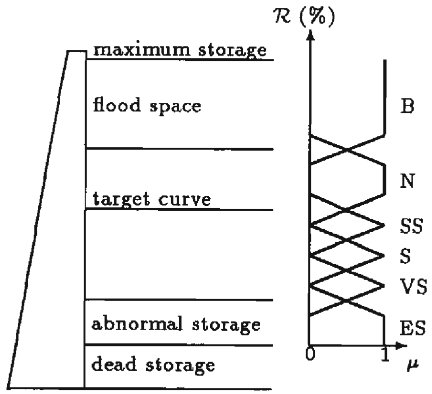


Fig. 7. Membership function for "storage ratio" ($\boldsymbol{R}$) of the reservoir (case study).

against simulation results, since adequate interviews with the operation staff of the dam were not done. They have the same formulation as shown in the section 3, with the following parameterization:

- The membership functions for "storage ratio" $\boldsymbol{R}$ have the formulation of **Fig. 7**, and are subject to changes at every time interval depending on the rule curve and the other variables concerned.
- The parameters x_1 and x_2 for the membership functions of "difference in storage ratio" $\boldsymbol{D}$ have the values -40 and 40, respectively.
- The formulation of coefficient r is parameterized with $x_1=0.1$, $x_2=0.3$, $x_3=0.5$, $x_4=0.7$ and $x_5=0.9$.
- The membership functions of the "desirable control level parameter" $\tilde{B}$ and defined with $x_1=-1$, $x_2=-0.7$, $x_3=-0.3$, $x_4=0.3$, $x_5=0.7$, and $x_6=1$. The

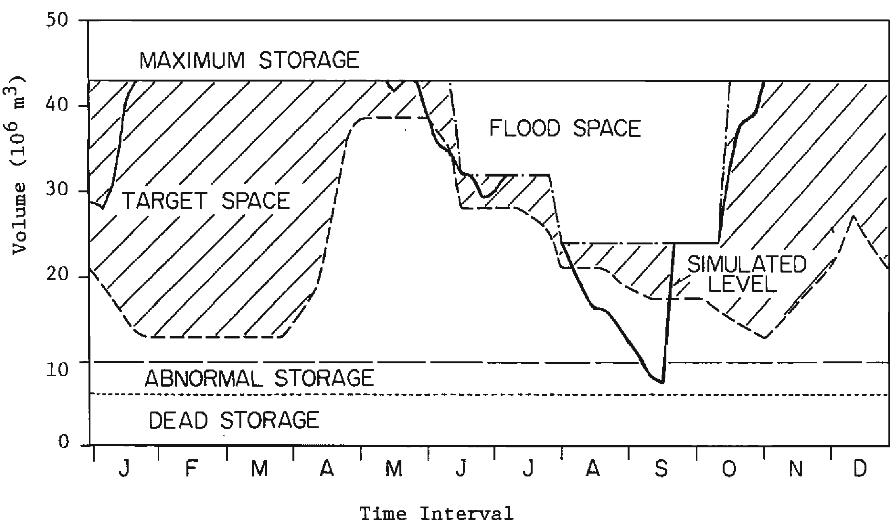


Fig. 8. Storage spaces and simulated operation.

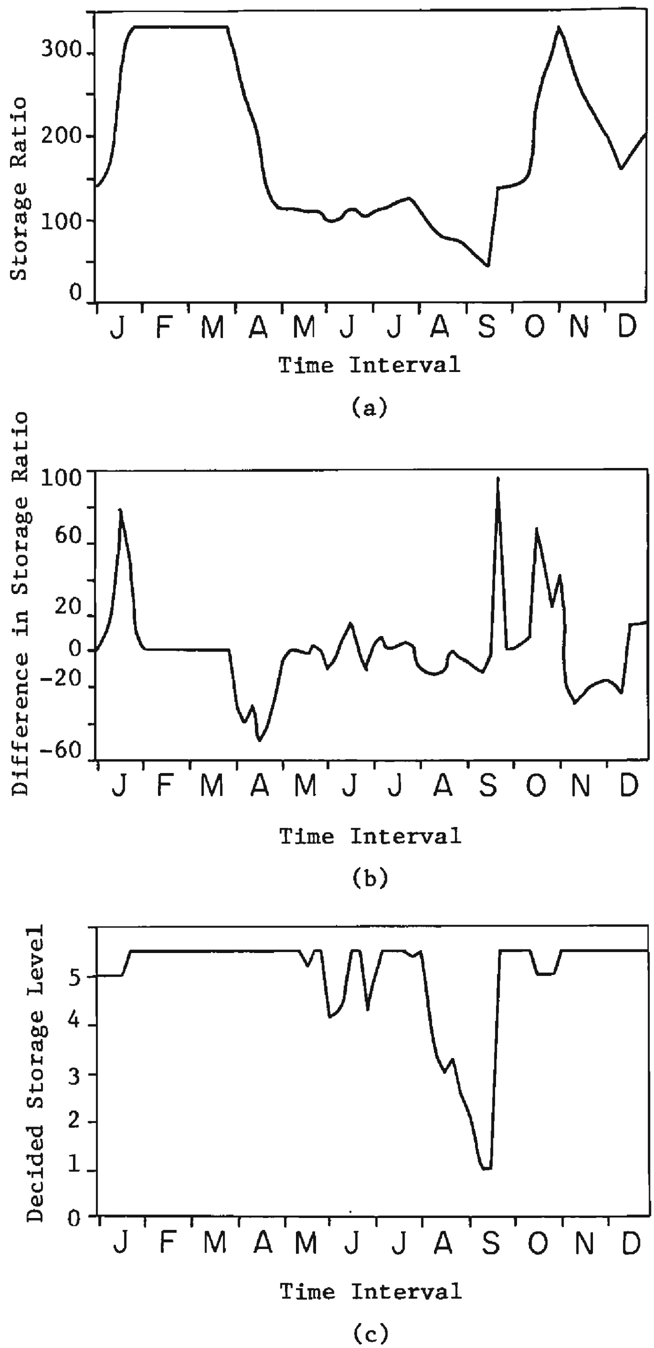


Fig. 9. Evaluation of storage level.

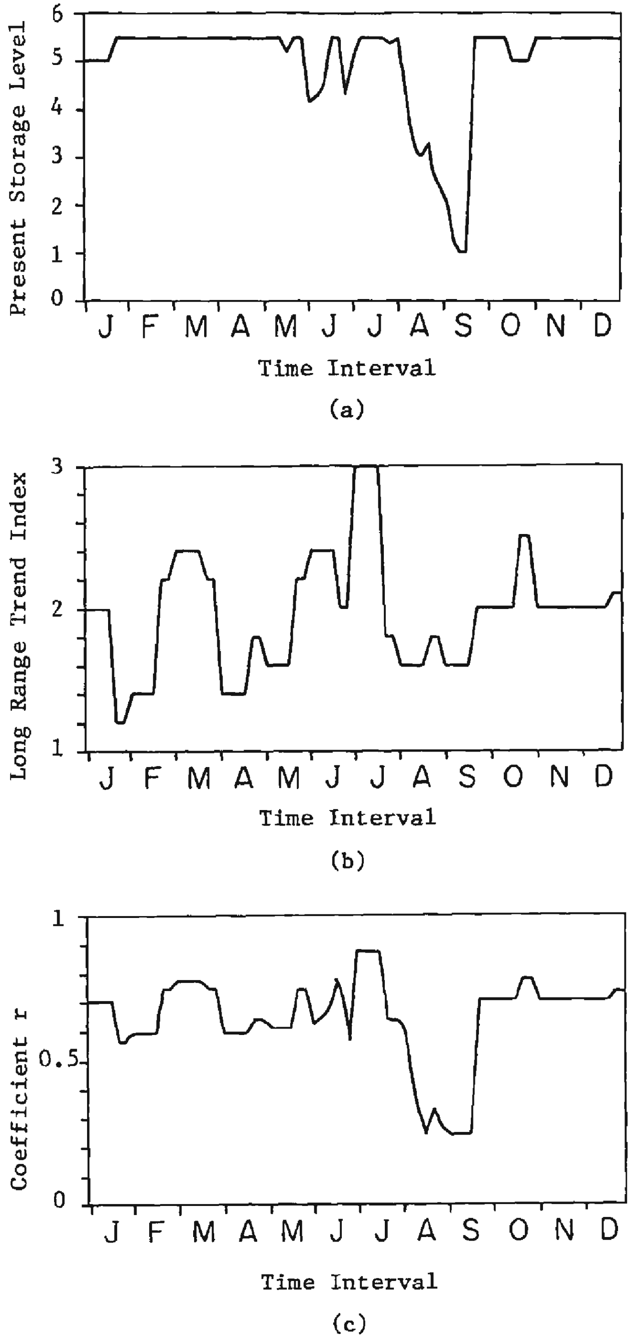


Fig. 10. Estimation of expected inflows.

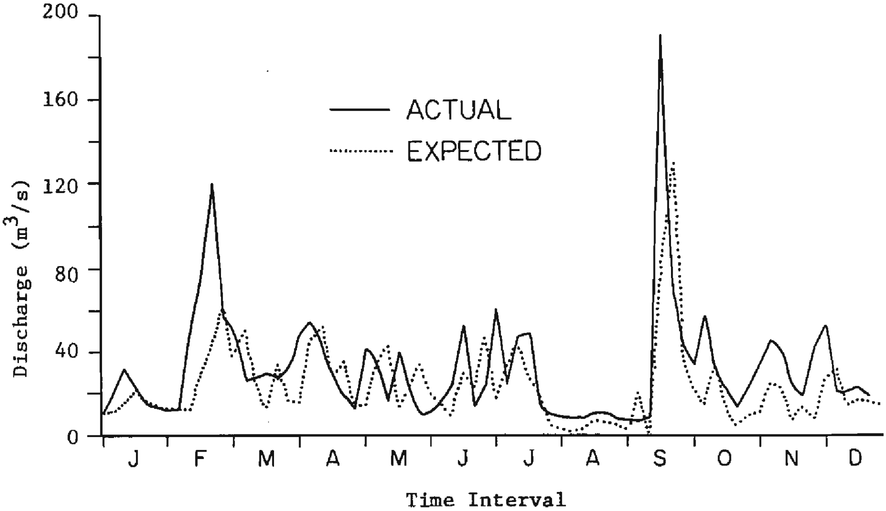


Fig. 11. Actual and expected inflows.

parameters u_1, u_2, d_1 and d_2, assume the same levels illustrated at section **3.5** and then have the numerical values $u_1=0.15$ ('positive small'), $u_2=0.85$ ('positive big'), $d_1=-0.50$ ('negative medium'), and $d_2=-0.85$ ('negative big').

- As for the operational policy the control levels are related to the actions described in **Table 1**. The releases for hydropower and irrigation are reduced to 80% of the target ones in case of "D" level, to 65% in case of "AD" level and to 50% in case of "E" level. The release for river preservation is reduced as:

$$R^r = R^{min} + (R^* - R^{min})k \tag{26}$$

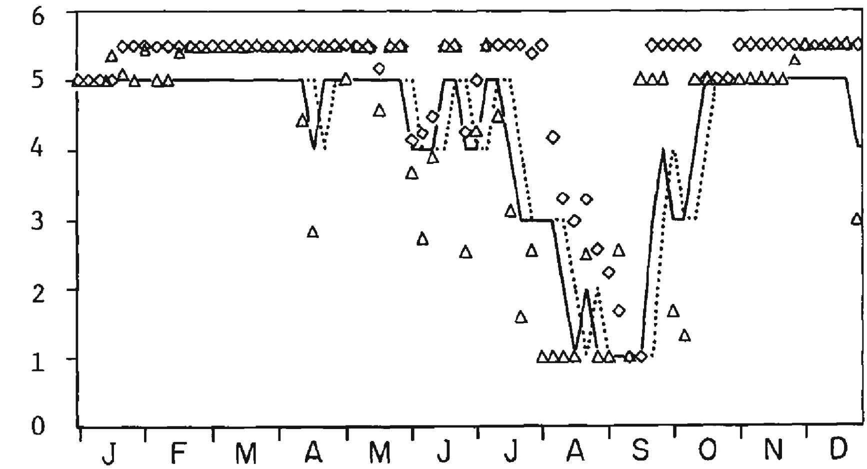
where,

R^r is the reduced release, R^{min} is the minimum allowed release, R^* is the target release, and k is a reduction coefficient ($k=0.5$ in case of "WD" level, $k=0.25$ in case of "D" level and $k=0$ in case of "AD" and "E" levels).

5.2.2 Operation behaviour

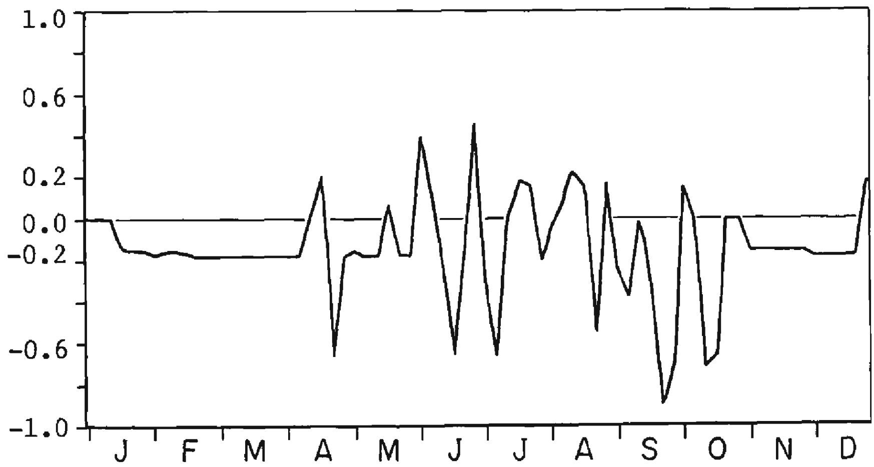
The year 1990 was simulated in order to test the model performance in a real situation. **Fig. 8** shows the reservoir storage spaces and the simulation performed. The decision variables and inferred results for storage level evaluation, estimation of expected inflow and decision of control level are shown in **Fig. 9, 10** and **12. Fig. 11** presents the comparison between the expected inflow estimated by the model inference and the actual observed values. The target and attended demands for irrigation, river preservation and hydropower are in **Fig. 13**. These results show that the operation was conducted according to the target levels during most of the year.

The period between June and October includes both a small and an abnormal shortages. This period is the most relevant for the analysis of the model behaviour coping with drought. **Fig. 14** shows the relevant variables involved in the operation process



(a) Decision of Control Level

— NEW CL ······ PRES CL ◇ PRES SL △ FUT SL



(b) Decision Control Level Parameter

Fig. 12. Decision of control level.

and the simulation during these five months.

This period is marked by the possibility of occurring very heavy storms (as occurred in the interval Sep/4) that cause extraordinary floods. This fact imposes extra releases in order to form the flood storage space, that rests on from the normal rainy season (June) until the beginning of the autumn. The capacity of the reservoir is not large, and the demands are considerable (reaching around 30% of the total effective capacity, and

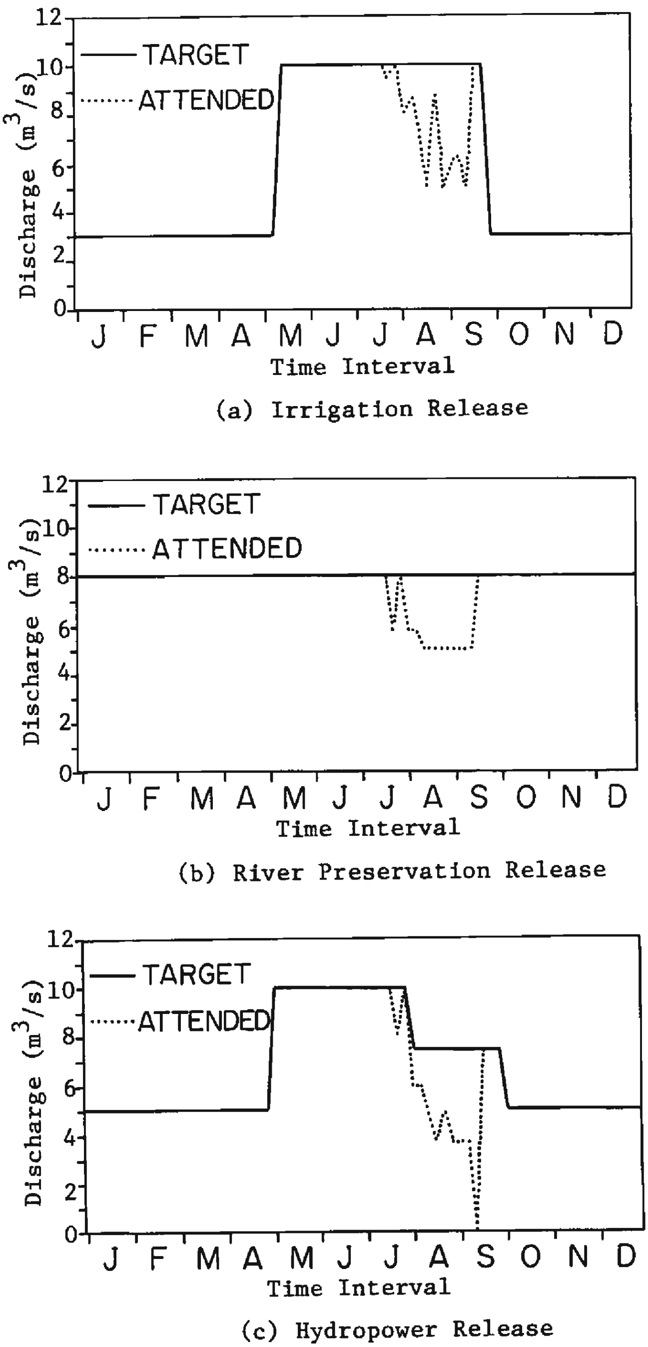


Fig. 13. Target and attended demands.

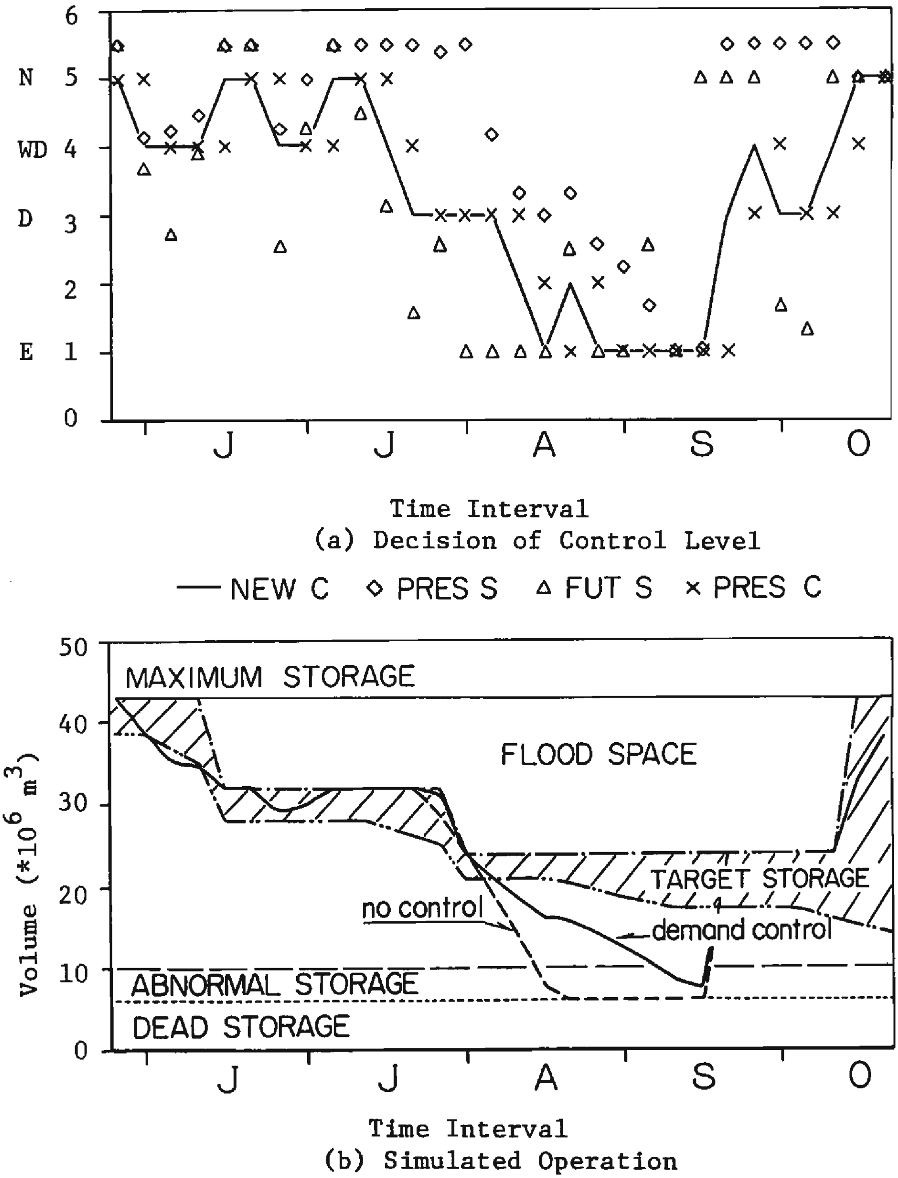


Fig. 14. Simulated operation in June—October 1990.

60% of the effective capacity in the flood period). This set of constraints makes the operation a very difficult task. Even a short distance from the target levels may be crucial, if storms do not happen. This is observed from the end of July until the middle of September.

Until the end of May the operation is done normally, keeping the storage levels as "normal". In the beginning of June the forecast is not favorable and the control level goes down. Until mid-July the operation is done satisfactorily due to a series of high inflows and extra releases to form the flood space. However the forecasts are not favorable and the control levels oscillate between "normal" and "warning for drought".

From mid-July until mid-September the reservoir experiences lower control levels, reaching the "emergency" level. The decision of changing the control levels is done by the model gradually, which may be thought as close to a real decision making in such situation. The demands are not fully attended to (**Fig. 13**), but the restrictions imposed on the system avoids a complete shortage, as may be observed in **Fig. 14. Fig. 14** also shows a simulation considering the case in which the demands are fully attended ("no control") and the system soon collapses.

6. Conclusions

The work done so far presents a rule based reservoir operation model, with a fuzzy logic inference module, as a promising approach for drought management.

Further improvements in the present model are of importance. Adaptive operation is a desired capability hindered only by the difficulty of acquiring knowledge from the operator, either by the necessity of tuning the operation model to new reservoir systems or when facing unusual circumstances. The incorporation of a knowledge base to the system is another feature that would lead to better inferences.

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