HYDROLOGY AND WATER RESOURCES IN ARIZONA AND THE SOUTHWEST, VOLUME 7, p. 207-218

Proceedings of the 1977 meetings of the Arizona Section of the American Water Resources Association and the Hydrology Section of the Arizona Academy of Science, held in Las Vegas, Nevada, April 15-16.

A UTILITY CRITERION FOR REAL-TIME RESERVOIR OPERATION

by

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ABSTRACT

A dual purpose reservoir control problem can logically be modelled as a game against nature. The first purpose of the reservoir is flood control under uncertain inflow, which corresponds to short-range operation (SRO); the second purpose, which the present model imbeds into the first one, is water supply after the flood has receded, and corresponds to long-range operation (LRO). The reservoir manager makes release decisions based on his SRO risk. The trade-offs involved in his decision are described by a utility function, which is constructed within the framework of Keeney's multiattribute utility theory. The underlying assumptions appear to be quite natural for the reservoir control problem. To test the model, an experiment assessing the utility criterion of individuals has been performed; the results tend to confirm the plausibility of the approach. In particular, most individuals appear to have a risk-averse attitude for small floods and a risk-taking attitude for large ones.

INTRODUCTION

The purpose of this paper is to present a development of a *utility criterion* for real-time reservoir operation under uncertainty. In recent years, intensive studies have been emerging concerning applications of statistical decision theory, subjective probabilities and utility theory. Real-time operation of a reservoir constitutes a scenario which exhibits all features needed to exemplify the above concepts in a direct and very natural manner.

In brief, the reservoir has a random input, the forecasting of which is provided by skillful meteorologists and hydrologists whose *subjective judgments* and *assessments of uncertainties* are indispensable in the present state-of-the-art in river forecasting. Next, there is a reservoir manager (also called the decision maker) whose experience provides *preferences* for making risky decisions and crucial trade-offs between operating objectives. The whole decision problem is, nevertheless, too complex to be analyzed directly by a human decision maker, so that the aid of a mathematical model is called for.

Despite a large research effort in the area of reservoir operation, there has been very little done to bridge the gap between river *forecasting* and *decision making* on the *operational level* - in the day-to-day, hour-to-hour operation. One way to link probabilistic forecasting (by and large subjective) with preferential reservoir operation is to resort to the decision theory. Bayesian approach offers a decision-making framework which accounts explicitly for uncertainty on reservoir inflow and for preferences over operational attributes.

In the context of a decision theoretic framework, this paper develops a utility criterion for real-time reservoir operation under uncertainty. Toward this aim, the decision problem is analyzed, and multiattribute utility theory (Keeney, 1974) is applied. It is shown that short-range reservoir operation may be modeled naturally as a game against nature, and, therefore, that a very realistic framework for assessing the reservoir manager's utility function can be obtained. Once the preferences of the manager are quantified in terms of the utility criterion, a decision model can be formally employed in solving complex operation problems in a real-time setting.

The paper is organized as follows. The next section defines the reservoir operation problem and presents a concept for imbedding short-range operation into long-range operation. In Section 3, short-range operation is viewed as a game against nature. The risk present in that game is described, and a need for a measure of the decision maker's preferences in the reservoir operation is exposed. In Section 4 a utility model is developed, and in the next Section the assessment procedure is discussed. Section 6 reports results of an experiment in assessing utility criterion.

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RESERVOIR OPERATION PROBLEM

TYPES OF RESERVOIR OPERATION

Consider a single, multi-purpose reservoir. Two types of operation are identified as follows. *Short-range operation* (SRO) is defined by purpose set

PS = {flood control}.

Long-range operation (LRO) is defined by a set of purposes

PL = {1. water supply (irrigational, industrial, municipal),
2. hydroelectric power generation,
3. low flow augmentation (navigation, fish and wildlife, recreation),
4. lake recreation}.

In a particular situation, the elements of PS and PL can be modified, but it is assumed that, always, $PS \cap PL = \emptyset$. Furthermore, it is assumed that SRO and LRO are performed over nonoverlapping finite time intervals (Figure 1). It follows that SRO is implemented during floods and that LRO is implemented between successive flood events. This fact is emphasized inasmuch as the definition of LRO bears on operational viewpoint and differs considerably from what planners usually mean by the long-range (seasonal) reservoir operation. The principal hydrologic and decision characteristics of both types of operation are summarized in Table 1. Although all of them are essential, attention is focused on characteristic number four to justify the definition of SRO and LRO over nonoverlapping intervals of the reservoir input.

To restate the approach, the analysis will concentrate on SRO; at the same time, through an appropriate imbedding of SRO into LRO, it will be guaranteed that, at any time, SRO is directed toward satisfying both sets of purposes PS and PL. The basic reason for imbedding is to assure that the operation explicitly considers the trade-offs between conflicting sets of purposes PS and PL. Thus, in the sequel, reservoir operation will always mean SRO which satisfies imbedding conditions into LRO.

IMBEDDING SRO INTO LRO

In this section, the decision problem in SRO is defined; then it is shown that the appropriate choice of the outcome space provides an easy imbedding of SRO into LRO.

The decision problem in SRO will be analyzed under the following assumptions: (1) SRO is initiated whenever the forecasted P[inflow rate > threshold value] >0, where it is understood that the forecast containing probability P is valid over a finite time interval, e.g., successive 24 hours. (2) Storage space at the beginning of SRO is a known parameter, and it results from the preceding LRO. (3) The decision maker can only make one decision for the entire period of SRO. Although this assumption may not be quite realistic, it is imposed here only to simplify the presentation. In fact, each decision in a sequential-decision operation is of the same nature. Therefore, for the purpose of encoding the decision maker's preferences, it is sufficient to analyze a single-decision problem; yet, the utility criterion developed in this way can be used in a sequential-decision operation, if needed.

The *decision problem* in SRO is now structured. Let the *state space* = {inflow hydrograph} be discrete and finite, and suppose that the nature chooses an inflow hydrograph in accordance with a known distribution law. The *decision space* = {rate of release from the reservoir}, and the *consequence space* (outcome space) = Z x Y, where

$z \in Z$ is the *maximum flood level* (flood crest) measured above initial damage level at a specified location below the reservoir, and
$y \in Y$ is the *storage space* (storage deficit) at the end of the flood.

With each of the sets PS, PL, and PS x PL, one associates a set of *measures of consequences* (effectiveness) $\{G_i : Z \times Y \to Re\}$ $i = S, L, SL$, with Re an abstract set. Examples of measures of consequences are stage-damage curve: $G_S : Z \to \$$, and a relation between storage deficit and dollar loss in irrigation: $G_L : Y \to \$$. The following two assumptions are introduced:

ASSUMPTION 1. *In reservoir operation problem defined by PS x PL, G_S is defined on Z, G_L is defined on Y, and $G_{SL} = f(G_S, G_L)$.*

Roughly speaking, Assumption 1 says that the measures of consequences for SRO and LRO are separable. Accordingly, the performance of LRO (SRO) can be adequately expressed as a univariate function defined on Y(Z). That is to say, for a given input over period of LRO, the performance of LRO depends only upon the initial storage space y. Since y is also the final storage space in SRO, it provides a means of *imbedding* SRO into LRO. The mere fact that a consequence of SRO constitutes an initial condition for LRO will be referred to as an *imbedding condition.*

ASSUMPTION 2. *With $\succ$ a binary preference relation on Z and Y, the decision maker possesses a preference which satisfies the property that for any $z_1 < z_2$ and $y_1 < y_2$, $z_i \in Z$, $y_i \in Y (i=1,2)$, $z_1 \succ z_2$ and $y_1 \succ y_2$. We shall denote by z_o and y_o the most desirable consequences; by definition $z_o = 0$ and $y_o = 0$.*

RESERVOIR OPERATION AS A GAME AGAINST NATURE

The object of this section is to reveal the nature of the decision problem as defined in Section 2. Ultimately, it is to indicate the existence of a fair agreement between the mechanism of SRO and the mechanism of the von Neumann-Morgenstern (1947) scheme for utility assessment. First, let the SRO decision problem be analyzed within the framework of a game against nature (Luce and Raiffa, 1957).

Owing to Assumption 2, *pure decision* is defined as one which for a given inflow hydrograph yields minimal value of z and y_o. We introduce an intuitive notion of "small flood", MF, and "large flood", AF. A forecasting procedure specifies the probability of having either MF or AF as (p,1-p), $0 \leq p \leq 1$. The appropriate pure decisions will be denoted by M and A respectively. For short-hand, let $[(z,y);p;(z_1,y_1)]$ denote a game yielding either (z,y) with probability p or (z_1,y_1) with probability 1-p, $0 \leq p \leq 1$.

Now the decision problem may be presented as a game where the decision maker chooses one from among two *decisions* (M,A) and then nature takes on one of two *states* (MF, AF) with probabilities (p,1-p). The *consequences* of the game are shown in Table 2, a payoff table. The scheme of Figure 2 may help to visualize this game. For simplicity, let the flood level z be the rate of release from the reservoir.

Observe the following. By definition of the game, $z_{AM} = z_{AA} = z_A > z_o$, and $y_{MM} = y_{AA} = y_o = 0$. Also $y_{MA} = 0$ since the reservoir is overtopped due to too small release rate M. Finally, $z_{MM} < z_A < z_{MA}$, and $y_o < y_{AM}$. These observations yield to the modified game as presented in Table 3 in which the payoff table is given separately for each consequence for easy visualization.

Summing up, the decision maker is faced with the necessity of choosing between two decisions when the true magnitude of the oncoming flood is uncertain. To arrive at the choice, he must decide in his mind whether he prefers the game $[(z_{MM},y_o); p; (z_{MA},y_o)]$ to the game $[(z_A,y_{AM}); p; (z_A,y_o)]$ or conversely. The choice of the decision M results in a certain value of the storage space y_o and in a gamble over maximum flood level (z_{MM} or z_{MA}). Conversely, the choice of the decision A results in a certain value of the flood crest z_A and in a gamble over storage space (y_{AM} or y_o).

The point is probably obvious that the disutility of flooding the plain or emptying the reservoir and the willingness to "take a chance" may play an important role in choosing the decision. That is to say, the consequence (z,y) is a psychological variable (Coombs and Beardslee, 1954) and in this case the criterion of minimizing expected monetary loss may not mirror the decision maker's risk behavior. Furthermore, it was recognized (Kates and White, 1961) that many man-made decisions concerning flood hazard result from an individual's attitude toward taking or toward averting risk rather than from pure evaluation of monetary consequences. We accept, thus, in this study a psychological hypothesis that in reservoir operation, the decision maker chooses that decision which minimizes his expected utility.

The von Neumann-Morgenstern (1947) scheme for utility assessment is based upon the expected utility hypothesis

$$u(c) = pu(a)+(1-p)u(b) \tag{1}$$

for an indifference relation $c \sim [a;p;b]$. Specifically, this relation implies that the individual is indifferent in the choice between the certain consequence c and the gamble yielding the consequence a with probability p and the consequence b with probability 1-p.

We are now in a position to indicate the direct equivalence between the risky situation in reservoir operation, as presented in the framework of the two-state flood game (Table 3), and the problem of choice, as imposed by relation (1). The von Neumann-Morgenstern scheme for utility assessment seems to be, in the case of reservoir operation, a very realistic procedure. Particularly, if the decision maker has some utility or disutility for risk (gambling) then this is exactly what we want to extract from him because the same personal characteristic may significantly influence the decision maker's perceptions of the real reservoir operation.

UTILITY MODEL

Under conditions induced by the von Neumann-Morgenstern axioms (1947), the utility function u is defined over attribute set Z x Y. We assume boundness of this set in the sense that there exists the most desirable attribute (z_o,y_o) and the least desirable attribute (z_e,y_e). To arrive at a functional form for u, heuristic assumption concerning the decision maker's preferences in SRO is made.

ASSUMPTION 3. *In SRO, Z and Y are mutually utility independent.* (For definition of utility independence the reader may wish to consult Keeney (1974)). Our heuristic support proceeds as follows. Although Z and Y are related physically to one another through basic laws of hydraulics, they are controls for independent sets of purposes PS and PL. Along with Assumption 1, this assures that the decision maker's preferences over any attribute induced by Z should be independent of the value of any other attribute induced by Y and vice versa. Particularly, this assertion holds if Z and Y are considered to be attributes themselves.

By virtue of Theorem 1 in Keeney (1972), Assumption 3 indicates a separable form for u(z,y) is appropriate. We selected

$$u(z,y) = u_1(z) + u_2(y) + f_1(z)\ f_2(y) \tag{2}$$

Theoretical development of this model, along with necessary and sufficient preference conditions and admissible transformation, is given by Fishburn (1974). Model (2) holds under the generalized utility independence condition which allows for reversals of preferences. Although under certain circumstances one could expect reversals in preferences over Z x Y, especially in the games with extreme values of the attributes, such situations will not be considered here. In most cases, more restrictive definition of the utility independence, as that of Keeney (1972), should be sufficient. Accordingly, (2) can be written operationally as

$$u(z,y) = k_z u_z(z) + k_y u_y(y) + k k_z k_y u_z(z)\, u_y(y), \quad (3)$$

with u_z, u_y, $u \varepsilon [0,1]$; $u_z(z_0) = u_y(y_0) = u(z_0,y_0) = 0$; $u_z(z_e) = u_y(y_e) = u(z_e,y_e) = 1$; and constants $k_z, k_y \varepsilon (0,1)$. The scaling constant k is determined by the relation

$$k = (1-k_z-k_y)/k_z k_y. \quad (4)$$

Strictly speaking, u as defined above is disutility function. Hence an appropriate decision criterion is minimization of the expected value of u.

Since the corner utilities in (3) are $u(z_e,y_0) = k_z$ and $u(z_0,y_e) = k_y$, from the estimates for k_z and k_y one can infer the decision maker's multivariate risk behavior as defined by Scott (1975). Accordingly, the decision maker is strictly multivariate risk averse (SMRA) if $k_z + k_y < 1$; strictly multivariate risk seeking (SMRS) if $k_z + k_y > 1$; and multivariate risk neutral (MRN) if $k_z + k_y = 1$.

ASSESSMENT PROCEDURES

PRINCIPLES

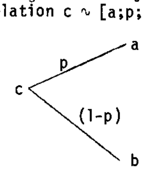
Derivations of utility functions from the decision maker's responses have been reported in the literature by many authors, such as Davidson et al. (1957); Schlaifer (1969); Halter and Dean (1971); Keeney (1975). Therefore, this section does not discuss details of the assessment schemes which already have been widely publicized. However, the procedures which to some extent are uncommon are thoroughly presented. They are based on the findings from present experiments in assessing the utility function in the specific context of reservoir operation. It is encouraging to find that these results concur with those of different experiments reported by behavioral scientists.

The development of the assessment procedures have been based on the following principles:

1. *Games with choices between extreme values of the attributes should be avoided.* It is a standard approach to begin the assessment of a single-attribute utility function u_z with a game $z_1 \sim [z_0;p;z_e]$. We found that the utility function obtained in this way may have a substantial bias for at least two reasons. First, it was indicated (Sheridan and Ferrell, 1974) that the more extreme, and thus usually the less likely to occur, the values of the attributes, the more likely anomalous behavior of the subject is to be observed. This can be especially so in reservoir operation because the necessity of making a compromised decision between a disastrous drought and a catastrophic flood is very unrealistic. Second, since the remaining subject's responses are quantified in relation to the first, even small bias in the first response may drastically affect the shape of the utility function. Thus a mistaken image of the decision maker's behavior can easily be produced. Such effects can be seen in Figure 3.

2. *The range and variance of the outcomes from the games should be realistic.* This is because, as found by Edwards (Sheridan and Ferrell, 1974), many subjects' preferences are apparently affected by the range and variance of the outcomes from a gamble; it is thus important that the utility function account for this type of preference. Then, for the purpose of encoding the preference structure which results from the subject's perception of the real decision situation, it is necessary that the range and variance of the games outcome be similar to those in reality. Also, the sequencing of games over various ranges of attributes should be carefully thought out to stimulate the subject to perceive the assessment process as a real-decision making situation in which he can fully use his managerial experience.

The assessment process reported herein is based upon the above principles in conjunction with the results of works by Becker et al.(1964) and Keeney (1975). It is conducted in a step-by-step manner and typically consists of a sequence of games satisfying the expected utility equation (1). Schematically, a game with an indifference relation $c \sim [a;p;b]$ will be represented as



The subject's response may be in terms of the one attributed value (a,b, or c) for the two other given values and probability p, or in terms of the probability p for the given attribute values a,b, or c. For clarity, the value to be assessed by the subject will be marked by *.

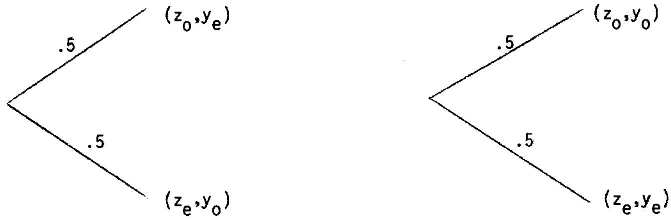
The assessment process consists of three stages:

1. verification of the risk behavior,
2. assessment of single-attribute utility functions,
3. assessment of the corner utilities (trade-offs).

VERIFICATION OF THE RISK BEHAVIOR

To verify the type of multivariate risk behavior, the decision maker is presented with a choice between the two games:

game 1 game 2



The decision maker is SMRA if game 1 $\succ$ game 2; SMRS if game 2 $\succ$ game 1; and MRN if game 1 $\sim$ game 2.

ASSESSMENT OF SINGLE-ATTRIBUTE UTILITY FUNCTIONS

The assessment procedure is shown for attribute Z; assessment of u_y proceeds along the same way. The procedure consists of a sequence of games specified in Table 4 and explained as follows:

Step 1. Choose an arbitrary point z_n such that $z_o < z_n < z_e$.

Step 2. Assess utility function u_o for $z\varepsilon[z_o,z_n]$ on [0,1] scale, i.e., $u_o(z_o) = 0$, $u_o(z_n) = 1$. This can be accomplished by playing the games 1-3, but more games can be considered if needed for better accuracy or the consistency check.

Step 3. Assess utility function u_n for $z\varepsilon[z_n,z_e]$ on [0,1] scale, i.e., $u_n(z_n) = 0$, $u_n(z_e) = 1$ (games 4-6).

Step 4. Perform the game 7 (and 8 for the consistency check), and link the two utility functions u_o and u_n so as to obtain a function u_z defined on $[z_o,z_e]$ and scaled on [0,1]. This can be done as follows. By the fact that the utility function is unique up to a positive linear transformation, there exists a constant h>0 such that

$$u_o(z) = h\cdot u_n(z) + 1, \qquad \text{all } z\ \varepsilon[z_o,z_e].$$

Hence

$$h = (u_o(z)-1)\ /u_n(z). \tag{5}$$

If $z_7 < z_n$ then from the expected utility equation for the game 7

$$u_o(z_6) = 2u_o(z_7) = u_o(z_3)$$

and (5) can be evaluated in z_6 since $u_n(z_6)$ is known. If $z_7 > z_n$ then the expected utility equation for the game 7, written in terms of u_n, gives

$$u_n(z_3) = 2u_n(z_7) - u_n(z_6)$$

and (5) can be evaluated in z_3 since $u_o(z_3)$ is known. In the same manner h can be computed from the game 8, providing thus the consistency check.

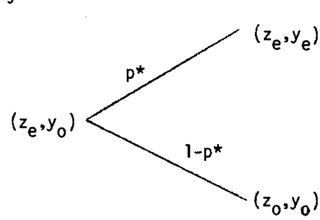
Now the utility function u_z can be defined on $[z_o,z_e]$ as follows

$$u_z(z) = \begin{cases} u_o(z)/(1+h) & \text{for } z_o \le z \le z_n \\ [h\ u_n(z) + 1]/(1+h) & \text{for } z_n \le z \le z_e \end{cases} \tag{6}$$

where u_z is scaled on [0,1].

ASSESSMENT OF THE CORNER UTILITIES

From (3), the corner utilities are found to be $u(z_e,y_o) = k_z$, and $u(z_o,y_e) = k_y$. Assessment of k_z (and in a similar fashion of k_y) can easily be accomplished from the game



Expected utility equation for this game yields $u(z_e,y_o) = p$, and so $k_z = p$. This method of assessing corner utilities was used by Keeney (1975). Although this scheme is remarkably simple, it does not satisfy the first principle of avoiding games between extremes, discussed earlier. The alternative scheme proposed here was developed from that of Keeney by eliminating the games which included solely extreme values of attributes and responses in terms of probability.

Step 1. First the approach of Yntema and Torgerson (described in Sheridan and Ferrell, 1974) is used. The decision-maker is asked to locate the "corners" (z_e,y_o) and (z_o,y_e) directly on [0,1] interval scale of worth with 0 representing corner (z_o,y_o) and 1 representing corner (z_e,y_e). Inasmuch as such direct response may be subjected to a large perceptional error, in the next steps k_z and k_y are derived from a sequence of responses. Then the results from both methods can be compared for consistency.

Step 2. Assess indifference pairs.

For an arbitrary z_1, $z_o < z_1 < z_e$, assess y_1^* such that $(z_o,y_1^*) \sim (z_1,y_o)$, which implies that $u(z_o,y_1) = u(z_1,y_o)$ and by (3) $k_y u_y(y_1) = k_z u_z(z_1)$. Consequently,

$$k_z = k_y \frac{u_y(y_1)}{u_z(z_1)} \tag{7}$$

To check the consistency, another indifference pair $(z_2^*,y_e) \sim (z_e,y_2)$ can be assessed for an arbitrary y_2, $y_o < y_2 < y_e$. In terms of (3) it implies that

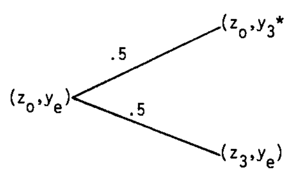
$$k_z u_z(z_2) + k_y + k k_z k_y u_z(z_2) = k_z + k_y u_y(y_2) + k k_z k_y u_y(y_2)$$

and substituting (4) for k

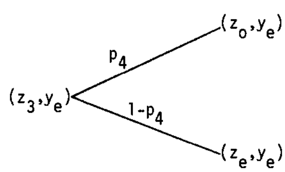
$$k_z = [k_y(1-u_z(z_2)) + u_z(z_2) - u_y(y_2)]/(1-u_y(y_2)). \tag{8}$$

Step 3. Find corner utilities.

For an arbitrary z_3, $z_o < z_3 < z_e$, conduct a game



and consider also a game



Solution of the expected utility equations for these games gives

$$k_y = (1-p_4)/(2-p_4-u_y(y_3)).$$

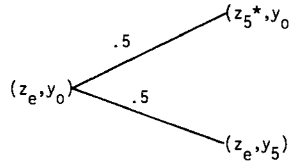
The second game need not be conducted with the decision-maker. Observe that the value of the attribute Y in this game is constant. Since Z is utility independent of Y, the expected utility equation for this game can be written as

$$u_z(z_3) = p_4 u_z(z_o) + (1-p_4)u_z(z_e).$$

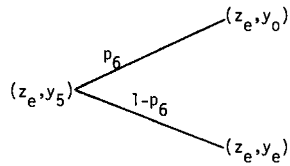
Since $u_z(z)$ has already been assessed, p_4 can be found directly from the relation $p_4 = 1-u_z(z_3)$. Hence the equation for k_y becomes

$$k_y = \frac{u_z(z_3)}{1 + u_z(z_3) - u_y(y_3)} . \tag{9}$$

In a similar manner k_z can be obtained by conducting, for an arbitrary y_5, $y_o < y_5 < y_e$, a game



and considering also a game



Solution of the expected utility equations yields

$$k_z = \frac{u_y(y_5)}{1 + u_y(y_5) - u_z(z_5)} \tag{10}$$

Inasmuch as Equations (7) and (9) uniquely determine the corner utilities, only responses y_1* and y_3* have to be obtained. If the responses z_2* and z_5* are also determined, then Equations (8) and (10) may serve as the consistency check.

EXPERIMENT IN UTILITY ASSESSMENT

The experimental assessment of the reservoir control utility function was conducted with five professional hydrologists. In a hypothetical operation problem, the reservoir was assumed to serve the following sets of purposes:

PS = {flood control},

PL = {power generation, navigation}.

The ranges of the attributes were $z \in [0,24]$ feet and $y \in [0,300] \times 10^3$ acre-feet. In addition to the description of the decision problem, the subjects were presented with engineering stimuli. For assessing u_z these were cross-sections and photomaps of the floodplain, pictures of the floodplain from the past floods, and the stage-damage function. In assessing u_y, the primary stimulus was a function relating storage deficit y to the expected monetary loss. Also, a description of nonmonetary consequences for various values of y was given.

After the assessment process had been completed, the results were discussed with each subject. Particularly, correct interpretations of doubtful responses, like inflection points on the utility curve, were being checked. The subject could then refine his responses if any inconsistencies became apparent.

The results are presented for three subjects out of five who participated in the experiment. Figure 3 shows single attribute utilities u_z and u_y. The values of the corner utilities k_z and k_y are given in Table 5.

RESULTS

1. An operational interpretation of the risk taking and risk averting behaviors is given first. Let two decision makers be faced with a necessity of choosing the operational rate of release from the reservoir. If the decision makers' behavior in this choice situation is consistent with their utility functions, then the release rate chosen by the risk averter should be greater than the release rate chosen by the risk taker.

2. The shape of u_z heavily depends upon location of various establishments in the floodplain. In this sense all subjects appeared to be risk takers (concave u_z) for some flood levels and at the same time risk averters (convex u_z) for other flood levels. For example, subject 4 shows the risk taking behavior for low flood levels. At level 10 (above which the residential and industrial area extends), he becomes very strongly a risk averter. That is, whenever the forecast indicates a positive probability of having a flood with $z > 10$, he easily decides on an advanced discharge up to level 10 in order to prepare the reservoir for the largest forecasted flood and thus reduce the chance of flooding the levels greater than 10. But when levels 10-13 become flooded, he prefers, again, gambling.

3. Utility functions of five subjects and the monetary loss function (which was used as a stimulus) rescaled to the interval [0,1], have been plotted in Figure 4 which gives an idea about the difference between individual perceptions of the same decision problem. Also the considerable diversity between criterion functions when utilities instead of monetary losses are considered is quite apparent.

4. The large bias which may be introduced into the subject's preference structure by the range of the games in the assessment process is illustrated in Figure 3 which shows the response obtained from the game over the entire range of an attribute (game [0;.5;24] for z, and game [0;.5;300] for y). When this inconsistency was pointed out to the subjects, they did not change their responses (or changed them only slightly), stating that it is hard to perceive such drastically diverse consequences, and that, therefore, their response is based upon an undefined feeling rather than upon a rational judgment. Interestingly, in most cases, the responses are biased in the direction of risk aversion. This example may well serve as a warning against unaware application of utility assessment schemes which require unrealistic judgments from the decision maker.

5. An intriguing dilemma emerged from verification of the multivariate risk behavior. In 3 cases out of 5, the subjects were found to be SMRA by application of the choice test. However, after assessing corner utilities, all subjects appeared to be SMRS. Reconsideration of the assessment process did not change the subjects' responses; moreover, they did not see any inconsistency in their answers. Although this result could cast doubt upon the adequacy of the utility concept as a decision behavior model of the subjects, we still think that the model can be very useful on the basis of hydrological considerations. First, the subjects' behavior, though inconsistent within the framework of the utility model, can still be considered as rational. The fact that $[(z_o,y_e);.5;(z_e,y_o)] \succ [(z_o,y_o);.5;(z_e,y_e)]$ does not preclude one's opinion that the "half-disastrous" consequences (z_o,y_e) and (z_e,y_o) are both closer, on the preference scale, to the worst consequences (z_e,y_e) than to the best consequence (z_o,y_o), and thus that $k_z + k_y > 1$. Secondly, there is a hope that the model may, nevertheless, perform satisfactorily provided the choices between extreme values of the attributes are excluded. Inasmuch as real-time reservoir operation satisfies, in general, this condition, this optimism is perhaps not without grounds.

CONCLUSIONS

1. It may be possible to predict the sequential behavior of a decision maker faced with a reservoir operation problem by assessing his utility for a single decision. For this purpose, the SRO should be imbedded in the LRO.

2. The reservoir operation problem may be modelled as a game against nature of the von Neumann-Morgenstern type.

3. The assumption that utility independence holds in SRO leads to a multiplicative utility function.

4. In the assessment of a multiattribute utility function, games between extremes are not acceptable because they bias the subject's response.

5. For similar reasons, the range and variance of state and decision variables in the experiments should be close to the range and variance in the real-life decision situations.

6. An algorithm compatible with the latter two points has been applied to assess the utility function of five hydrologists, who are all found to be risk averters for small floods and risk takers for large ones.

7. Results of the experiments lead to certain inconsistencies which may be explained in terms of the particular hydrological situation chosen for the tests.

ACKNOWLEDGEMENTS

The authors are greatly indebted to Professor William R. Ferrell for helpful discussions and valued suggestions concerning the assessment procedure. Authors' thanks also go to the colleagues from whose enthusiastic participation in the experiment this research greatly benefited.

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Table 1. Basic characteristics of short-range operation (SRO) and long-range operation (LRO)

SRO	LRO
1. Short operating horizon (measured in terms of hours or days).	1. Long operating horizon (measured in terms of weeks or months).
2. "Immediate" decisions are required (on an hourly basis).	2. Decision-making process can be extended in time (over days or even weeks).
3. High variability of the inflow rate.	3. Low variability of the inflow rate.
4. Input is forecasted in terms of rate of flow, and the operation concerns directly the rate of release from the reservoir.	4. Input is forecasted in terms of flow volumes over certain periods of time, so that the scheduling of releases concerns the volumes of outflow.
5. Usually the reservoir is refilled.	5. Usually the reservoir is drawn down.

Table 2. Two-state flood game

		DECISION	
		M	A
STATE OF NATURE	MF	z_{MM}, y_{MM}	z_{AM}, y_{AM}
	AF	z_{MA}, y_{MA}	z_{AA}, y_{AA}

Table 3. Modified two-state flood game

		DECISION	
		M	A
STATE OF NATURE	MF	z_{MM}	z_A
	AF	z_{MA}	

		DECISION	
		M	A
STATE OF NATURE	MF	y_o	y_{AM}
	AF		y_o

Table 4. Example of a sequence of games for assessing u_z

STEP	Game i	a_i	b_i	c_i
2	1	z_o	z_n	z_1^*
	2	z_o	z_1	z_2^*
	3	z_1	z_n	z_3^*
3	4	z_n	z_e	z_4^*
	5	z_4	z_e	z_5^*
	6	z_n	z_4	z_6^*
4	7	z_3	z_6	z_7^*
	8	z_1	z_4	z_8^*

Table 5. Corner utilities and multivariate risk behavior

Subject		1	2	3	4	5
k_z		.94	.82	.76	.93	.78
k_y		.82	.52	.42	.62	.40
$k_z + k_y$		1.76	1.34	1.18	1.55	1.18
Multivariate risk behavior	From $k_z + k_y$	SMRS	SMRS	SMRS	SMRS	SMRS
	From choice test	SMRA	SMRS	SMRA	SMRA	SMRS

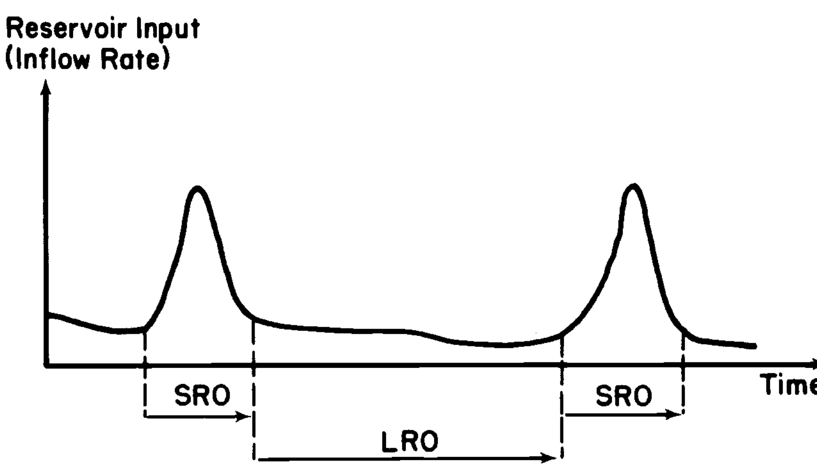


Figure 1. Input versus definition of short-range operation (SRO) and long-range operation (LRO)

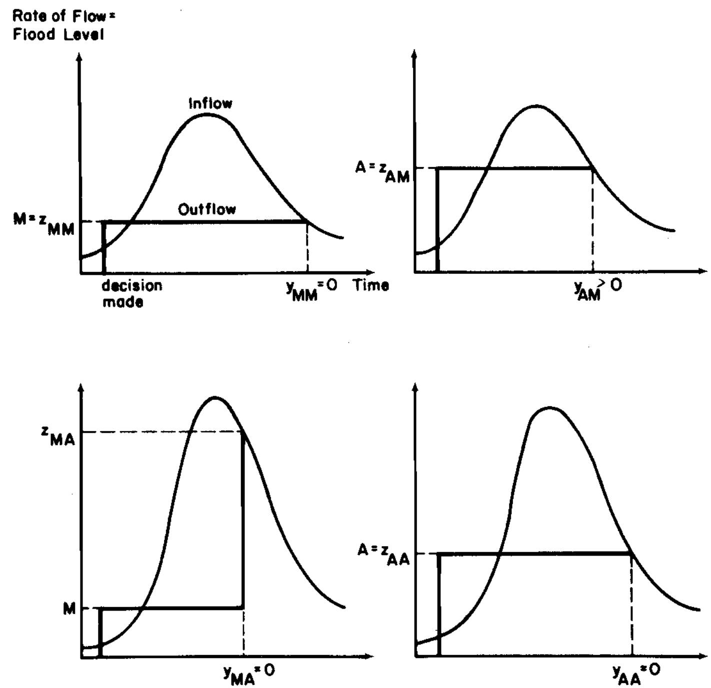
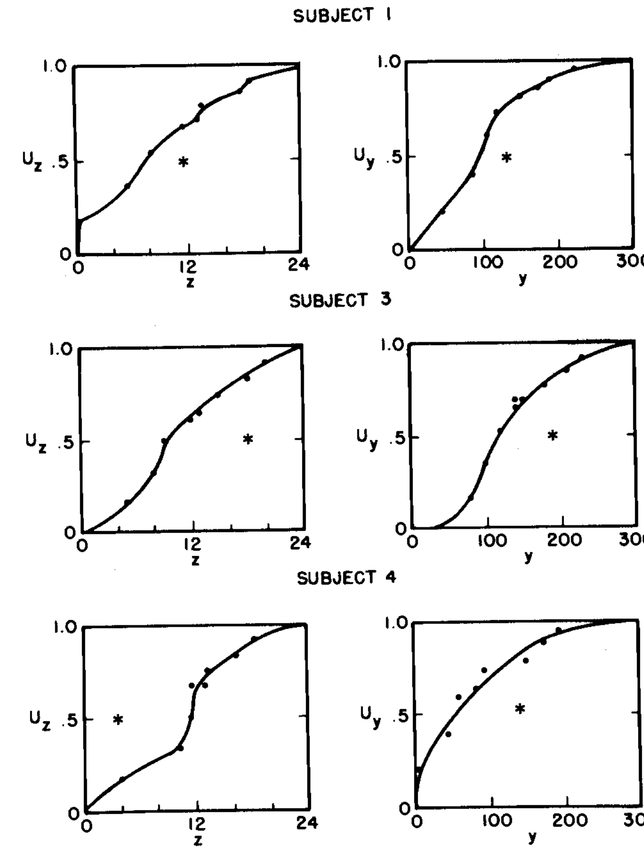


Figure 2. Schematic presentation of the outcomes of the two-state flood game



• Subject's response
* Subject's response from the game over the entire range of the attribute

Figure 3. Single-attribute utility functions

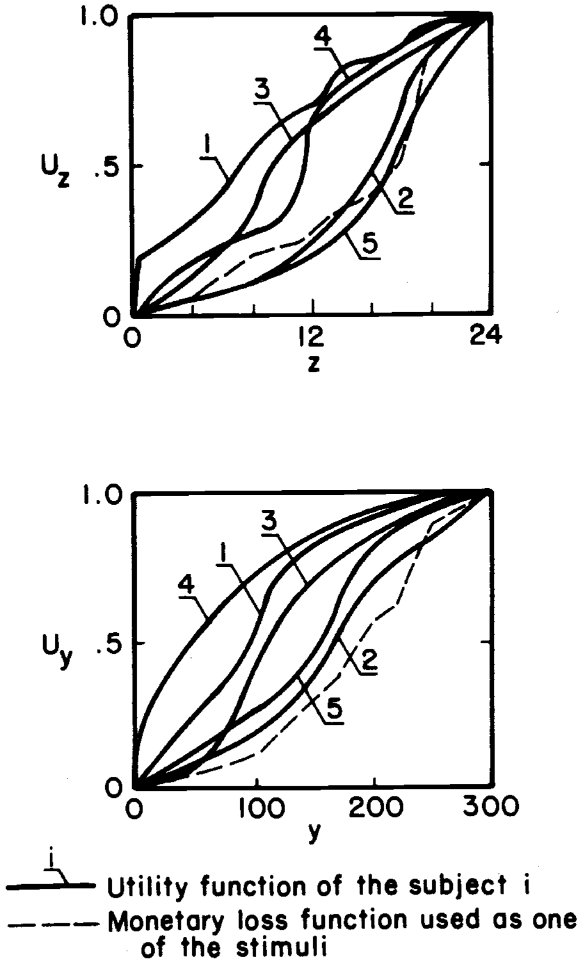


Figure 4. Single-attribute utility functions and economic loss functions