# Comparative Evaluation of Multipurpose Reservoir Operating Rules Using Multicriterion Decision Analysis Techniques

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Abstract/Selection of the best operating rule among a set of alternatives for a multipurpose reservoir system operation requires to evaluate many minor criteria in addition to the major objectives assessed to the system. These problems are sufficiently complex and difficult that they are beyond heuristic decision rules and experiences in case several noncommensurable multiple criteria are included in the evaluation. With the assistance of multicriterion decision analysis techniques, it is possible to select the best one among various alternatives by systematically comparing and ranking the alternatives with respect to the criteria of choice.

Evaluation criteria for multipurpose reservoir system operating rules were identified and defined, and the multicriterion decision analysis techniques were applied to evaluate the four existing operating rules of the Chungju multipurpose project according to the identified nine multiple criteria. The application results show that the methodology is very efficient to select the best operation alternative among a finite number of operating rules with many evaluation criteria for a large-scale reservoir system operation.

## 1. Introduction

For the efficient operation of a multipurpose reservoir system, it is necessary to give consideration to some combinations of benefits from flood control, hydropower generation, municipal, industrial and irrigation water supply, inland navigation, enhancement of recreation activities, water quality control and environmental protect. With regard to these objectives, conflictions of whether it is necessary to conserve water by maintaining water level high or discharge water by lowering water level may be arisen at any time to accomplish the objectives on the whole or in partial.

Especially, it is not easy to supply water in time and in right place only with natural surface water as rainfall is one of the most unpredictable and uncontrollable phenomena in nature. Moreover, tem-

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poral and spatial variations in rainfall are extremely severe in Korea due to the effect of monsoon climate. Therefore, a storage reservoir plays an important role and efficient utilization of water from a reservoir depends on multiple functions of the system which allows us to appropriately control and utilize the inflows of temporal and spatial distribution in quantity and quality.

In order to maximize the multiple functions of reservoir systems, many scholars have exerted themselves in making a long-term analysis with optimization models by using the historic or generated inflow data to derive operation criteria or the operating rules for the multipurpose reservoirs. If it is required to carry out a multi-objective analysis by using a mathematical model such as optimization model which considers all the functions of the multipurpose reservoir, tradeoff evaluation between the considered objectives must be performed.

However, it is very difficult to select an optimal alternative among the numerous non-dominated solutions as the tradeoff evaluation is complex and time-consuming if there are number of objective functions simultaneously considered (Cohon and Marks, 1975). To avoid this complexity, a methodology was suggested in which simulation or optimization models are used considering only several main objectives imposed to the multipurpose reservoir system, and then the optimal alternative is selected after performing the evaluation of each objective in detail by using the multicriterion decision analysis techniques (Harboe, 1986; Ko, 1989).

In the evaluation of the operating rules for a multipurpose reservoir, simulation must be performed according to the suggested operating rules by using the historic or generated inflow data to evaluate the accomplishment of each objective assigned to the reservoir system. For the selection of an operating rule of the multipurpose reservoir which has several conflicting objectives such as water supply, hydropower generation and water quality control, it sometimes needs to apply a technique in order to select an appropriate alternative which is better than any other alternatives in economic point of view and the equality of supply. It also requires the introduction of the multicriterion decision analysis techniques which simultaneously take account of all the objectives excluded from simulation or optimization of reservoir system operation due to the complexity of simultaneous evaluation.

This study aims at suggesting the evaluation criteria of the operating rules for the multipurpose reservoir system which has several alternative operating rules, as well as suggesting a methodology in order to select the optimal alternative by using the multicriterion decision analysis technique in accordance with the suggested evaluation criteria. For the application of this technique to the evaluation of the Chungju Reservoir System operating rules of conservation purpose, the existing operating rules of the reservoir system were examined, and simulation program for the evaluation and calibration of the operating rules were developed. And the most preferred operating rule was derived by ranking the operating rules by applying the multicriterion decision analysis techniques.

## 2. Evaluation of the Operating Rules by the Multicriterion Decision Analysis Techniques

### 2.1 Evaluation Criteria for Multipurpose Reservoir Operating Rules

Operating rules of a reservoir system have been utilized to cope with the uncertainty of variable inflows into a reservoir, and the rules have to improve the multiple functions of the system by giving guidelines of suitable discharges or storage levels of the reservoir. In order to select the best one among the several reservoir operating rules developed for this purpose, it is necessary to take account not only the benefit or effect from the main objectives which were taken into consideration in the planning stage, but also the incidental benefit or effect which may be occurred when the reservoir is operated according to the operating rules.

For example, the evaluation criteria of the major multipurpose reservoirs in Korea may be established by considering only their main objectives such as water supply, hydropower generation and flood control. However, it is necessary to include additional effects such as environmental improvement or recreation activities through low flow augmentation by increasing the firm flows from reservoirs.

Figure 1 shows the evaluation criteria of the operating rules for the Chungju Multipurpose Reservoir System. These include 4 main criteria of hydropower generation, water supply, flood control and environmental improvement as well as 2 or 3 sub-criteria for each main criteria. As shown in these criteria, the variation of power or energy production may be considered as one of the hydropower evaluation criteria in addition to the peak energy, secondary energy and 90% firm power.

In Figure 1, as an evaluation criterion of water supply, firm flows and maximum shortage below the monthly target level in respect of water supply for municipal and industrial use, irrigation use or river maintenance water are used. However, the effects on navigation or recreation activities in the downstream reaches may be included if there is excess release more than the planned flood discharge.

In respect of flood control criterion, benefit from flood control storage above the normal high water level, which was basically assigned to the system, was excluded from the evaluation criteria as it can be assumed to be invariable in respect of conservation use. However, reservoir space below the normal high water level in the flood season was included as it may contribute on the benefit of flood control subject to the reservoir operating rule. The minimum storage must be also included in the evaluation criteria as the extremely lowered reservoir water level may result in the decreased reliability on water supply or hydropower generation in the dry season. And it can be considered that if the higher water level with small fluctuation is maintained, the more benefit can be obtained in respect of inland navigation, tourism or recreation activities in the reservoir areas.

Ecological and environmental impacts are greatly affected by the variance in reservoir water level or the fluctuation range or the fluctuation rate of the discharges from a reservoir (Odum, 1971). Especially in the growth of aquatic insects, it is desirable to variably control the reservoir water level. However, the more flows with small fluctuation in the discharge is allowed, the greater utilization can be obtained in respect of environmental protection including recreation in the downstream reaches of a reservoir.

| Main-Criteria | Sub-Criteria |
|---|---|
| A. Hydro Power | 1. Firm Energy Production (GWH)<br>2. Secondary Energy Production (GWH)<br>3. Firm Power (90% Firmness, MW) |
| B. Water Supply Navigation | 4. Firm Flow (90% Firmness, MCM)<br>5. Maximum Shortage (MCM/Mon) |
| C. Flood Control & Reliability | 6. Additional Flood Control Shortage During Flood Period (MCM)<br>7. Minimum Available Storage During Operation (MCM) |
| D. Environment & Recreation | 8. Recreation and Reservoir Transportation<br>9. Variation of Release |

**Figure 1** Evaluation Criteria for Reservoir System Operation Rule

### 2.2 Application of Multicriterion Decision Analysis Techniques

In order to evaluate multipurpose reservoir operating rules for the selection of the best alternative, various objectives and evaluation criteria have to be taken into consideration as shown in Figure 1. In the evaluation of the operating rules, as it is necessary to consider the evaluation criteria with different units or qualitative criteria, a decision maker or a system engineer may be encountered with extremely complex problems beyond his experience or insight when he try to select the best one among several alternatives. With the multicriterion decision analysis techniques, one can systematically analyze the complex problem such as selection of the multipurpose reservoir operating rules which have many evaluation criteria. For the application of these techniques, simulations have to be performed according to each alternative operating rules by using the historic or generated inflow data. Then pay-off matrix, which shows the performance of each alternative, is calculated according to each evaluation criterion as shown in Figure 1 in order to carry out multicriterion decision analysis (Goicoechea et al., 1982).

As a rule to find out the best one among the alternatives with various criteria (objectives), many techniques on the multicriterion decision analysis have been suggested to the present. Among the various techniques, weighted average method, ELECTRE I (Benayoun et al., 1966), ELECTRE II (Roy and Bertier, 1971), discrete compromise programming (Duckstein and Opricovic, 1980), analytic hierarchy process (AHP; Saaty, 1982), as well as PROMETHEE (Brans et al., 1984) and cooperative game theory (Nash, 1953; Harsanyi, 1977) are representatively applied currently to the water resource system analysis.

Weighted average method is probably the easiest and the most commonly using technique for the comparative evaluation of alternatives. The worth of each alternative is determined by summation of the weighted numerical values of each criterion. The alternative which has the greatest worth is the best alternative for decision. But this method can not be realistically used for problems in which criteria are not commensurable. Furthermore, it has a contradiction of selecting an alternative as the best one even if it has an evaluation criterion below the worst level when other criteria are superior.

The analytic hierarchy process (AHP) was developed by Saaty (1982). He describes the decision making process as a hierarchical process. By breaking the process into levels, the decision maker can focus on smaller sets of decisions. For this evaluation, a relative weight matrix is formulated by comparing pairwise alternatives according to the scale of measurement which has a value between 1 and 9 proposed by Saaty. The relative weight matrix is formulated by evaluating one alternative to another rather than evaluating all alternatives simultaneously. From this matrix, a vector of weights (priorities) is derived using the eigenvector method developed by Saaty.

$$Aw = 1_{max}\, w \tag{1}$$

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots\cdots & a_{1n} \\ a_{21} & a_{22} & \cdots\cdots & a_{2n} \\ \vdots & \vdots & \cdots\cdots & \vdots \\ a_{n1} & a_{n2} & \cdots\cdots & a_{nn} \end{bmatrix} \tag{2}$$

$$w^T = (w_1, \cdots\cdots, w_n) \tag{3}$$

Where, $a_{ij}=1/a_{ji}$ for all i, j = 1, 2, ……, n. The elements $a_{ij}$ represents the scale of the importance of alternative i relative to j for the considering objective which has "n" alternatives. $1_{max}$ is the maximum eigenvector, w is the weight of each alternative which can be obtained from the equation (4). It is known that AHP method is useful especially when there are noncommensurable evaluation criteria, and suitable when the number of the alternatives are less than 7±2.

$$w_i = \frac{\sum\limits_{j=1}^{n} a_{ij} w_j}{1_{max}} \quad ; \text{for all } i=1, 2, \cdots\cdots, n \tag{4}$$

The compromise programming was developed for the multiobjective analysis of continuous problems, a variation of the compromise programming method has been used for the evaluation of discrete multiobjective problems. This technique finds the alternative that is closest to the ideal solution which satisfies all the evaluation criteria to their optimum (Zeleny, 1982).

$$L(x) = \min \sum_{i=1}^{k} [w_i \frac{v_i^{*} - v_i(x)}{v_i^{*} - v_i^{**}}]^p \tag{5}$$

Where, L(x) is an evaluation function for the alternatives composed of function of x, which implies the summated variation to the ideal solution; $w_i$ are weights to each evaluation criteria; k is the number of evaluation criteria (objectives) of multicriterion analysis; $v_i^*$ and $v_i^{**}$ are the maximum and the minimum solutions of the individual problems; p is a power parameter indicating the importance of the maximum variation among each evaluation criterion, for which 1, 2 or an infinite value is used.

Elimination and (et) Choice Translating Algorithm, ELECTRE Ⅰ was suggested by Benayoun et al (1966). The basic concept of ELECTRE Ⅰ is to select those alternatives which are preferred for most of the criteria without violating an acceptable level of discontent for any one criterion. This procedure is performed by comparing pairwise alternatives among members of a set of alternatives.

A concord (concordance) index and a discord (discordance) index are important factors in ELECTRE Ⅰ as well as ELECTRE Ⅱ to measure the preference and disagreement of one alternative to another. The concord index measures the weighted number of criteria for which one alternative is preferred to or equal to another. The discord index measures the strength of the greatest discontent or disagreement among all criteria in which case one alternative is selected over another. These indices are used to define the outranking relationships of alternatives for the specified minimum level of concordance and allowable maximum level of discordance. While ELECTRE Ⅰ provides only a partial ranking of the alternatives, ELECTRE Ⅱ gives a complete ranking. The use of concord and discord indices in ELECTRE Ⅱ is the same as in ELECTRE Ⅰ, and it was developed by Roy and Bertier (1971).

## 3. Application and Analysis

### 3.1 Operating Rules for the Chungju Reservoir System

As the largest multipurpose dam in Korea, the Chungju reservoir system completed in 1985 has a storage capacity of 2,750 MCM (million cubic meters), average annual hydro energy output of 844.1 GWH (giga watt hour), which is generated from main dam power plant with a capacity of 400 MW (mega watt) and the reregulation dam power plant with capacity of 12 MW, and downstream water supply of 3,380 MCM for various purposes. For the effective operation of this system, KOWACO have developed several operating rules. Followings are the summarized descriptions on them which have been developed for the conservation management of the Chungju system.

#### (1) Operating Rule at the Time of Construction (Rule No.1)

In compliance with a request by the Industrial Sites and Water Resources Development Corporation (ISWACO; later KOWACO) in 1985, the Nippon Koei Company (N.K.C.) suggested an operating rule for the increase in hydropower energy output using the monthly inflow data from 1966 to 1983 (ISWACO, 1985). At that time, an analysis was performed for the 4 cases of monthly limited water levels with 5 cases of monthly target water levels. In order to select the best operating rule which met the downstream water supply and maximizing annual energy output, simulations were performed corresponding to the designated monthly limited water levels and target water levels.

According to the derived best operating rule, hydropower energy could be maximized when the target water level set to the normal high level in the dry season, and keep the water level lower than the normal high water level in the flood season. Table 1 shows the monthly target water levels for the operating rules suggested to be the best among the five alternatives. However, this operating rule has not been used since the target water supply was fixed too small compared with the actual downstream requirement, and the power plant at the reregulation dam was not taken into consideration.

**Table 1** Monthly Target Water Levels Suggested by N.K.C. (ISWACO, 1985)

| Date | Water Level(El. M) | | Date | Water Level(El. M) | |
|---|---|---|---|---|---|
| | Target | N. H. W. L. | | Target | N. H. W. L. |
| Jan 1 | 141.0 | 141.0 | Jul 1 | 136.0 | 138.0 |
| Feb 1 | 141.0 | 141.0 | Aug 1 | 136.0 | 138.0 |
| Mar 1 | 141.0 | 141.0 | Sep 1 | 137.2 | 138.0 |
| Apr 1 | 141.0 | 141.0 | Sep 20 | 138.0 | 138.0 |
| May 1 | 141.0 | 141.0 | Oct 1 | 141.0 | 141.0 |
| Jun 1 | 141.0 | 141.0 | Nov 1 | 141.0 | 141.0 |
| Jun 20 | 136.0 | 138.0 | Dec 1 | 141.0 | 141.0 |

### (2) Operating Rule Reported to the KNCOLD (Rule No.2)

At the 7th annual seminar on the dam construction & management techniques hosted by Korea National Committee on Large Dams (KNCOLD) in 1986, Ko (1986) presented an operation rule based on the optimal operation by the dynamic programming algorithm using the long-term observed historic inflow data. Performed a regression analysis on the optimal discharges according to the monthly storage state by using the optimal operating trajectory, he suggested a diagram of multi-stage linear allocation of reservoir storage as shown in Figure 2.

The operating rule was suggested by a set of quadratic equations through a regression analysis on the relation between beginning of the month storage and the optimal discharges, and the optimal power plant factors based on the optimal operation. The 52 years' monthly inflow data from 1917 to 1940 and 1956 to 1983 were used for this optimal operation. At this time, objective functions for optimal operation were assumed to maximize the annual hydro energy generation from the main and the reregulation reservoirs, provided with the conditions of water supply and the physical characteristics of the reservoir as constraints. In case of operating the reservoir according to the Figure 2, the plant factor of the main dam which is defined as the ratio of actual operating time to the reservoir operation unit period, is obtained from the following equations.

$$\text{Zone-1}: O_F = O_B + (1 - O_B) * \frac{S(WL - WL_L)}{S(WL_U - WL_L)} \quad (6)$$

$$\text{Zone-2}: O_F = O_P + (O_B - O_P) * \frac{S(WL - WL_L)}{S(WL_U - WL_L)} \quad (7)$$

Where, $O_F$ is the plant factor of the main dam power plant, $O_B$ is baseline of the plant factor of the specific month as shown in Table 2, and $O_P$ is the plant factor for annual average peak operation of 0.1083 which is equivalent to 2.6 hours a day. $S(WL_U - WL_L)$ is the storage of the Zone-1 or Zone-2 and $S(WL - WL_L)$ is the storage between present water level and the lowest water level of the Zone-

1 or Zone–2. If current water level is indicated at the Zone–3, the plant factor is determined according to the downstream water demand but it must not exceed the peak plant factor. If the water level is indicated at the Zone–4, the reservoir is operated so as to return to the Zone–3 by reducing the water supply at the rate of current storage above the low water level to the storage of the Zone–4.

**Table 2** Monthly Average Plant Factor ($O_B$)

| Month | Factor | Month | Factor |
|---|---|---|---|
| Jan | 0.1162 | Jul | 0.4542 |
| Feb | 0.1169 | Aug | 0.3950 |
| Mar | 0.1187 | Sep | 0.2425 |
| Apr | 0.1336 | Oct | 0.1387 |
| May | 0.1548 | Nnv | 0.1230 |
| Jun | 0.2170 | Dec | 0.1243 |

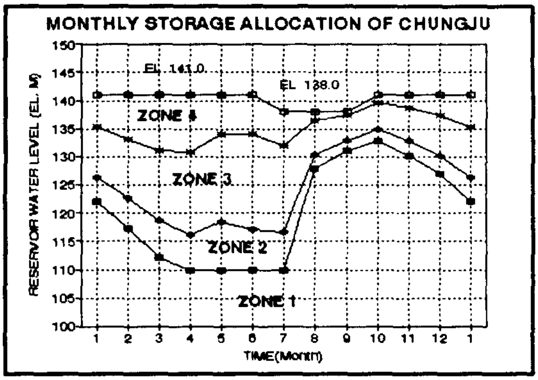

**Figure 2** Zoning of the Chungju Storages Suggested by Ko (1986)

(3) Operating Rule with Reliability (Rule No.3 & Rule No.4)

The Korea Water Resources Corporation (KOWACO) developed operating rules with which it is possible to determine the discharges, considering the reliability and the risk levels, in accordance with the storage conditions and the monthly reservoir inflows. It was found that the rules can significantly increase the benefit compared with the historical result from the reservoir system. Based on the methodology, monthly operating rules considering reliability levels were derived to operate the Chungju multipurpose reservoir in combining with its reregulation reservoir (Lee at al., 1991).

The suggested operating rules are consisted of the monthly operating rule curves, and the storage allocation with reliability levels and the monthly zoning of the available storage. With the suggested operating rules, it is possible to increase the benefit of multiple objectives from the system by determining discharge policies incorporated with the desired range of reliability levels without a long–term forecasting of uncertain inflows to the reservoir. As for these operating rules, two rule curves were developed as follows; Rule No.3 based on the main reservoir system only and Rule No.4 based on the main and reregulation reservoirs. However, there was no definite verifications on both rules for which rule is better.

Rule No.3 : $Q_{1t}=a_{1t}V_t+b_{1t}$; $V_t=X_{1t}+I_{1t}$ (8)

Rule No.4 : $Q_{2t}=a_{2t}S_t+b_{2t}$; $S_t=X_{1t}+I_{1t}+I_{2t}$ (9)

Where, $Q_{1t}$ and $Q_{2t}$ are monthly discharges from the main and the reregulation reservoirs; $X_{1t}$ is beginning of the month storage of the main reservoir; $I_{1t}$ and $I_{2t}$ are monthly local inflows to the main and the reregulation reservoirs. As shown in Table 3, $a_{1t}$, $a_{2t}$, $b_{1t}$ and $b_{2t}$ are monthly regression parameters calculated by piecewise linear regressions.

**Table 3** Monthly Operating Rules for Chungju SyStem (Lee et al., 1991)

| Mon | Rule No. 3 | | | Rule No. 4 | | |
|---|---|---|---|---|---|---|
| | Zoning (MCM) | Regression Coef | | Zoning (MCM) | Regression Coef | |
| | | $a_{1t}$ | $b_{1t}$ | | $a_{2t}$ | $b_{2t}$ |
| 1 | $650<V_t<1400$ | +0.151817 | + 83 | $669<S_t<1300$ | +0.335367 | − 87 |
| | $1400<V_t<2500$ | +0.004303 | + 278 | $1300<S_t<2500$ | +0.002989 | + 285 |
| 2 | $614<V_t<1100$ | +0.363028 | − 122 | $622<S_t<1050$ | +0.609618 | − 346 |
| | $1100<V_t<2400$ | −0.017452 | + 273 | $1050<S_t<2450$ | +0.000140 | + 264 |
| 3 | $646<V_t<1000$ | +0.573369 | − 267 | $658<S_t<900$ | +1.000032 | − 598 |
| | $1000<V_t<2500$ | −0.017447 | + 285 | $900<S_t<2550$ | +0.012767 | + 267 |
| | $2500<V_t$ | +0.899242 | −2087 | $2550<S_t$ | +0.903950 | −2095 |
| 4 | $668<V_t<1200$ | +0.345767 | − 112 | $679<S_t<1200$ | +0.466724 | − 248 |
| | $1200<V_t<2580$ | −0.032885 | + 298 | $1200<S_t<2600$ | +0.013846 | + 260 |
| | $2600<V_t$ | +0.989813 | −2357 | $2600<S_t$ | +0.961633 | −2267 |
| 5 | $772<V_t<900$ | +1.087842 | − 687 | $803<S_t<1000$ | +0.741966 | − 403 |
| | $900<V_t<2600$ | −0.092287 | + 123 | $1000<S_t<2800$ | +0.132547 | + 79 |
| | $2600<V_t$ | +0.750958 | −1520 | $2800<S_t$ | +0.689281 | −1268 |
| 6 | $775<V_t<900$ | +0.999354 | − 598 | $806<S_t<900$ | +0.999208 | − 598 |
| | $900<V_t<2300$ | +0.308852 | − 53 | $900<S_t<2400$ | +0.364571 | − 127 |
| | $2300<V_t$ | +0.588528 | − 777 | $2400<S_t$ | +0.845764 | −1456 |
| 7 | $982<V_t<2400$ | +0.091171 | + 126 | $992<S_t<2650$ | +0.191279 | − 26 |
| | $2400<V_t<$ | +0.921483 | −1819 | $2650<S_t<$ | +0.959904 | +1941 |
| 8 | $985<V_t<2300$ | −0.017188 | + 268 | $1026<S_t<1026$ | +0.001484 | + 291 |
| | $2300<V_t<$ | +0.951233 | −1954 | $2400<S_t<$ | +0.970399 | −2004 |
| 9 | $1133<V_t<2600$ | −0.098096 | + 449 | $1158<S_t<2800$ | −0.003418 | + 303 |
| | $2600<V_t<$ | +0.998282 | −2382 | $2800<S_t<2550$ | +0.998617 | −2382 |
| 10 | $668<V_t<1800$ | +0.163906 | + 6 | $695<S_t<1700$ | +0.299939 | − 112 |
| | $1800<V_t<2600$ | −0.015230 | + 294 | $1700<S_t<2700$ | +0.005906 | + 276 |
| | $2600<V_t$ | +0.983959 | −2337 | $2700<S_t$ | +1.009896 | −2412 |
| 11 | $693<V_t<1600$ | +0.198203 | − 41 | $724<S_t<1400$ | +0.236047 | − 45 |
| | $1600<V_t<2600$ | +0.016520 | + 288 | $1400<S_t<2700$ | +0.007889 | + 263 |
| | $2600<V_t$ | +0.889484 | −2087 | $2700<S_t$ | +0.986707 | −2351 |
| 12 | $674<V_t<1700$ | +0.144228 | + 36 | $697<S_t<1400$ | +0.346955 | − 142 |
| | $1700<V_t<2500$ | −0.013256 | + 295 | $1400<S_t<2700$ | +0.005623 | + 278 |
| | $2500<V_t$ | +0.295522 | − 504 | $2700<S_t$ | +0.951118 | −2251 |

### 3.2 Simulation According to the Operating Rules

For the comparative analysis on the effectiveness of reservoir operation in accordance with the considered four alternative operating rules, a simulation program based on each operating rule was developed. This program simulates and shows the operation results using the hiStorical monthly inflow data according to the selected operating rule by a user's option. The operation result shows monthly reservoir water level, Storage, discharges and monthly hydropower energy generation from the main and reregulation power plants as well as firm power, firm energy and firm water supply according to the discrete reliability levels.

For these simulations according to four alternative operating rules, the historic monthly inflow data of 59 years (1917–1940, 1956–1990) to the Chungju main and the reregulation reservoirs were used.

**Table 4** Performances of Developed Operating Rules

| Operating Rules | Annual Energy (GWH/Yr) | 90% Firm Power (MW) | 90% Firm Energy (GWH/Yr) | 90% Firm Water Supply (MCM/Yr) |
|---|---|---|---|---|
| Optimization | 867.73<br>(100.0%) | 397.76<br>(100.0%) | 40.23<br>(100.0%) | 3264.9<br>(100.0%) |
| Rule No. 1 | 894.00<br>(103.0%) | 179.70<br>(45.2%) | 7.82<br>(19.4%) | 400.2<br>(12.2%) |
| Rule No. 2 | 816.40<br>(94.1%) | 340.90<br>(85.7%) | 33.36<br>(82.9%) | 2645.4<br>(81.0%) |
| Rule No. 3 | 820.90<br>(94.6%) | 377.66<br>(94.9%) | 37.20<br>(92.5%) | 3105.5<br>(95.0%) |
| Ruel No. 4 | 839.30<br>(96.7%) | 371.20<br>(93.3%) | 36.40<br>(90.5%) | 3156.9<br>(96.7%) |

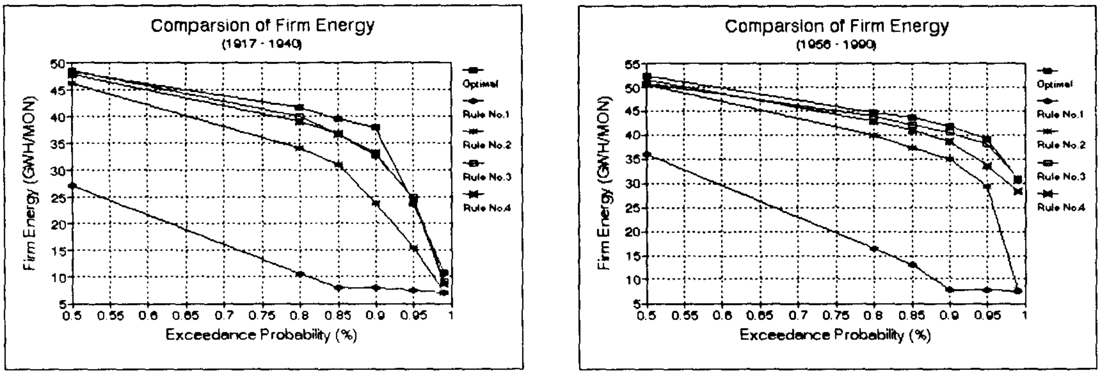

**Figure 3** Comparison of Operating Rules, Firm Energy

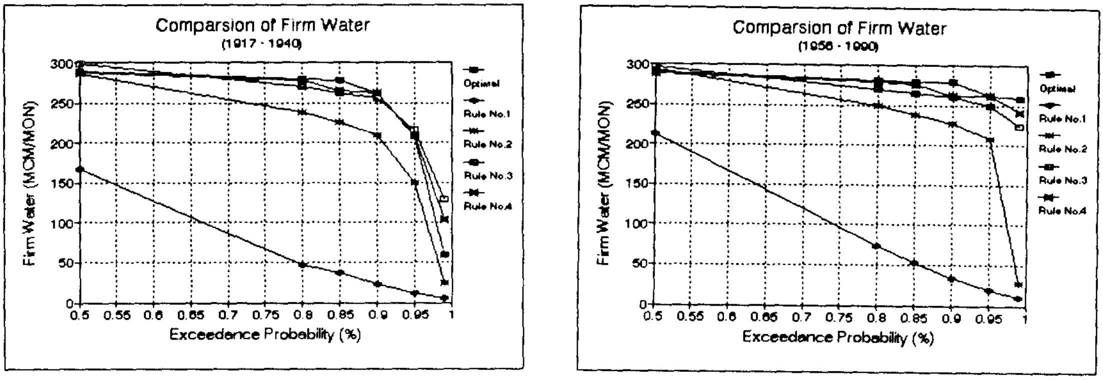

Figure 4 Comparison of Operating Rules, Firm Water Supply

Table 4 shows a comparison between the optimal operation result by the dynamic programming which was designed to develop No.3 and No.4 rule curves, and the simulation results according to each of operating rules. Figures 3 and 4 show the firm energy and the firm water supply versus discretized exceedance probability levels when simulated according to the four alternative operating rules. They show that the recently developed No.3 and No.4 rules are much closer to the result of the optimal operation.

### 3.3 Evaluation of Operating Rules

In order to evaluate the operating rules by using the multicriterion decision analysis technique, a pay-off matrix was developed as shown in Table 5. This pay-off matrix which indicates the evaluated performances according to the criteria shown in Table 1. The performance of the matrix was calculated from simulation results according to the alternative operating rules. The weights of the evaluation criteria were decided by reflecting the opinions of the dam operators and the system engineers working for the Chungju reservoir system.

Maximization concept was introduced to evaluate the hydropower evaluation criterion, firm and secondary energy production and firm power, and minimization was applied to the shortage in water supply during the period. Maximization concept was also applied to evaluate additional flood control storage during the flood season and minimum available storage during operation, but minimization was used to the standard deviation which implies variation of release.

While, the performances of recreation and transportation in reservoir areas were calculated as the percentage of performance considering the variations of reservoir water levels and releases during the operation period.

Table 6 shows the evaluation results of each operating rule calculated from the pay-off matrix shown in Table 5 through application of the multicriterion decision analysis techniques of weighted average method, discrete compromise programming (CP), analytic hierarchy process (AHP) and ELECTRE II.

**Table 5** Pay-off Matrix for the Alternative Operating Rules

| Criteria (Table 1) | Weights | Unit | Operating Rules | | | | Remarks |
|---|---|---|---|---|---|---|---|
| | | | No. 1 | No. 2 | No. 3 | No. 4 | |
| 1 | 20.0 | GWH/Yr | 93.8 | 400.3 | 446.4 | 436.8 | Max |
| 2 | 15.0 | GWH/Yr | 801.2 | 416.1 | 374.5 | 402.5 | Max |
| 3 | 5.0 | MW | 179.7 | 340.9 | 377.6 | 371.2 | Max |
| 4 | 25.0 | MCM/Yr | 400.2 | 2645.4 | 3105.5 | 3156.7 | Max |
| 5 | 5.0 | MCM/M | 282.0 | 267.5 | 66.8 | 49.7 | Min |
| 6 | 7.5 | MCM | 0.3 | 401.2 | 362.4 | 357.3 | Max |
| 7 | 7.5 | MCM | 2134.0 | 596.6 | 610.7 | 598.7 | Max |
| 8 | 10.0 | % | 100.0 | 60.0 | 65.0 | 65.0 | Max |
| 9 | 5.0 | MCM | 305.6 | 199.4 | 212.2 | 185.5 | Min |

For the application of the weighted average method, the maximum values were used for the maximization and the minimum values for the minimization problem according to the evaluation criteria of Table 5. Then these values were converted into the ratio of attainment for the weighted summation of these criteria values. For the application of the discrete CP, two values of 1 and 2 were used for the power coefficient of p according to the equation (5). The AHP and the ELECTRE II were evaluated by applying the generalized computer programs developed by Ko (1989).

A sensitivity analysis was performed in consideration of the uncertainty due to the weights shown in Table 5. Equal weights were given to all the evaluation criteria instead of the weights assigned in the Table 5, but the result was almost same and the ranks were remained almost same.

From the results shown in Table 6, excluding the ELECTRE II, Rule No.4 has been proved to be the best alternative which decides the discharges in consideration of beginning of the month storage of the main reservoir and the inflows of the main and reregulation reservoirs. The second best alternative is Rule No.3 by which it is possible to estimate the discharge according to beginning of the month storage and inflow to the main dam.

**Table 6** Ranking of the Chungju System Operating Rules

| Multicriterion Decision Analysis Techniques | Ranking of Operating Rules | | | |
|---|---|---|---|---|
| | Rule ♯ 1 | Rule ♯ 2 | Rule ♯ 3 | Rule ♯ 4 |
| Weighted Average Method | 4 | 3 | 2 | 1 |
| Discrete CP(p=1) | 3 | 4 | 2 | 1 |
| Discrete CP(p=2) | 4 | 3 | 2 | 1 |
| Analytic Hierarchy Process | 3 | 4 | 2 | 1 |
| ELECTRE II | 4 | 3 | 1 | 2 |

## 4. Conclusions

For the evaluation of the operating rules of multipurpose reservoir systems, usually various minor objectives have to be considered in addition to the major objectives. However, as the number of objectives are increased in the mathematical formulation of the commonly using multi-objective analysis programming, it becomes difficult to select the most preferred solution due to the complexity in the evaluation of the tradeoffs between various objectives. These problems are sufficiently complex and difficult that they are beyond heuristic decision rules and experiences.

In order to overcome these difficulties, multicriterion decision analysis techniques have been applied to select an operation rule for a multiple objective reservoir system which has many conflicting objectives and evaluation criteria. By applying the multicriterion decision analysis techniques, it was possible to select the best one among various alternatives by systematically comparing and ranking the alternatives with respect to the criteria of choice.

For the evaluation of the operating rules of large-scale multipurpose reservoir systems, the additional factors such as environmental impact, recreation or ecology in addition to the main objectives such as water supply, hydropower and flood control have to be considered. In this study, the evaluation criteria of this kind of operating rules were defined and suggested.

With this technique, four existing operating rules were examined and evaluated, which were developed for the Chungju multipurpose reservoir system, the largest water project in Korea. Prior to the evaluation, simulations were performed according to each operating rule, and four multicriterion decision analysis techniques were applied on basis of the results of the simulation.

For the application of these technique, a pay-off matrix was formulated by evaluating the simulated results based on the considered four operating rules according to the nine evaluation criteria. It was possible to select the most preferred alternative operating rule by considering all the considered evaluation criteria. And one of the newly developed rule was proved to be the best one as it showed little difference regardless of the applied techniques. Furthermore, the multicriterion decision analysis techniques were found to be very effective in case of evaluating the several alternatives which have many evaluation criteria such as the operating rules of the large-scale multipurpose reservoir system.

## References

1. Benayoun, R., B. Roy, and B. Sussman, (1966). "ELECTRE : Une Methode Pour Guider le Choix en Presence de Points de Vue Multiples", SEMA (Metra International), Direction Scientifique, Note de Travail No. 49, Paris, France.
2. Brans, J.P., B. Mareschal, and Vincke, (1984). "PROMETHEE : A New Family of Outranking Methods in Multicriteria Analysis", in *Operational Research '84*, J. P. Brans (ed.), pp. 477-490,

North– Holland, Amsterdam.

3. Cohon, J. L. and D. H. Marks, (1975). "A Review and Evaluation of Multiobjective Programming Techniques", Water Resources Research, Vol. 11, No. 2, pp. 208–220.
4. Duckstein, L. and S. Opricovic, (1980). "Multiobjective Optimiza– tion in River Basin Development", Water Resources Research, Vol. 16, No. 1, pp. 14–20.
5. Goicoechea, A., D. R. Hansen, and L. Duckstein, (1982). *Multi–objective Decision Analysis with Engineering and Business Appli– cation*, John Wiley & Sons, New York, NY.
6. Harboe, R., (1986). "Optimization, Simulation and Multiobjective Analysis of Operating Rules for Reservoir Systems", Water Forum, Vol. 1, pp. 1026–1040, ASCE.
7. Harsanyi, J. C., (1977). *Rational Behaviour and Bargaining Equili–brium in Games and Social Situations*, Cambridge University Press, London.
8. ISWACO, (1985). "Recommendation on Reservoir Operation Rule for Production of Maximum Output, Chungju Multipurpose Dam Project," Prepared by Nippon Koei Co. Ltd. for Industrial Sites and Water Resources development Corporation.
9. Ko, S.K., (1986). "A Study on the Derivation of Reservoir Operating Rule for the Effective Operation of Multipurpose Reservoir System," Presented at the 7th Annual Seminar on Dam Construction and Manage– ment Techniques, Korea National Committee on Large Dams.
10. Ko, S.K., (1989). "Optimizing Reservoir Systems Operation with Multiobjective Decision Analysis," Dissertation Submitted for the Degree of Ph.D., Colorado State University, Fort Collins, Co.
11. Lee, H.S., S.B. Shim, and S.K. Ko, (1992). "Monthly Operating Rules Considering Reliability Levels for Multipurpose Reservoir Systems," J. of Korean Association of Hydrological Science, Vol. 25, No. 1. pp. 75–82.
12. Nash, J., (1953). "Two Person Cooperative Games", Econometrica, Vol. 21, No. 1, pp. 128–140.
13. Odum, E. P., (1971). *Fundamentals of Ecology*, 3rd Edition, W.B. Saunders Company.
14. Roy, B. and B. Bertier, (1971). "La Methode ELECTRE II : Une Methode de Classment en Presence de Criteres Multiples", Direction Scienti– fique, Groupe Metra, Note de Travail 142, Paries, France.
15. Saaty, T. L., (1982). *Decision Making for Leaders : The Analytical Hierarchy Process for Decisions in a Complex World*, Lifetime Learning Publications, Wadsworth, Inc., Belmont, CA.
16. Zeleny, M., (1982). *Multiple Criteria Decision Making*, McGraw-Hill Book Co., New York, NY.

AbbreviationsAHP : Analytic Hierarchy ProcessCP : Compromise ProgrammingELECTRE : Elimination and (et) Choice Translating AlgorithmGWH : Giga Watt Hour (Million Kilo Watt Hour)ISWACO : Industrial Sites and Water Resources Development CorporationKOWACO : Korea Water Resources Corporation MCM : Million Cubic MetersMW : Mega-Watt (Million Watt)N.K.C. : Nippon Koei Company

## Abbreviations

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