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Reevaluation of Operational Policies for a Reservoir System

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Abstract □ The need for integrated reservoir system operation become more intense as the demands from the system increase. A deterministic, three-dimensional discrete incremental dynamic programming approach is presented to derive reservoirs system operational planning strategies. The developed H3DP model optimizes the monthly operation of the Hwachon and Soyang Projects on the North Han river and Chungju Main Project on the South Han river. By using the H3DP model, Hwachon project was reevaluated as a component of the upstream multipurpose storage reservoirs in the basin based on 1993 hydrology. This case study demonstrates the practical use of the developed model for the basin multi-reservoir system operation in an integrated, multipurpose fashion.

Keywords □ reevaluation, multi-reservoir system, optimization, incremental dynamic programming.

I. Introduction

Numerous models have been developed for sizing reservoir storage capacities and establishing operating policies during project planning, for reevaluating the operating policies of existing projects, and for supporting release decisions during real-time operations. Nowadays, increasing attention is being given to developing or reevaluating operating policies to improve the effectiveness and efficiency of the existing reservoir systems. Many researchers have reported the possibilities of practical increases in revenue by improving the operating policies of the existing reservoir systems through the use of modern system analysis techniques (Allen et al., 1986, Johnson et al., 1990, and Simonovic et al., 1993). This research presents a basin-wide, multipurpose, multi-reservoir system optimization model, H3DP, using a generalized CSUDP dynamic programming software (Labadie, 1990). With the developed reservoir system operation model, reevaluation of Hwachon hydropower dam and reservoir operation for multipurpose use was carried out.

II. Dynamic Programming Technique for Multi-reservoir System Analysis

Dynamic programming, formulated largely by Bellman (1957), is particularly suitable for multi-stage sequential decision problems such as reservoirs system operation. Its methodology is based on "Bellman's Principal of Optimality". DP has its ability to decompose complex optimization problems involving large numbers of variables into an equivalent sequence of smaller problems that must be solved one stage at a time recursively. However, the computational burden of the discrete DP increases exponentially with the number of state variables which is called "Curse of Dimensionality of DP".

Various modified solution procedures have been proposed to reduce or circumvent the computational burden. Larson (1968) developed incremental dynamic programming (IDP) by reducing the number of discretizations without sacrificing the accuracy of the solution. Multi-reservoir system operation using DP requires the definition of a recursive optimal returnfunction, $F_t(\underline{X}_t)$ as follows :

$$F^*_t(\underline{X}_t) = \underset{X_{t+1}}{Max}\left[f_t(\underline{X}_t, \underline{X}_{t+1}, u_t) + F^*_{t+1}(\underline{X}_{t+1})\right] \quad (1)$$

Subject to

$$\underline{u}_t = \underline{X}_t - \underline{X}_{t+1} + \underline{I}_t + \underline{R}_{ij}\underline{u}_t \quad (2)$$

$$\underline{X}_{t\text{-min}} \leq \underline{X}_t \leq \underline{X}_{t\text{-max}} \text{ for } t=1, \cdots, T+1 \quad (3)$$

$$\underline{u}_{t\text{-min}} \leq \underline{u}_t \leq \underline{u}_{t\text{-max}} \text{ for } t=1, \cdots, T \quad (4)$$

Where,

$\underline{X}_t$=Reservoir storage at time t;

$\underline{u}_t$=Reservoir release at time t;

$\underline{X}_{t\text{-min}}$, $\underline{X}_{t\text{-max}}$=Lower and upper bound on reservoir storage at time t;

$\underline{u}_{t\text{-min}}$, $\underline{u}_{t\text{-max}}$=Lower and upper bound on reservoir release at time t;

$\underline{I}_t$ =Reservoir inflows at time t;

$\underline{R}_{ij}$=Routing matrix;

$\underline{f}_t(\cdot)$=Incremental or stage benefit at time t;

In this problem formulation, $\underline{X}_t$, $\underline{u}_t$, and $\underline{I}_t$ are N∗1 vectors, respectively, where N is the number of reservoirs for the multi-reservoir system. The routing matrix, R_{ij} is used to account for flow from upstream to downstream reservoirs which is determined by the layout configuration of the system as an N∗N matrix with elements of zeros and ones. The matrix element R_{ij} has a numerical value of one when reservoir i receives release from upstream reservoir j, otherwise R_{ij} is zero if the two reservoirs are not connected each other.

$F^*_t(\underline{X}_t)$ represents the maximum total return for stages t to T, when the system starts at stage t with state $\underline{X}_t$. The value of the terminal return function $F_{t+1}(\underline{X}_{t+1})$ is assumed to be known. For solving multi-dimensional problems with the IDP algorithm, the formulation of Equation (1) is associated with the inverted form of the state equation as shown in Equation (2) and optimization is performed directly over $\underline{X}_{t+1}$.

III. Han River-Reservoir System Optimization Model

1. Reservoir System in the Basin

There are nine reservoirs with hydropower plants in the Han River basin. Two multipurpose storage reservoirs including Soyang and Chungju Main, and one flow-through reservoir, Chungju R/R, are managed by Korea Water Resources Corporation (KOWACO). The other storage reservoir, Hwachon, and five other small-scale flow-through reservoirs are managed by Korea Electric Power Corporation (KEPCO) for the single purpose of hydro energy generation. Fig. 1 shows the schematic layout of the Han river reservoir system representing storage projects, depletion points, and gauging stations.

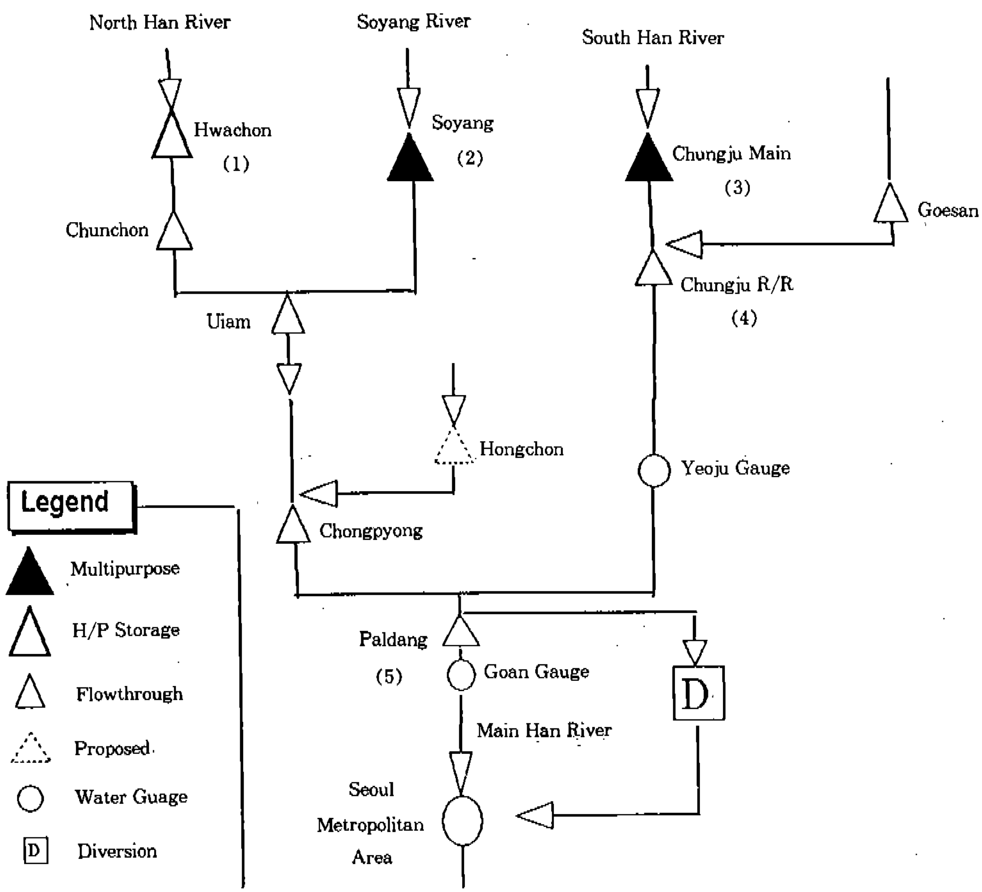


Fig. 1. Schematic of the Han River reservoir system

2. Problem Formulation

A deterministic, three-dimensional discrete incremental dynamic programming approach was used to develop the Han river reservoir system optimization model. The weighting method (Zadeh, 1963) is used for the problem formulation to combine the following five objectives into a single scalar function. To convert all objectives into summation type objective(F_1), the four max(min) objectives were transformed into summation type objectives by minimizing the squared sum of deviations from targets of firm flow.

F_1=Maximization of the total annual energy from all of the hydropower plants considered in the system.

F_2, F_3, and F_4=Maximization of monthly firm water supply from Hwachon, Soyang, and Chungju reservoirs, respectively.

F_5=Maximization of monthly firm basin water supply at the downstream control point (Paldang reservoir).

Where,

$$F_1 = \sum_{t=1}^{T} P_t \tag{5}$$

$$P_t = \sum_{i=1}^{4} G^i(X_{it}, X_{i,t+1}, u_{it}) \tag{6}$$

$$F_2 = \max - \left[\sum_{t=1}^{T} (Sw_{1t})^2 \right] \tag{7}$$

$Sw_{1t} = Tw_{1t} - u_{1t}$; for $u_{1t} < Tw_{1t}$
$Sw_{1t} = 0.0$; for $u_{1t} \geq Tw_{1t}$

$$F_3 = \max - \left[\sum_{t=1}^{T} (Sw_{2t})^2 \right] \tag{8}$$

$Sw_{2t} = Tw_{2t} - u_{2t}$; for $u_{2t} < Tw_{2t}$
$Sw_{2t} = 0.0$; for $u_{2t} \geq Tw_{2t}$

$$F_4 = \max - \left[\sum_{t=1}^{T} (Sw_{4t})^2 \right] \tag{9}$$

$Sw_{4t} = Tw_{4t} - u_{4t}$; for $u_{4t} < Tw_{4t}$
$Sw_{4t} = 0.0$; for $u_{4t} \geq Tw_{4t}$

$$F_5 = \max - \left[\sum_{t=1}^{T} (Sw_{5t})^2 \right] \tag{10}$$

$Sw_{5t} = Tw_{5t} - u_{5t}$; for $u_{5t} < Tw_{5t}$
$Sw_{5t} = 0.0$; for $u_{5t} \geq Tw_{5t}$

Where,

- u_{it} =i-th reservoir release during period t;
- X_{it} =i-th reservoir storage at the beginning period of t;
- $X_{i,t+1}$ =i-th reservoir storage at the end period of t;
- P_t =Total hydro-energy generated during period t;
- $G^i(\cdot)$ =Energy generation function of the i-th power plant;
- Sw_{it} =Shortage of water supply from the i-th reservoir during period t;
- Tw_{it} =Target firm flow from the i-th reservoir during period t;
- i =subscript i stands for each reservoir or power plant

(1=Hwachon, 2=Soyang, 3=Chungju Main, 4=Chungju R/R, 5=Paldang);

Then the model for the Han river basin, H3DP, can be expressed as the following vector optimization problem subject to system state equations and corresponding system boundary constraints :

$$F = Max[w_1 F_1 + w_2 F_2 + w_3 F_3 + w_4 F_4 + w_5 F_5] \tag{11}$$

Subject to,

$$u_{it} = X_{it} - X_{i,t+1} + I_{it} - E_t(X_{it} - X_{i,t+1}) - D_{it} + R_{ij}u_{it} \text{ ; for } t=1, \cdots, T, \; i=1, 2, 3 \tag{12}$$

$$u_{4t}=I_{4t}+u_{3t}-E_t(X_{3t})-D_{4t}$$
$$;\ \text{for } t=1,\cdots,T,\ i=4 \qquad (13)$$

$$X_{it\,\min}\leq X_{it}\leq X_{it\,\max}$$
$$;\ \text{for } t=1,\cdots,T+1,\ i=1,2,3,4 \qquad (14)$$

$$u_{it\,\min}\leq u_{it}\leq u_{it\,\max}$$
$$;\ \text{for } t=1,\cdots\cdots,T,\ i=1,2,3,4 \qquad (15)$$

Where,

I_{it} =Reservoir inflow to i-th reservoir during period t;

$E_t(X_{it},\ X_{i,t+1})$=Volume of evaporation loss from i-th reservoir during period t as a function of average surface area of the i-th reservoir during the period;

D_{it}=Water depletion from upstream of the i-th reservoir during period t;

R_{ij} =System configuration matrix (N*N vector);

w_k =Weightig factor for k-th objective, k =1, 2, 3, 4, 5;

The developed H3DP model optimizes the monthly operation of the Hwachon and Soyang Projects on the North Han river and Chungju Main Project on the South Han river. Since the Chungju Re-regulation reservoir is considered as a flow-through reservoir, its storage level is assumed to be constant. Objectives of flood control and direct depletion for diversion are considered as fixed constraints in the model. The other flow-through reservoir, Paldang, which is located at the confluence of the North and the South Han rivers, is considered as control point (basin firm water supply) due to its important functions as a principal water depletion site for the downstream lower Han river basin where the Seoul Metropolitan area is located.

3. Model Structure and Input Data

The H3DP model structure consists of user-supplied subroutines READIN, STATE, OBJECT, POWER, FIRMEW, and XPRINT. This model is an upgraded version of the previous HYDRODP model developed by KOWACO (Ko et al.,1991). The one-dimensional HYDRODP model is designed for single reservoir and optimizes monthly reservoir operating policies for Chungju Reservoir.

The CSUDP main program computes the optimal value of the recursion relationship using the user-defined subroutines. Subroutine STATE computes the state transition equation by calculating monthly evaporation of each reservoir and releases from the upstream three reservoirs. Subroutine OBJECT computes the individual stage hydro-energy and water supply related objective functions. Subroutine READIN reads input problem specific data from file H3DP.ADD. Subroutine XPRINT outputs user-customized results to file H3DP.RES. Subroutines POWER is called from Subroutine OBJECT to calculate power and energy from each hydro-power plant considered in the system. Subroutine FIRMEW is called from Subroutine XPRINT to output firm energy and firm water at the final stage of the system analysis. The H3DP.DAT file contains the control data for the dynamic programming using the IDP algorithm. The other input data file, H3DP. ADD, is supplied by the user for additional problem specific input. The H3DP.ADD file contains physical and operational reservoir and hydropower plant data that will not change, as well as, hydrologic and operational data that will be changed to specify the alternative operations.

4. Model Calibration and Verification

Based on the problem formulation for the Han river reservoir system optimization and the corresponding input data files, calibration and verification of the H3DP verified that the model had the ability to closely represent the physical processes. Two years (1992 and 1993) of monthly inflow data, reservoir and hydropower plant operation data were chosen for this work. Calibration was initiated using 1993 inflow data together with the reservoir and power plant operation record. Verification was performed using a different set of flow and operational records for 1992. Incremental local flow between three upstream reservoirs and the downstream control point (Paldang) was calculated by subtracting upstream reservoir release records (Hwachon, Soyang, and Chungju R/R) from observed inflow records at Paldang. Initial and final storages of each reservoir were adopted as boundary conditions of the system based on their historic record and each reservoir's beginning of the month storage was input as initial storage trajectories.

IV. Application to the Han River Basin

1. Performance Evaluation for Initial Set of Objectives

In this case study, reevaluation and other alternative analysis of Hwachon hydropower dam and reservoir operation for multipurpose use were carried out. A monthly time step for a one year operation period was selected. The analyses were based on 1993 hydrologic conditions.

Table 1 is an initial set of six reservoir system operation alternatives based on the defined five objectives. The evaluation results based on these alternatives are summarized in Table 2. The evaluation results reveal that Alternatives 1, 2, and 4 are not feasible due to large water supply shortages at the Paldang area. Alternative 3 also is not a viable strategy because of its low hydro-energy production. Among the remaining Alternatives 5 and 6, Alternative 6 has less annual

Table 1. Initial set of reservoir system operation alternatives

Alternative	Scenario of configuration	$w_i(F_i)$
1	Maximize basin hydro-energy production only	$w_1(F_1)=1.0$
2	Maximize firm water supply from the three upstream reservoirs only	$w_i(F_i)=0.2$ for i=2,3,4
3	Maximize firm water suply at downstream Paldang reservoir only	$w_5(F_5)=0.3$
4	Combination of Alternatives 1 & 2	$w_1(F_1)=1.0$ $w_i(F_i)=0.2$ for i=2,3,4
5	Combination of Alternatives 1 & 3	$w_1(F_1)=1.0$ $w_5(F_5)=0.2$
6	Combination of Alternatives 1, 2 & 3	$w_1(F_1)=1.0$ $w_i(F_i)=0.2$ for i=2,3,4 $w_5(F_5)=0.3$

Table 2. Summary of evaluation results for reservoir system operation alternatives

Alt.	Energy (GWh)	Water supply (MCM/yr)	Annual water supply shortage(MCM)			
			Hwachon	Soyang	Chungju	Paldang
1	1957.8	16581.2	—	288.8	119.8	778.6
2	1835.9	16582.6	—	—	—	283.0
3	1805.4	16582.0	0.2	503.6	3.3	—
4	1922.2	16585.1	—	—	—	113.6
5	1938.9	16584.0	12.7	250.0	51.7	—
6	1920.2	16585.3	—	—	—	—

energy production than Alternative 5, but has no water supply shortage from the three upstream reservoirs and at the downstream Paldang area. Considering the increased importance of maintaining firm water supply in the basin, Alternative 6 was selected for further case study examination.

2. Reevaluation of Multipurpose Use of the Hwachon Hydropower Reservoir

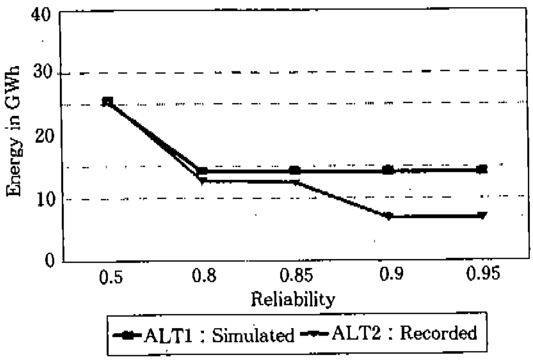
Considering rapidly increasing water demand, and a scarcity of large-scale storage development sites in the basin, it is important to operate all the large scale reservoir system in a truly multipurpose fashion to improve current operational efficiencies of the existing system.

Although the Hwachon reservoir in the North Han river has been constructed with effective storage of 940.7 MCM, the project has been operated by KEPCO for hydropower purposes only. In this case study, the Hwachon project was reevaluated as a component of the upstream multipurpose storage reservoirs based on 1993 hydrology and the initial and final reservoir operation conditions. Based on the project's water supply capacity, target monthly water supply by Hwachon was assumed as 31.7 CMS. The comparison of the results of monthly energy production, and firm energy and water supply between the simulated results and the operation records is summarized in Table 3. and displayed

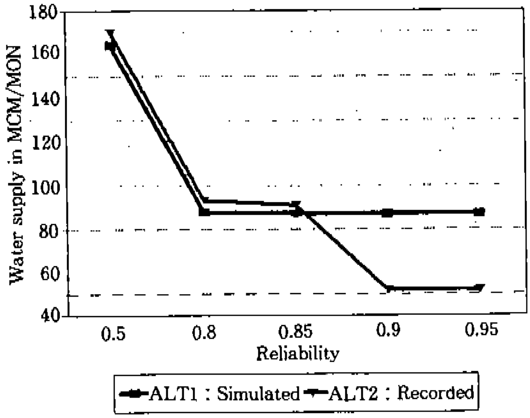
Table 3. Comparison of operation results of Hwachon Project

Classification		Optimization	'93 Operation	Increments	Ratio (%)
Annual energy production(GWh)	Hwachon	432.5	405.5	27.0	6.7
	Basin[1]	1970.6	1845.2	124.5	6.8
95% firm energy (GWh/Mon)	Hwachon	14.1	6.8	7.3	107.4
	Basin[1]	81.4	71.8	9.6	13.4
95% firm water (GWh/Mon)	Hwachon	86.9	51.8	35.1	67.8
	Basin[1]	480.2	422.0	58.2	13.8

Note 1) Sum of operation results from Hwachon, Soyang and Chungju storage projects.



(a) Firm energy



(b) Firm water supply

Fig. 2. Comparison of firm energy and water for Hwachon Project

in Fig. 2.

The results show that by operating the Hwachon project in an integrated, multipurpose fashion, the annual energy from Hwachon resulted in 432.5 GWh which is a 6.7 % increase over the historic operation. Moreover, the 95 % firm energy and water have drastically increased by 107.4 and 67.8 %, respectively, compared to the historical operation record.

V. Conclusions

Case studies for the Han river reservoir system operational planning by using the H3DP model which is upgraded from HYDRODP model were performed. Conclusions based on the considered fiven objectives were the follows :

1) Performance of the multi-reservoir system has shown that Alternative 6, which considered objectives for basin hydro-energy and firm water supply from the three upstream reservoirs and at the downstream Paldang reservoir, was the most appropriate scenario among the six alternatives.

2) Reevaluation of the Hwachon project as a component of the multipurpose storage reservoirs in the system showed the practical possibility of deriving optimal integrated multi-reservoir system operational strategies for the basin.

Nondominated solutions for further tradeoff analysis to assess the variability of system benefit from a multi-reservoir system with ease by parametrically changing the assigned weights for water management objectives and running H3DP model.

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