An Optimization Model to Mitigate Conflicts in the Geum River Basin, Korea

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Abstract

The Geum River basin, one of most important river basins in Korea, is located in the South Central portion of the country. Water conflicts have erupted in the Geum River basin twice recently, during the droughts of 1995 and 2001. These recent events have accentuated the need for careful planning in the basin and focused attention on the conjunctive operation of Daechong Dam and the Yongdam Dam (constructed in 2001). This paper describes the development of an optimization model that enhances understanding of water planning in the basin and provides a disciplined method for developing and comparing robust and reliable reservoir operation alternatives for the Geum River basin. The mathematical objective function of the model is to minimize the maximum difference between supply and demand subject to constraints representing: (1) conjunctive dam operation, (2) instream flows downstream of the dams, and (3) increasing water demands in Jonju area. Stochastic constraints, as well as deterministic constraints, are included to develop robust operating alternatives. Most significant among the uncertainties that must be included in the models are those associated with future water demands and streamflow forecasts.

Introduction

The Geum River basin (Figure 1) contains 9,810 square kilometers and has a mainstem length of 396 kilometers. Two major dams are located on the Geum River. Daechong Dam (which creates a reservoir of approximately 1,500 million cubic meters) provides water to several major cities including Daejon, Chongju and Chonan. Upstream of Daechong Dam is Yongdam Dam. This dam was completed in 2001 and creates a reservoir of approximately 815 million cubic meters. Both dams play a key role in flood control, hydropower production, water supply, and irrigation. The construction of Yongdam Dam and its subsequent operation have raised many of the classical conflicts associated with upstream vs. downstream water use, in addition to concerns about instream flow requirements for fish.

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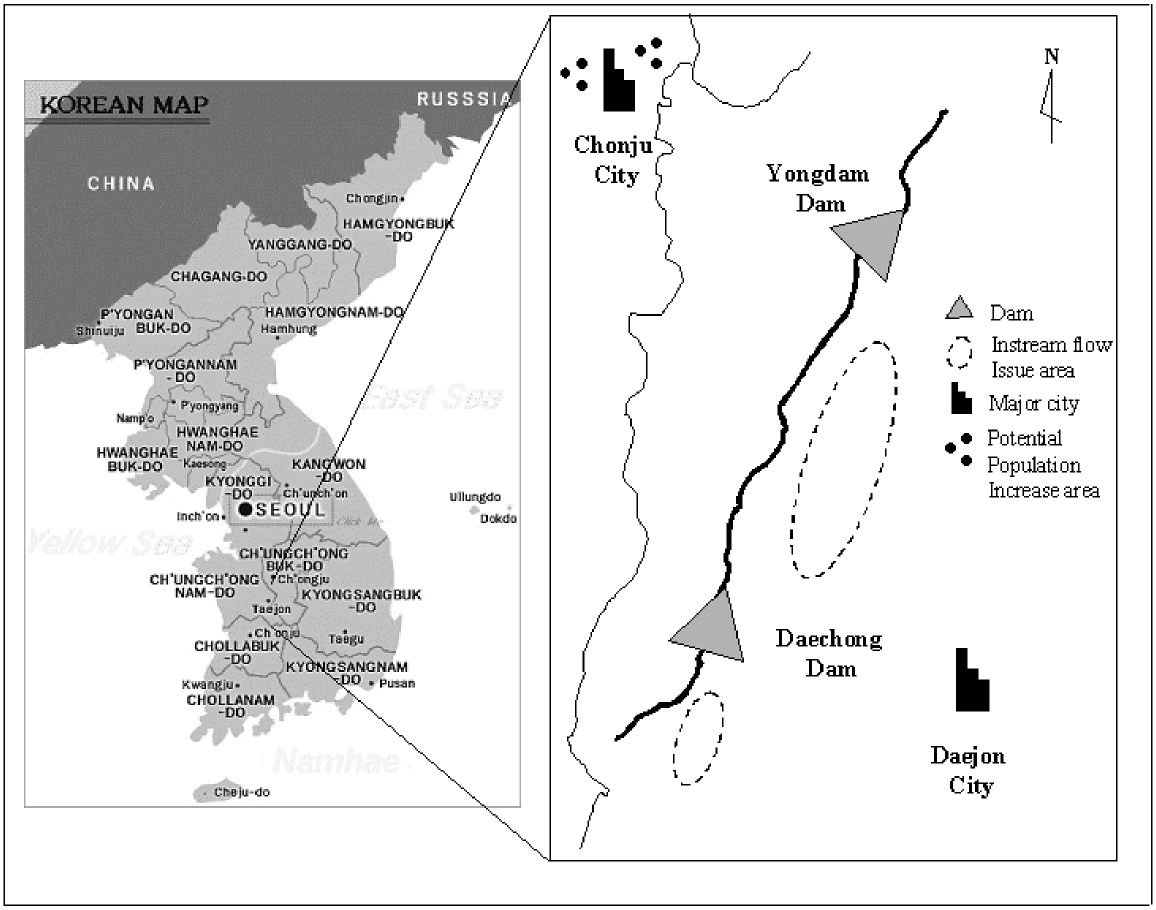

Figure 1. Map of Water System in Kum River Basin

There are three primary issues around which conflict has centered. The first issue is the quantity of water released from Yongdam Dam. Two target values have been suggested, 5.4 m^3/sec and 12 m^3/sec. This water serves two purposes, to provide instream flows in the stretch of river between the two dams and to provide inflow into the Daechong Dam. The larger the release, the more water available for fish and the more the upstream reservoir supplements the downstream reservoir. Downstream users support the greater target, however, this target can negatively impact the storage available in the Youngdam Dam. The second issue is the release made from Daechong Dam. The environmental flow target for this dam has been suggested to be 21m^3/sec. This release serves to provide water for fish, but is lost to water supply uses. The final issue is the rate of regional growth and the associated water demands. Both regions claim the need for increase water allocations in the future. Much of this debate revolves around water demand forecasts for Jonju, which range from 2.5 to 3.5 million people in the year 2021. Table 1 summarizes some of the basin's major issues.

Previous research focused on modeling water conflicts, identified clear conflicts between the environmental flows established downstream of Daechong and the amount of water that can be diverted for municipal, industrial and agricultural water supply from that dam. There are also clear conflicts between the environmental flows established between the two dams and the ability to supply water from Yongdam Dam. Based on those results, this research focuses on what specific value and appropriate for minimizing maximum deviation between supply and demand. These results provide useful insights to potential operation of the dams. In addition, the results of this study can contribute to refine operational decision in the simulation model developed in phase 1 project period. The remainder of this paper is organized as follows. A brief review of linear program technique used in water resource management is presented. Next, a management problem of models used in water resource conflict is formulated. Then, the solution procedure is described for Geum River basin reservoir systems. This is followed the result of the linear programming model. Finally, future work is described.

Table 1. Major Conflicts in Geum River Basin

	Daechong Dam serving Daejon (Downstream)	Yongdam Dam serving Jonju (Upstream)
Instream flow of between dams	12.4 m^3/s	5.4 m^3/s
Instream flow of downstream of Daechong Dam	21 m^3/s	Less than 21 m^3/s (Need to be reconsidered)
Population forecast for Jonju city	2.5 million	3.5 million
Yongdam Dam Operation	Disagree	Agree

Review of Linear Programming

Optimization models have been widely used in reservoir system studies as well as water allocation studies. Many different methods, such as linear, non-linear, and dynamic programming for water management modeling environment have been developed during last decades. The application of optimization techniques has attempted to automate the process of finding optimal real-time operation policies. Linear programming has been one of the most widely used techniques in water resources management. A typical planning objective might be to minimize the capacity (or the cost) of the reservoir that meets all of the system constraints or to maximize the total net benefit associated with a function of storage and release in each presumed operation period. Dorfman (1962) demonstrated three different version of linear programming with increasing complexity. Yeh (1981) compiled a variety of reservoir management and operation models, and classified several different types of linear programming including chance-constrained linear programming, stochastic linear programming, and stochastic programming with recourse. Furthermore, Jenkins et al. (2000) has applied linear programming to an economic-engineering modeling approach associated with shortage management options. When these models are applied, the time step mainly depends on model framework. For this study, weekly time step have been used to monitor drought behavior.

Model Application

The remainder of this paper focuses the application of a linear programming on water conflict resolution model to Geum River basin in Korea. The purpose of this research is to assess an existing plan, to develop alternatives for the management of water resources in the region, and to resolve the water conflict based on an appropriate mechanism for implementing the plan.

As mentioned previously, there are a number of operational issues associated with the current water resources conflict in the Geum River basin. Instream flows downstream of Daechong Dam and instream flows between reservoirs are under debate and distinctly different values are being suggested. The construction of Yongdam Dam and the continued growth in this basin has created the need to address a number of fundamental water resource questions. The models developed in this research address specific planning issues that must be obtained in the basin. These issues include: 1) An appropriate instream flow target below the Daechong dam and between dams; 2) Benefits of stochastic inflow and demand; and 3) Most appropriate instream flow target during drought in this basin. These general concerns can be framed into a series of questions that explore system operation and management, including:

1. What is an appropriate value of instream flow target below the Daechong dam without Youngdam dam?
2. What is an appropriate value of instream flow target between dams?
3. How are these two instream flow targets related?
4. If stochastic inflows or/and stochastic demands are incorporated into model, will they impact the appropriate instream flow?
5. What are the benefits of stochastic variables in this research?

Development of the Model

Two types of reservoir operation models were applied in this study. To determine the safe yield from Daechong reservoir during drought, an optimization model is applied using the yield modeling concept (Locks et al. 1981). If the coefficient of safe yield is greater than one, the entire period is classified as a “normal year.” Otherwise, it is classified as a “drought year.” The most severe drought on record for these basins occurs in 1994. Therefore, a weekly operating policy was produced by the model that accepted equally large deviations from the target during the drawdown period in 1994. Although this policy would not be followed in practice, it provides a clear indication of the quantity of reductions that would be necessary during the drought of 1994. As water conservation and curtailments are enforced during within-year period, future reservoir operations would be modified.

This analysis involved three distinct steps. The first step evaluated the system with only the Daechong Dam and the releases associated with instream flow, hydropower, and M&I demands. The second step involves conjunctive dam operation satisfying water demands for both systems. The third step involves stochastic variables, such as stochastic inflows and demands incorporated into optimization model.

Geum River Basin Optimal Policy

Objective Functions

Deviation of supply from demand can be characterized in variety of ways; three common expressions are the least square, the simple error, and the min-max error. These characterizations can be introduced mathematically as:

$$Minimize \sum_{t=1}^{T}\left[supply - demand\right]^2 \quad . \tag{1}$$

$$Minimize \sum_{t=1}^{T}\left|supply - demand\right| \tag{2}$$

$$Minimize \max_{t=1,\ldots,T}\left|supply - demand\right| \tag{3}$$

where supply is a function of the current reservoir storage and current inflow, and demand is a function of hydropower, instream flow, municipal and industrial water use. The third approach, minimizing the maximum weekly shortfall is chosen as the most appropriate objective for this study. This objective focuses on operating a system so that the magnitude of a "worst case scenario" (an extremely large deviation from a demand) is minimized.

Geum River System

The Geum River model optimizes operation over one year, at a weekly time step (Figure 2). The system supplies water for irrigation, power generation, instream requirement, and municipal and industrial demand. The amount of water in each reservoir is denoted as $S_{i,t}$, for reservoir index i = 1, 2, and time t = 1, 2, …, 52, where each S_i is expressed in normalized units (million cubic meter per week).

The model's objective is to minimize the maximum deviation between supply and demand. Two additional variables are incorporated. U_1 and U_2 represent maximum deviation between supply and demand for Youngdam and Daechong system, respectively. Since the hydropower release and instream flow coexist, it can be denoted as one variable

G. the value of G should be greater than sum of hydropower release and instream flow target. This objective function can be written as:

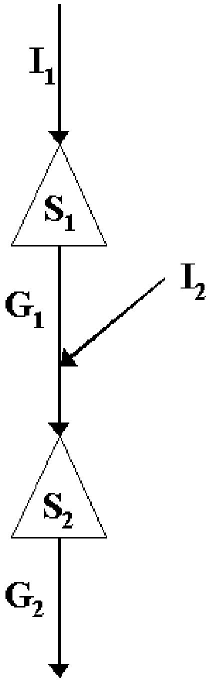

Figure 2. Schematic of Geum River System

$$Minimize\ U_1 + U_2 \tag{4}$$

subject to additional variable and constraints.

$$U_1 \geq \left| S_{1,t} + I_{1,t} - G_{1,t} - DP_{1,t} \right| \tag{5}$$

$$U_2 \geq \left| S_{2,t} + I_{2,t} + G_{1,t} - G_{2,t} - DP_{1,t} \right| \tag{6}$$

$$G_{1,t} \geq (DH_{1,t} + DF_{1,t}) \tag{7}$$

$$G_{2,t} \geq (DH_{2,t} + DF_{2,t}) \tag{8}$$

Where,

$S_{1,t}$: *Youngdam storage at given time t*

$S_{2,t}$: *Daechong storage at given time t*

$I_{1,t}$: *Yongdam inflow at given time t*

$I_{2,t}$: *Daechong inflow at given time t*

$DH_{1,t}$: *Yongdam Hydropower requirment at given time t*

$DH_{2,t}$: *Daechong Hydropower requirment at given time t*

$DF_{1,t}$: *instreamflow between dams at given time t*

$DF_{2,t}$: *instreamflow below Daechong dam at given time t*

$DP_{1,t}$: *Yongdam M & I demand at given time t*

$DP_{2,t}$: *Daechong M & I demand at given time t*

Constraints

The aforementioned objective function is subject to the following constraints.

1. Water levels at the end of a period must be higher than the minimum level (dead storage) and lower than reservoir operation rule curve regarding flood control,
2. All diversion facility and power plant turbine capacity determine the maximum diversion and release from each reservoir, and
3. Minimum instream flow below each dam must be satisfied.

For the 1994 drought period, the specific input information to optimization model run are: (1) The instream flow sequence during 1994; (2) the appropriate reservoir operation rule for each dams over historical period; (3) the known municipal and industrial water demand at 1994; (4) the facility information of both diversion and power plant equipment capacity; (5) the suggested minimum instream target flow; (6) stochastic inflow and water demand. The model decision variables include instream flow below the Daechong dam and between dams, and instream flow associated with uncertain inflow and water demand. The optimization model was coded in MATLAB® (linear programming toolbox).

Analysis Output

Each of the six management questions is answered in turn and is described below.

Fish flow below Daechong Dam

For the 1994 drought scenario, the maximum quantity of water that can be delivered down stream of Daechong Dam while meeting all of the municipal and industrial (M&I) water demand is 21 cubic meters per second (m^3/s). This assume that the Yongdam Dam he not yet been constructed. This does not imply that 21 m^3/s is optimal for fish, only that if more the 21 m^3/s is required to remain in the stream, shortfalls to M&I demand would occur.

Fish flow between dams

Because of water quality concerns, the flow between the two dams is very important. The flow established can help the system support the upstream and downstream M&I water demands and the fish flow demands below Daechong. If the the instreamflow is too great, the water supply reliability of the Yongdam Dam will be compromised. If the value is too small, water will be needlessly storage upstream and not made available to the down users. Tentative model results suggest that an instream flow of 12.4m^3/s between the two reservoirs provides an appropriate compromise between upstream and downstream uses. This value allows both reservoirs to meet their respective M&I demands and to maintain the instream flow target below Daechong Dam. In addition, the result from optimization with conjunctive operation shows that 4 m^3/s more water can be allocated to instream flow below Daechong dam. This additional flow is a regional benefit of conjunctive operation and the existence of Yongdam Dam.

Impact of Stochastic input on the value of instream flow

To begin the process of evaluating the impacts of stochastic and uncertain parameter values, a sensitivity analysis was performed on inflow and future water demand. Table 2 shows that the possible distributions of stochastic input for each run. When the only variable modified is the inflows into the system for the 1994 drought, the optimal instream flows between the dams remains at 12.4 m^3/s. This indicates that there is sufficient storage and inflows to meet the current demands, even if the inflows are significantly reduced. Similarly, if demands are increased, there are still no deviations and the optimal flow between the dams remains close to 12.4 m^3/s. However, if inflows are decreased and demands are increased, it is best to reduce the water that flows between the dams.

Table 2. Possible distribution of stochastic inflow and demand

Inflows (% change) Corresponding to year 1994 drought condition	Demand (% change) Corresponding to year 1994 drought condition	The value of instream flow between dams, m^3/s
20% decrease	No change	12.4
50% decrease	No change	12.4
No change	20% increase	12.3
No change	50% increase	12.3
20% decrease	20% increase	11.2
20% decrease	50% increase	8.0
50% decrease	20% increase	6.5
50% decrease	50% increase	5.4 m^3/s

Furthermore, if inflows are decreased by 50% and demands are increased by 50%, the instream value between dams drop to 5.4m3/s, which is the minimum value that system allows, as defined as an operational constraint. It is noted that determining instream flow between dams is crucial to resolve water conflict.

Implications of the Results on Conflict Resolution

This analysis illustrates some of the benefits that can be obtained during drought years similar to 1994 by the construction of the Yongdam Dam. The advantage of a model such as the one developed in this research is that these values of instream flow during drought can be clearly illustrated to stakeholder groups to support decision making. Since uncertain inflows and demands play a key role in real decision making, they should be integrated in modeling framework. To further enhance the modeling capability associated uncertain variable, short-term (3 month or 6 month) stream flow and water demand forecast will be useful indicator to resolve current water conflict more efficiently. For example, a variety of forecast scenarios associated with stochastic variables can be incorporated into linear programming to obtain appropriate instream flow to minimize the maximum deviation between supply and demand. Some range of instream flow would be predicted and tested. The system behavior would be monitored and evaluated continuously at a prescribed time step (such as weekly). Appropriate instream flow would be also updated during prescribed time period. Subsequently, if the system state deteriorates more than anticipated, a new round of optimizations would be performed and a new instream established. This approach can be triggered to not only minimize the maximum deviation between supply and demand, but also maximize system reliability particularly during drought.

Future Work

With the completion of the optimization model of the Geum River basin, the authors anticipate continued efforts to evaluate potential water management trade-offs in the basin and the opportunity to work with stakeholders to better incorporate regional considerations, constraints, and objectives. Because the establishment of environmental flows will have a significant impact on system yield and because the region continues to grow, the conflicts will worsen unless cooperative solutions can be reached.

A number of improvements, enhancements, and new directions can be taken to provide increased decision support in the Geum River basin. These new directions may include:

- Development of short-term inflow forecast,
- Development of a multi-objective programming to support system operation and management during periods of low flow,
- Development of a detailed Drought Management Plan to support system operation and management during periods of low flow,

- Advanced analysis of the influence that instream flow requirements have on system safe yield, and

- Stochastic optimization based on diverse forecast indications.

- Identify instream flow during normal condition

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References

Dorfman, R., Mathematical models: The multi-structure approach, in *Design of Water Resources Systems*, edited by A. Maass, Harvard University Press, Cambridge, Mass., 1962.

Jenkins, M. W., Lund, J. R., Integrating Yield and Shortage Management under Multiple uncertainty, Journal of Water Resources Planning and Management, 126(5), 288-297, 2000

Loucks, D. P, Stedinger, J. R., Haith, D. A., Water Resource Systems Planning and Analysis, Prentice-Hall, Inc, Englewood Cliffs, New Jersey, 1981.

Yeh, W. W-G., Reservoir Management and Operations Models: A State-of-the-Art Review, Water Resources Research, 21(12), 1797-1818, 1985.