

## Development of multi-objective reservoir operation rules for integrated water resources management

T. S. Cheong, I. Ko and J. W. Labadie

### ABSTRACT

Real-time monitoring, databases, optimization models and visualization tools have been integrated into a Decision Support System (DSS) for optimal water resources management of two water supply reservoirs, the Daechung Reservoir and the Yongdam Reservoir of the Geum River basin, Daejeon, Korea. The KModSim as a DSS has been designed to provide information on current reservoir conditions to operational staff and to help in making decisions for short- and long-term management. For the physical calibration, the network simulations in seasonal water allocation of both reservoirs are performed for 23 years from January 1 1983 to June 30 2006. Linear and nonlinear operating rules are developed by using the actual reservoir operation data obtained from both reservoirs which are then used in KModSim by the hydrologic state method to estimate optimized target storages of both reservoirs. For validation of hydrologic states in KModSim and scenario testing for the management simulations, the optimal network simulation for the seasonal water allocations from October 1 2002 to June 30 2006 were also performed. The results' simulation by new rules fit the measured actual reservoir storage and represent well the various outflow discharge curves measured at the gauging stations of Geum River. The developed operating rules are proven to be superior in explaining actual reservoir operation as compared to the simulated target storages by existing optimization models.

**Key words** | decision support systems, geographic user interface, network flow simulation, river basin management

### INTRODUCTION

Multi-objective analyses are gaining importance in reservoir management, because of their inherent ability to include different alternative scenarios such as maximization of net benefits, maximization of electric power generation and minimization of water deficit (Chang *et al.* 1995; Raju & Kumar 1999; Palmer *et al.* 1999), for the selection of the best operation alternative. Many studies have been made of multi-objective planning under various conditions (Goicoechea *et al.* 1976; Yeh & Becker 1982; Glover & Martinson 1987; Ko *et al.* 1992; Ridgely & Gianbelluca 1992; Bella *et al.* 1996; Raju & Kumar 1999; Shiau & Lee 2005). The water resources operation of integrated basin systems within reservoirs requires specific operating guide rules for

water conservation and release policies. These rules typically consider the varying states of inflow and physical characteristics of a reservoir in each time period. There are several types of rules for guide curves ranging from simple and static to complex and dynamic, which rule curves usually specify the target storage at the end of each target period. For development of reservoir operating guide rules, linear models are as good as, or sometimes better than, nonlinear models (Bhaskar & Whitlatch 1980). However, Vasiliadis & Karamouz (1994) developed optimal operating policies for integrated water operation derived from a stochastic dynamic programming model.

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doi: 10.2166/hydro.2009.054

Integrated operation of most multiple reservoir systems is a complex and complementary multiple issue affected by social, environmental and political factors. The guidelines for reservoir operation have been used in Daecheong Reservoir, Korea for almost 25 years to reduce operating costs by controlling the overdrawn and recharge of reservoirs. The multi-reservoir operating policies are usually defined by rule curves that specify either the desired individual reservoir target storage volumes or the desired target releases based on the time of year and the existing total storage volume in all reservoirs (Oliviera & Loucks 1997; Thorne *et al.* 2003). Reservoirs can have multiple rule curves made up of summer recharge curves and winter drawdown curves to provide criteria for supply deviations from target conditions. The overall aim of rule curves is to minimize variance from the desired conditions and prevent infringements of the mandatory regulations.

Water management models and decision support systems can play a crucial role in simulation, analysis and adaptation of water management strategies. Such models range from simple models that use a point system, categorization and ranking to evaluate the scores of the various components and strategies of the water resources management (Manios & Tsanis 2006) to more sophisticated decision support systems (Kazeli *et al.* 2003). Nowadays, the importance of sustainable management and management of conflicting purposes for existing water projects and facilities are magnified because of political, economic and environmental obstacles. River basin management DSSs are designed to aid decision-makers or stakeholders in developing a shared vision of planning and management goals, while gaining a better understanding of the need for coordinated operations in complex river basin systems that may impact multiple jurisdictional entities. They allow evaluation of hydrologic, economic, environmental and institutional/legal impacts as related to alternative development and management scenarios.

The more robust river basin DSSs can provide both a planning framework for integrated river basin development and management, as well as aid in real-time river basin operations and control. Although some river basin DSSs are suitable for flood control operations, emergency flood conditions or disaster management generally require more detailed hydraulic and contaminant transport models

operating over short time steps of an hour or less. MIKE BASIN (DHI Water & Environment 2006), IQQM (Hameed & O'Neill 2005), RIBASIM (Delft Hydraulics 2006) and WEAP (Yates *et al.* 2005) are popular river basin management DSSs that have been implemented world-wide in a large number of river basin systems and incorporate most of the desirable attributes of a DSS. As valuable as these DSSs have been for many applications, each lacks effective customization capability, which limits their adaptability to unique river basin conditions, particularly with respect to complex administrative rules and policies.

KWater is developing a prototype DSS for the Geum River basin, Daejeon, Korea from a generalized river basin DSS, KModSim, designed as a computer-aided tool for developing improved basin-wide and regional strategies for short-term water management, long-term operational planning, drought contingency planning, water rights analysis and resolving conflicts among urban, agricultural and environmental concerns. A new DSS integrates the following interactive subsystems: (i) model base management subsystem; (ii) database management subsystem and (iii) dialog generation and management subsystem. The graphical user interface (GUI) connects KModSim with the various database management components and an efficient network flow optimization model. The interface also allows for user-defined output graph generation. This KModSim was developed by adapting and modifying the MODSIM into the KModSim developed specifically for application to the Korean situation. MODSIM is a network flow simulation model that employs optimization techniques to represent water management decisions at each sequential time step in an efficient manner (Faux *et al.* 1986; Law & Brown 1989; Fredericks *et al.* 1998; Leu 2001; Stillwater 2003).

KModSim was developed for real-time simulation of all features of the Geum River basin system that are most appropriate in terms of describing the physical and operational characteristics of the river systems. KModSim is presented as a comprehensive DSS for coordinated operation of multipurpose reservoir systems, conjunctive surface and groundwater management, and water quality management, with full consideration of the legal and administrative mechanisms governing water use. The KModSim network developed in this study was used to

test and evaluate operational scenarios being developed with other components of the DSS. Efforts in applying KModSim to the Geum River basin are for (i) development and calibration of the network due to lack of, or incompleteness in, the available physical, hydrologic and operational datasets; (ii) modify the flow routing routines in KModSim since routing lag times in the basin were in excess of one day and could be as long as five days; (iii) generate both actual and optimal integrated operational rules and targets and (iv) development and testing of various operational scenarios.

The objective of this research is to develop an improved methodology for identifying optimal control rules that ensure the required level of service and allow the allocation of excess water for large conjunctive use systems. Through refinement of the existing operational rules, operated by the Kwater Operation Center (KWater 2007), an optimum balance among environmental impacts/benefits, sustainable resources, drought-reliable yield and electric power generation can be achieved through allocation of water supply via a priority system dependent on storage levels in all reservoirs. For a reservoir operational policy, the historical results are used in this study. Using the actual data of both reservoir systems, monthly reservoir operational guide curves are derived by linear and nonlinear regression analysis of the optimal set of releases, downstream lateral flows and amounts of the trans-basin diversion. The optimal models such as SSDP (Faber & Stedinger 2001; Kim et al. 2001) for monthly target storage and SSDP-CoMOM (Randall et al. 1997; Kim et al. 2005) for daily target storage were also used for identifying optimal control rules. The four objectives evaluated for these optimal models were: maximizing total energy production, maximizing firm energy, maximizing minimum downstream discharges for water supply and water quality maintenance purposes, and maximizing the reliability of satisfying downstream water supply requirements. The hydrologic states' method in KModSim was used to represent the optimal operating rules developed in this research. The operation of the Kwater Reservoir Systems consisting of two reservoirs in the Geum River basin was studied. However, during the development of the revised operational operating rules the monetary cost of supply was not used as a parameter.

## Network development of the Geum River basin

There are two major reservoirs in the Geum River basin, of which the Daechong Reservoir serves approximately three million people living in major cities including Daejeon, Chongju and Chonan and the Yongdam Reservoir located upstream of the Daechong Reservoir serves approximately one and half million peoples in several cities including Jonju. The Daechong Reservoir plays a key role in flood control, the production of hydroelectric power and providing drinking and irrigation water in the regions including the southwestern Chungnam Province. A new network in the Geum River basin contains two reservoirs, 42 major demand nodes, about 40 confluence points and other important locations in the basin. All the pre-existing water rights in the 14 sub-basins are protected after the instream flows are satisfied. Instream flows are defined as the 85% exceedence percentile of natural flows for each sub-basin. Instream flow of the Geum River below the Yongdam Reservoir has been suggested as  $5.4 \text{ m}^3/\text{s}$  and for the Geum River below the Daechong Reservoir it has been suggested as  $21 \text{ m}^3/\text{s}$ . In the upper region of the Geum River basin, increasing instream flow requirements for aquatic habitats, recreational use and increasing water demands need more available water resources and the amount of streamflow is limited, particularly during low streamflow conditions.

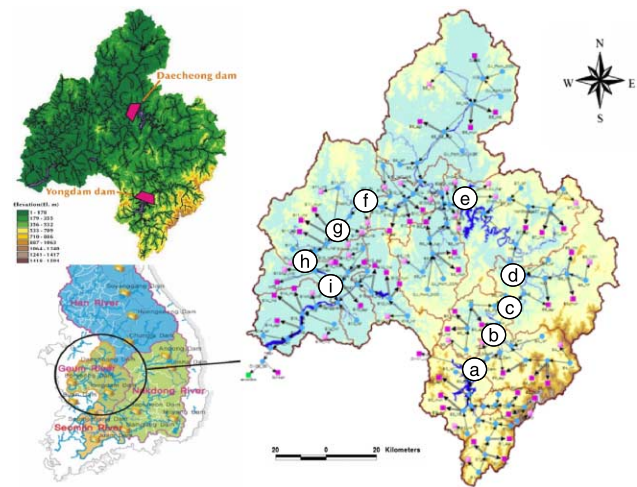
The priorities of water allocation in sub-basins are instream flows, domestic, industrial and agricultural water in descending order. The domestic and industrial water are estimated from records of previous water usage. The amount of return flow for domestic and industrial water is assumed to be 65% of the diversion amount. The agricultural water is estimated from an agricultural consumptive use model and the amount of return flow of agricultural water is assumed to be 35% of the diversion. Lagging of these return flows is not considered, so the return flows are returned to the river in the same time period as the diversion. Operational guidelines and constraints used in the simulation runs with the KModSim model are as follows: the highest priority at the Yongdam Reservoir is on the instream flow requirement in the Geum River and the second highest priority is on the Junju flow. The hydropower generation at Yongdam Dam has the lowest priority. Other important values in the Yongdam Reservoir

were 24 h of hydro-generation, a minimum storage of 68.75 MCM, a normal full storage of 742.5 MCM, a maximum power generation capacity of 59.43 MCM (first power generator) and 16.6 MCM (second power generator). Also hydropower generation in the Daecheong Reservoir has the lowest priority. Other important values in the Daecheong Reservoir were 24 h of hydro-generation, a minimum storage of 451.7 MCM, a normal full storage of 1241.7 MCM and a maximum power generation capacity of 707 MCM.

The network identifies the spatial locations in the system, which are needed for operational purposes and locations. The network was developed to simulate on both monthly and daily time steps. The network priority structures for both time steps are essentially the same, although some additional nodes and data are required in the daily time step to perform the Muskingum channel routing calculations. KModSim includes Muskingum-type or user-specified time-lagged hydrologic streamflow routing capabilities for daily simulation. An innovative backrouting procedure looks ahead to future time periods in order to maintain appropriate reservoir operations, minimize downstream spills and shortages, and ensure legal water allocation under water rights with consideration of time lag delays in delivering releases to downstream water users. Any link can be specified as a routing link. For details on backrouting, see [Labadie \(2004\)](#). The network design for the Geum River basin is illustrated in [Figure 1](#).

## METHODS

In this study, a Rainfall–Runoff Forecasting System (RRFS) for the natural inflows, Sampling Stochastic Dynamic Programming (SSDP) for the monthly target storage, the Coordinated Multi-reservoir Operating Model (CoMOM) for the daily target storage and multi-objective operating rules for the daily and monthly target storage are included in the DSS to evaluate long- and short-term management scenarios, and to forecast the effects from perturbations such as floods and drought. Local inflow is an input and local withdrawals are an output: both of these factors are likely to be unavailable from direct measurement and must be estimated. The most logical approach is then to make the



**Figure 1** | Both monthly and daily networks were developed for the Geum River basin. There are 14 gauging points including two reservoirs and some demand or diversion locations for the 14 sub-basins in the Geum River basin. The routing method was applied for daily simulation which the Geum River was divided by nine reaches such as a: Yongdam Reservoir; b: Sutong; c: Hotan; d: Okcheon; e: Daecheong Reservoir; f: Gongju; g: Seokhwa; h: Gyuam and i: Ganggyeong. Each time step network was individually calibrated to simulate the river basin and compare the simulation results with measured gauge flows at the Gongju point and reservoir storage levels at both the Yongdam and the Daechung reservoirs.

best estimate of the actual data and to make sure that the predicted flows match the trends and general magnitude of the observed data. The data for the upstream flow and the local inflow for the 14 sub-basins were estimated from the RRFS whose model was developed by [KWater \(2007\)](#). RRFS aims to analyze stream flow states at major control points in the main and tributary channels. Since the initial version of RRFS was developed by the Hydrosystems Engineering Center (HEC), the main programs and input data configuration have been upgraded to reflect users' requirements and to allow RRFS to be universally usable. The RRFS is a useful tool to analyze the real-time basin rainfall–runoff including rivers and reservoirs in the Geum River basin.

Stochastic optimization models were developed to derive monthly joint operating rules for the Geum River multi-reservoir system. The optimization models use a Stochastic Dynamic Programming (SDP) approach, called Sampling SDP (SSDP). The SSDP incorporates streamflow scenarios directly into the SDP formulation to reflect various characteristics of the stochastic streamflows. In this study we coupled the ensemble streamflow prediction (ESP) system with a monthly SSDP for the Geum River

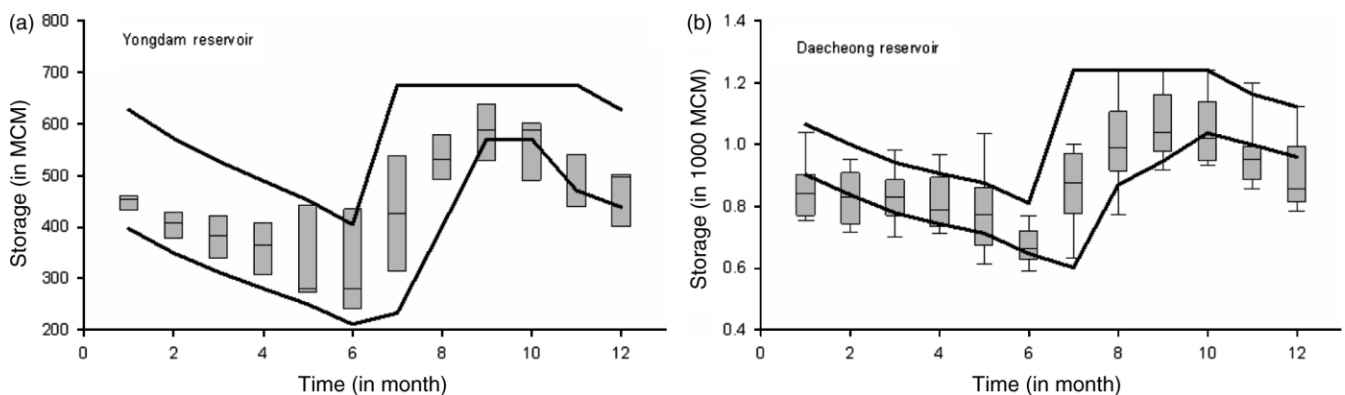
basin. The ESP is a well-known probabilistic forecasting technique in operational hydrology. It currently serves as a key component of the 21st century advanced hydrologic prediction system for the National Weather Service in the United States and has recently become an active research topic (Georgakakos & Krzysztofowicz 2001). In Korea, Kim *et al.* (2001) introduced ESP as an alternative probabilistic forecasting technique for improving the water supply outlook that is issued every month by the Ministry of Construction and Transportation (MCT) of Korea. To generate the ESP forecasts, this study selected RRFs as a rainfall–runoff model, because it is available in the public domain, and also the authors' institute has had experience in successfully applying this model to the same basin from a previous project. The main advantage of the coupled system is that an operating policy can be updated with the new ESP forecasts that are available every month.

The CoMOM was designed to help achieve daily targets in the establishment of reservoir operation policy and in integrated basin water management, and to maximize efficiency in operating reservoirs' daily basis. To evaluate the realistic application of the CoMOM model, a daily simulation under uncertainty is performed, in which the reservoir operation plan from the SSDP model is updated every month. A discrepancy between the actual storage attained and the desired storage suggested by the model is always possible due to the inflow uncertainty. To resolve this discrepancy, the reservoir operation plan from the model is updated every month. The daily simulation is performed assuming that the historical inflow from 1966 to 1996 occurs during the 31-year study period. The 100

inflow scenarios for the stochastic model are generated using the historical inflow statistics. The primary purpose of reservoir operation in Korea is water conservation for safe water supply. The CoMOM therefore included the storage maximization objective and assigned the high precedence value. Keeping a high water level may increase the capability of safe water supply for the future. Nevertheless, a low inflow may result in shortages in water demand if we try to keep the storage level high, whereas a high flow scenario may result in a spill, causing flooding conditions. So the storage level should ultimately be decided based on a trade-off analysis between the possibility of water shortage and spillage. The hydroelectric energy generation maximization is also considered.

### Operating rules

For the operating rules in the KModsim model, the existing operational rule for both reservoirs of the Yongdam and the Daecheong reservoirs are used. Both reservoirs have simple operational guide curves that accurately describe the operation of reservoirs. Figure 2 shows the general operational guidelines for the Yongdam and the Daecheong reservoirs superimposed upon the actual reservoir storage levels. This figure shows that the historical operations of both reservoirs have been variable to meet the demands under different hydrologic scenarios but the general guide curves produce a good simulation of the system for calibration purposes. This leads to an idea of trying to develop the monthly operational rule curves by historical operation results in which both reservoirs are operated



**Figure 2** | General operation guidelines for both the Yongdam and the Daecheong reservoirs superimposed on actual reservoir storage levels; —: general operation guidelines.

between the general guide curves. Historical storage, release and inflow data for both the Yongdam and the Daechung reservoirs were analyzed for 23 years of historical data to develop the operational rules.

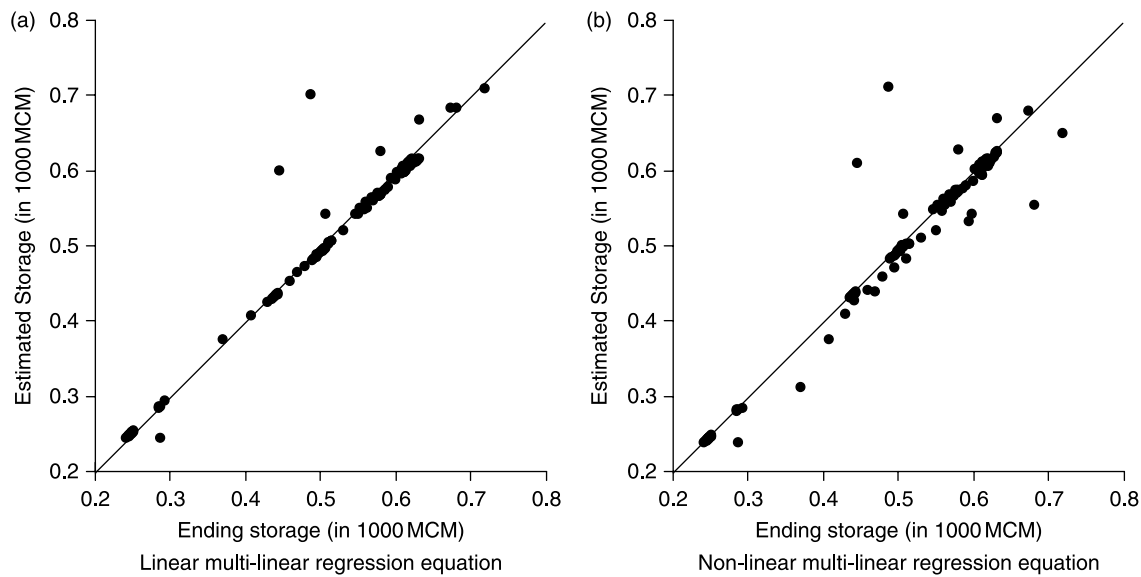
Optimal releases obtained from the historical guide curves are computed based on the independent variables of the inflow and the storage to derive monthly reservoir operating rules. In this study interaction effects were checked by the glmfit and regstats functions of Matlab and *p* values in which the variation in the target storage was significantly affected by inflow ( $p < 0.0001$ ) and storage ( $p < 0.0001$ ). Thus, the inflow and storage are selected to develop the operating rule curve in both reservoirs. The procedure for estimating operational guide curves consisted of a linear and nonlinear regression analysis among the storage, the forecasted inflow, the trans-basin diversion, the downstream release and lateral flows. The general form of a storage rule is  $S_t = \alpha + \beta I_t + \gamma S_{t-1}$  and  $S_t = \alpha I_t^\beta S_{t-1}^\gamma$  in which  $S_t$  is the reservoir storage at the end of the period,

$S_{t-1}$  is the storage at the beginning of each period and  $I_t$  is the current period forecasted inflow. Note that the current period forecasted inflow is an unknown. The historical inflow data are used to derive monthly reservoir operating rules in which the inflows are forecast without errors and regression results are in good agreement with the actual results. It is assumed that the use of the forecasted inflow values will not significantly impact the results of the operational policies. Rule curves used in this study are forms of simple operating policies in which predicted inflows are not used to compute the reservoir target in the coming months. The developed storage rule curves are listed in Table 1. Table 1 shows the monthly regression equations between ending storage and beginning storage.

Figure 3 is an illustration of the results of the regression rule developed from the Yongdam Reservoir data obtained in August in which it can be seen that the tested rule provides a reasonable fit to the data with only a few minor

Table 1 | The regression results for the Yongdam and Daecheong reservoir operating guide rules

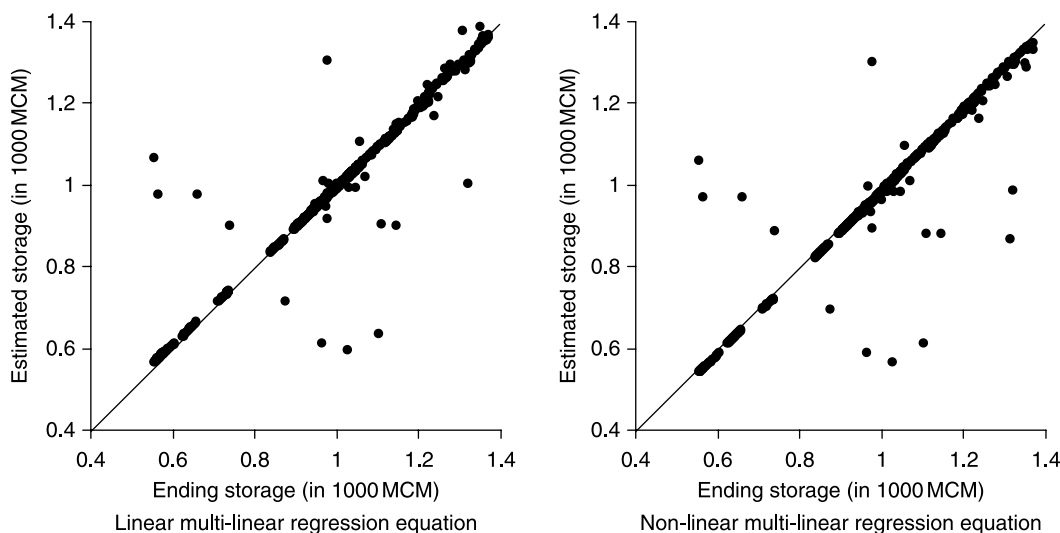
Coef.	Jan	Feb	Mar	Apr	May	Jun	Jul	Sep	Agu	Oct	Nov	Dec
<i>Daecheong reservoir target storage <math>T = \alpha I^\beta S^\gamma</math></i>												
$\alpha$	0.260	0.248	0.272	0.347	0.387	0.900	0.799	0.553	0.897	0.425	0.348	0.435
$\beta$	0.009	0.005	0.007	0.010	0.010	0.015	0.031	0.019	0.028	0.017	0.008	0.017
$\gamma$	0.961	0.962	0.958	0.946	0.940	0.859	0.870	0.914	0.863	0.936	0.948	0.934
$R^2$	0.987	0.986	0.983	0.982	0.980	0.974	0.953	0.976	0.953	0.974	0.971	0.974
<i>Daecheong reservoir target storage <math>T = \alpha + \beta I + \gamma S</math></i>												
$\alpha$	24.14	26.19	24.56	31.77	31.39	69.49	48.43	59.22	69.09	38.97	34.82	35.07
$\beta$	2.222	1.019	0.840	0.949	1.289	0.834	0.840	0.687	1.024	1.777	2.101	7.622
$\gamma$	0.961	0.962	0.958	0.946	0.940	0.859	0.870	0.914	0.863	0.936	0.948	0.934
$R^2$	0.987	0.986	0.983	0.983	0.982	0.975	0.955	0.986	0.973	0.974	0.972	0.974
<i>Yongdam reservoir target storage <math>T = \alpha I^\beta S^\gamma</math></i>												
$\alpha$	0.142	0.144	0.134	0.134	0.258	0.267	0.567	0.307	0.511	0.213	0.240	0.223
$\beta$	0.007	0.004	0.004	0.017	0.026	0.026	0.022	0.024	0.036	0.002	-0.001	-0.002
$\gamma$	0.961	0.962	0.958	0.946	0.940	0.859	0.870	0.914	0.863	0.936	0.948	0.934
$R^2$	0.969	0.969	0.967	0.964	0.968	0.922	0.940	0.957	0.950	0.968	0.967	0.965
<i>Yongdam reservoir target storage <math>T = \alpha + \beta I + \gamma S</math></i>												
$\alpha$	8.320	8.885	4.484	7.566	7.030	7.224	26.47	14.86	31.72	19.59	35.08	24.21
$\beta$	-0.03	-0.23	1.703	1.134	2.860	1.155	0.722	1.068	3.871	-0.451	-12.52	-6.851
$\gamma$	0.961	0.962	0.958	0.946	0.940	0.859	0.870	0.914	0.863	0.936	0.948	0.934
$R^2$	0.969	0.970	0.967	0.966	0.971	0.938	0.954	0.965	0.964	0.972	0.968	0.968



**Figure 3** | Historical operation rules for the Yongdam reservoir observed in August.

outliers. The fitting results of the rules for each month and the corresponding  $R^2$  values from the multi-linear and nonlinear regression analysis are provided in which correlation coefficients  $R^2 = 1 - SSE/SST$ , where  $SSE$  is sum of the squared errors of prediction and  $SST$  is the total variation in the provided flow values. The  $R^2$  values shown in Table 1 range from 0.922 in June to 0.969 in January. Figure 4 is an illustration of the results of the monthly hydrologic states for Daecheong Reservoir which it can be

seen that the tested rule provides a reasonable fit to the data with only a few minor outliers. The fitting results of the rules for each month and the corresponding  $R^2$  values from the multi-linear and nonlinear regression analysis are provided. The  $R^2$  values are shown in Table 1 range from 0.953 in July to 0.987 in January. To evaluate the overall performance of the guide rule curves, the KModSim river basin simulation model was used. The KModSim model allows the user to include the priorities of meeting the various demands and



**Figure 4** | Historical operation rules for the Daecheong reservoir observed in August.

the desire to maintain target storage levels in the reservoir. The hydrologic states' technique in KModSim was tested in this study.

### Hydrologic states

KModSim is designed to easily incorporate the operational policies from various other models for identifying opportunities to evaluate long- and short-term management scenarios, and to forecast effects from perturbations such as drought and pollutant accidents. Associated with each of these states is a corresponding set of reservoir operating rules with associated ranking priorities. In this study, the same priorities of states are used. The hydrologic states are computed at the beginning of each period for the user-selected reservoir subset through the following analysis:

$$R_{tm} = \sum_{i \in H_m} [S_{it} + F_{it}] \quad (1)$$

$$W_{tm} = \sum_{i \in H_m} S_{i,\max} \quad (2)$$

in which  $H_m$  is the set of node numbers of reservoirs in a specified subset defining hydrologic state designation  $m$ ;  $t$  is the current period of operation;  $F_{it}$  is a runoff forecast for reservoir  $i$  at period  $t$ ;  $S_{it}$  is the beginning storage in reservoir  $i$  at period  $t$  and  $S_{i,\max}$  is the maximum storage capacity for reservoir  $i$ . If inflows are already added to develop the operating rule  $F_{it}$  should be zero or if inflows are not added to develop the operating rule then  $F_{it}$  is inflow data into the reservoir whose inflows are usually forecast from runoff data. The ranges for each hydrologic state designation are defined by user input boundary factors  $\beta_{i\tau m}$  ( $i = 1, \dots, n - 1$ ) as fractions of total subsystem storage capacity,  $0 \leq \beta_{1\tau m} < \dots < \beta_{i\tau m} < \dots < \beta$  for seasonal period  $\tau$ , where  $\tau$  is the calendar month or day for monthly or daily time steps in the simulation. Boundaries dividing the hydrologic state ranges are then calculated as

$$B_{i\tau m} = \beta_{i\tau m} W_m \quad \text{for } i = 1, \dots, n - 1 \quad (3)$$

$$B_{n\tau m} = W_m \quad (4)$$

in which  $n$  is the number of hydrologic states in designation  $m$ ;  $B_{i\tau m}$  is the upper bound on hydrologic state  $i$  for period  $\tau$ ; period  $t$  is assumed to be in calendar month or day and

reservoir targets are constant with these hydrologic states. Conditional target storage levels can only vary within a computational cycle (i.e. one year for monthly time step simulation), although separate target storage levels can be specified for each hydrologic state. KModSim also allows differing priorities to be specified for any reservoir node corresponding to hydrologic state conditions as calculated by the above procedure.

Target storage levels can be input as a time series of ideal storage levels, or as a set of rules conditioning target storage settings on user-defined system state information at the current time step. The former approach is often utilized for calibrating the KModSim by specifying target storage levels as measured historical data and then adjusting various parameters in the KModSim to match available stream gauge records. The use of system state information is valuable for management runs of KModsim after calibration is completed. KModSim computes system states by considering current reservoir storage levels and current period inflows to a certain user-specified subset of reservoirs in the system that are indicative of hydrologic conditions in the basin. For several different hydrologic states, seven storage levels are considered in which the historical actual storage data were divided from minimum storage level to maximum storage level. Regression equations for storage level forecast in each month were developed by considering current reservoir storage levels and current inflows into the reservoir. Seven different hydrologic state subset designations are specified by linear interpolation analysis. Figure 5 shows the hydrologic states for storage level forecast in July of the Daecheong Reservoir which the actual storage data of 23 years from 1983 to 2006 were used to define seven hydrologic states.

Figure 6 shows the seven different hydrologic state values of each month designed for the Yongdam Reservoir. Figure 7 shows the hydrologic states for storage level forecast for each month in the Yongdam Reservoir where the actual storage data of 23 years from 1983 to 2006 were used to define seven hydrologic states. Figure 8 shows the seven different hydrologic state values of each month designed for the Daecheong Reservoir. Figure 9 shows the hydrologic states for storage level forecast for each month in the Daecheong Reservoir where the actual storage data of 23 years from 1983 to 2006 were used to define seven hydrologic states.



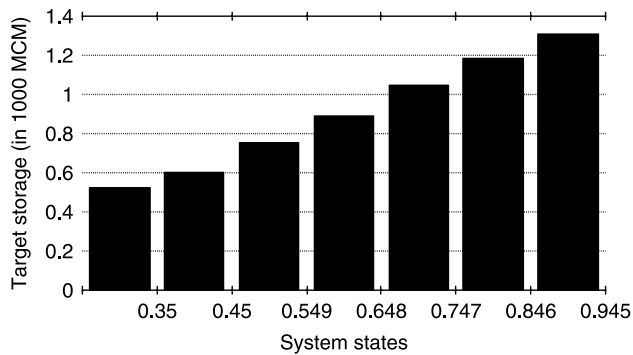


Figure 5 | Example of the hydrologic states in Daecheong reservoir.

### CALIBRATIONS OF SYSTEM NETWORKS

There are two kinds of calibration which are hydrologic calibration and water management simulation required for applying the KModSim to a river basin. Hydrologic calibration is used to calibrate the water mass balance in the system and to define deficiencies in the input data. In model calibration, the first step is to assume that the physical data, such as inflows and demands, are correct. Then the model is run using the observed reservoir storage level as the target storage. There are 14 gauging points including two reservoirs and some demand or diversion locations in the Geum River basin. Unfortunately for a river basin simulation model, the input data, geometry and hydraulics data are rarely available with the required precision and they are a significant source of uncertainty. Therefore the calibration process must address both the

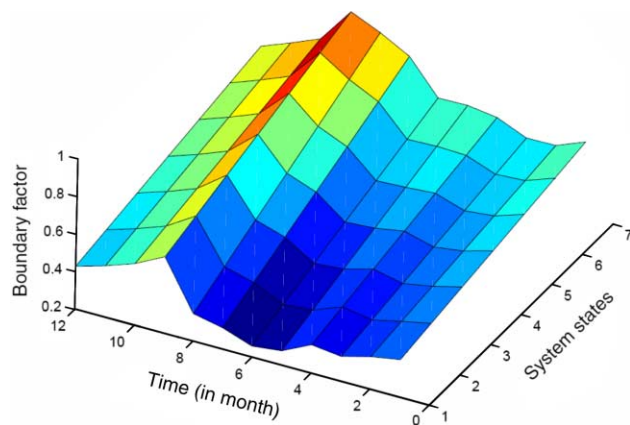


Figure 6 | The seven different hydrologic state values of each month designed for the Yongdam reservoir.

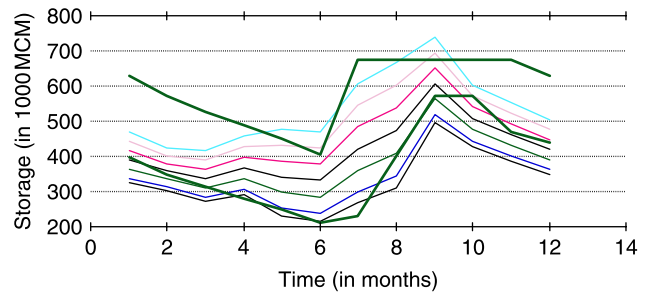


Figure 7 | The hydrologic states for storage level forecast in Yongdam reservoir.

parameters and the input data. The most logical approach is then to make the best estimate of the actual data and then to make sure that the predicted flows match the trends and general magnitude of the observed data. The data for the upstream flow, the local inflow for the 14 sub-basins, were estimated from the RRFS.

### Calibrations for the monthly network

Physical system calibration processes of adjusting the parameters such as groundwater return coefficient and lag coefficients were integrated with adjustments to the allocation priorities within the system. The KModSim model is ideal for adjusting the priorities to represent both the required preference in meeting the various demands and also as a way to give higher priority to better-quantified demands. The principle of the systematic allocation of water is to provide the water for domestic, industrial and agricultural uses at each sub-basin and instream flows at

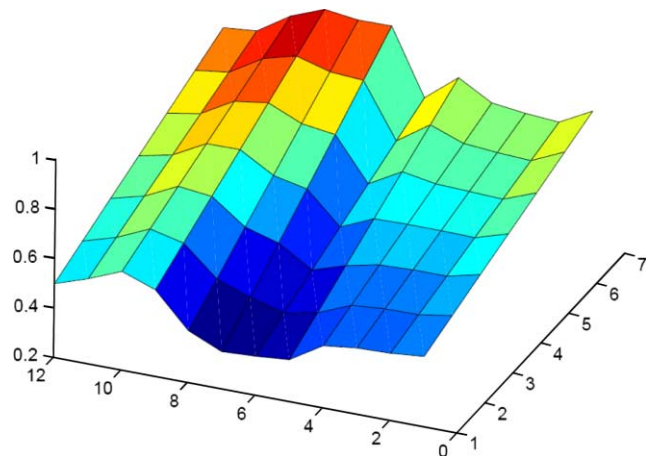
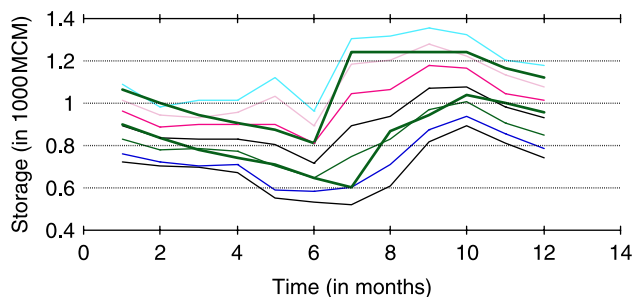
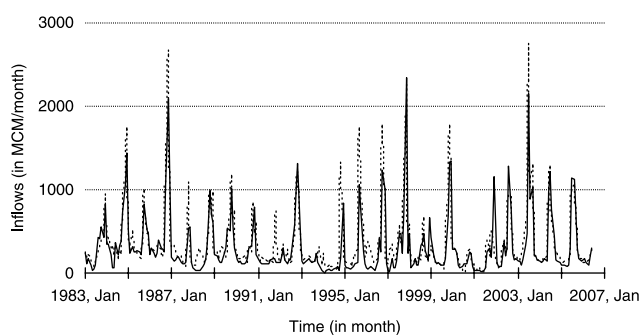


Figure 8 | Seven different hydrologic state values of each month designed for the Daecheong reservoir.



**Figure 9** | The hydrologic states for storage level forecast in the Daecheong reservoir.

both gauging points of Gongju and Gyuam from the highest to the lowest priority order. However, this allocation principle is only valid when the pre-existing diversions in 14 sub-basins are not damaged and those pre-existing diversions are limited to protecting the 15 percentile flows in each of the sub-basins. The simulated reservoir storage levels at two reservoirs and river flows at the 14 gauging points are compared with measured data in the Geum River basin. The reasonable physical calibrations of the monthly and daily time steps were achieved. The assessment of the calibration was based upon manual inspection of the results over time and space. Manual calibration is very time-consuming; however, it is preferable compared to any other quantitative methods such as an overall root mean square error. This study focused on matching gauged flows, reservoir levels and high priority demands. The results were carefully reviewed to determine any trends in errors or any actual errors. Graphs showing the detailed comparison of measured and simulated values of gauged flows at Gongju are shown in Figure 10. Figure 10 provides comparisons of flows at the Gongju gauge for approximately



**Figure 10** | Comparison of KModSim simulated inflows at the Gongju gaging point for approximately 20 years from 1983 to 2006. —: simulated; - - -: measured.

a 23-year time period. The reasonable calibration provided the confidence that the network design, selection of actual operational priorities and the basic data including hydrological inflows and demand data were sufficient for the management calibration and operational scenario analysis. The monthly hydrologic calibration was also used to identify the year to be used for calibration at the daily time step. Differences between KModSim calculated flows and gauged flow records were evaluated using average root-mean-square difference (RMSE) and correlation coefficients. For these three measures, the correlation coefficient for the Daecheong Reservoir inflow is 0.78, the correlation coefficient for the Gongju gauge inflow is 0.73 and the correlation coefficient for the Kyuam gauge inflow is 0.66. The average RMSE at the Daecheong Reservoir inflow is 10.3 MCM/month, the average RMSE at the Gongju gauge inflow is 39.4 MCM/month and the average RMSE at the Kyuam gauge inflow is 27.3 MCM/month. In general, KModSim results reveal a trend towards under-prediction of flows. This indicates that estimated local inflows are likely too small or estimated demands are too high, or both. In calibration it is important to focus on aspects of the model that are the most accurate. Both simulated the Daecheong Reservoir ending storage levels and Gongju flows match the historical data reasonably well and the errors are most likely due to the imprecision in the estimated demands and local inflows.

### Calibrations for the daily network

The daily KModSim network is essentially the same as the monthly network with the same priority structure for each of the water demands calibrated in the monthly model analysis. The major challenge in moving to the daily time step was translation of the monthly operational rules into daily operational rules. For the daily calibration, the model is run using the observed reservoir storage level as a storage target. The assessment of the calibration was based on the manual inspection of the results over time and space. This study focused on matching gauged flows, reservoir levels and high priority demands. The results show that the model reproduces the flow records quite well, considering that the demand data and local inflows in the daily model are highly uncertain. The reasonable calibration provided the

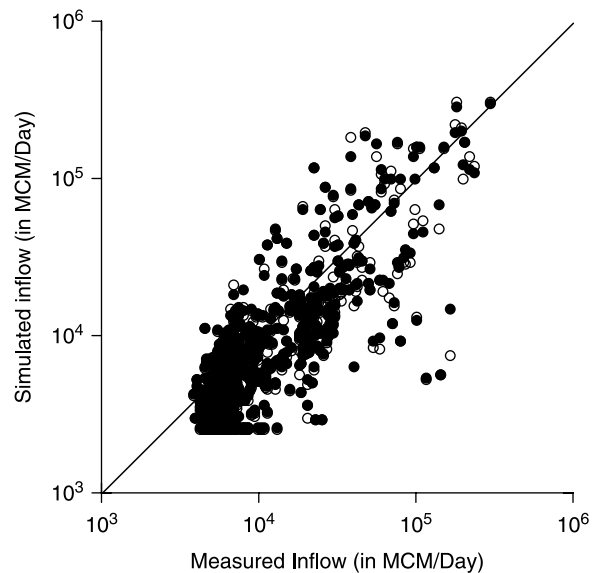
**Table 2** | Channel routing coefficients obtained at each locations in Geum River basin

Locations	Distance (km)	Flood wave (m/s)	Channel routing coefficient				
			C1	C2	C3	C4	C5
Yongdam–Sutong	43.10	0.70	0.334	0.622	0.044	–	–
Sutong–Hotan	27.40	0.60	0.473	0.527	–	–	–
Hotan–Okcheon	39.50	0.70	0.361	0.625	0.014	–	–
Daecheong–Gongju	48.90	0.50	0.161	0.622	0.161	0.042	0.014
Seokhwa–Gongju	26.60	0.50	0.398	0.588	0.014	–	–
Gongju–Gyuam	33.50	0.50	0.284	0.663	0.053	–	–
Gyuam–Ganggyeong	27.80	0.50	0.366	0.625	0.009	–	–

confidence that the network design, selection of actual operational priorities and the basic data including hydrological inflows and demand data were sufficient for the management calibration and operational scenario analysis. For these three measures, the correlation coefficient for the Daecheong Reservoir inflow is 0.80, the correlation coefficient for the Gongju gauge inflow is 0.76 and the correlation coefficient for the Kyuam gauge inflow is 0.62. The average RMSE at the Daecheong Reservoir inflow is 0.34 MCM/day, the average RMSE at the Gongju gauge inflow is 1.33 MCM/day and the average RMSE at the Kyuam gauge inflow is 0.9 MCM/day. In general, KModSim results reveal a trend towards under-prediction of flows. This indicates that estimated local inflows are likely too small or estimated demands are too high, or both. In calibration it is important to focus on aspects of the model that are the most accurate. Daily calibration was performed with and without the new backrouting and channel routing procedure in the KModSim. We used the routing coefficient obtained in this study as listed in Table 2.

The results compare the actual inflow to the gauges at Gongju using daily simulated flow for cases with channel routing and without channel routing. The complete results are shown in Figure 11. The represented trends of both simulated results are well reproduced to the measured data. It is also important to note that the addition of the channel routing methodology produces results that are closer to the measured data as compared to the model without channel routing. The daily network includes flow routing and so special considerations were needed to calibrate and validate the network system. The normal streamflow routing procedure employed in KModSim will produce

correct solutions as long as there is sufficient water to satisfy all demands, whether they are of low or high priority. Difficulties arise when there is insufficient water available to meet all demands, and priorities exist on the allocation of water. Under water shortage conditions and priorities on demands, routing time steps longer than one day can cause downstream demands to pull water from upstream reservoirs, although they do not receive this water immediately. This causes unnecessary releases of additional water from upstream reservoirs that are in excess of downstream demands. A backrouting methodology has been implemented in KModSim to overcome the problem of excessive reservoir drawdown associated with longer



**Figure 11** | Comparison results of the daily inflows measured at the Gongju gauging point with both simulation results such as ○: without channel routing and ●: with channel routing.

routing periods. In this approach, water delivery decisions for time step  $t$  are based on knowledge about future water system requirements that are calculated using several network runs over future concurrent times. The concept of concurrent time networks is based on the fact that, in time step  $t$ , only a fraction of the water available at any location in the network will actually reach the furthest downstream region of the network during the same time step. For the test of backrouting effects, the Sutong and Kankyung points were selected in which Sutong point is the upstream node directly connected to the Yongdam Reservoir and the Kankyung point is the furthest downstream node in the Geum River basin. This test attempts to illustrate the advantages of using the backrouting procedure to ensure that flow routing does not interfere with the priorities associated with water allocation in the network, particularly during drought or low-flow conditions.

The routing represents a case with time lags of more than one day, where the routing coefficients are listed in Table 2. In order to precondition the network for previous flow conditions due to flow routing, some units of flow are returned to below the node connected to the routing links in the first time step, since the real system will rarely be completely dry in the downstream section. The lack of returning routed flows in the first time step would cause excessively large reservoir releases, thereby moving the solution further from the real operation. The results in this test demonstrate the look-ahead capabilities of the

backrouting algorithm in the way that KModSim solves the network. The physical channel routing solution (i.e. without backrouting) releases all water from the reservoir in an attempt to satisfy the Sutong demands downstream of the routing link. The flow in the link going out from the reservoir is shown in Figure 12(a). Figure 12(a) shows that, under the backrouting solution, the model produces the exact reservoir releases needed to meet demands over the future time steps. In contrast to the solution under physical channel routing, the Sutong demand is able to receive sufficient flows to satisfy the demands through the first four time periods. Demands for the furthest downstream node (Kangkyung) are generally satisfied under both cases without backrouting and with backrouting (Figure 12(b)), although some shortage occurs in the first period since it is physically impossible for the furthest downstream node, which node is senior, to demand to receive water from the reservoir until the second time step due to the time lags. The benefits of backrouting are demonstrated by the fact that no spills occur (Table 3).

### EVALUATION OF OPERATIONAL GUIDE CURVES USING KMODSIM

For the application test of the hydrologic states we consider current period forecasts for a developed subset of both the Yongdam and the Daecheong reservoirs in the system that

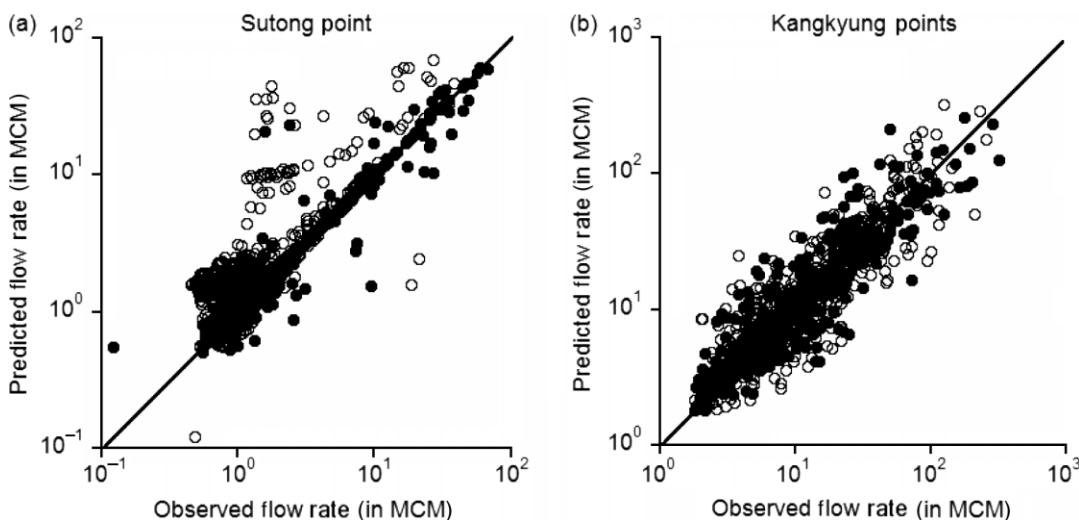


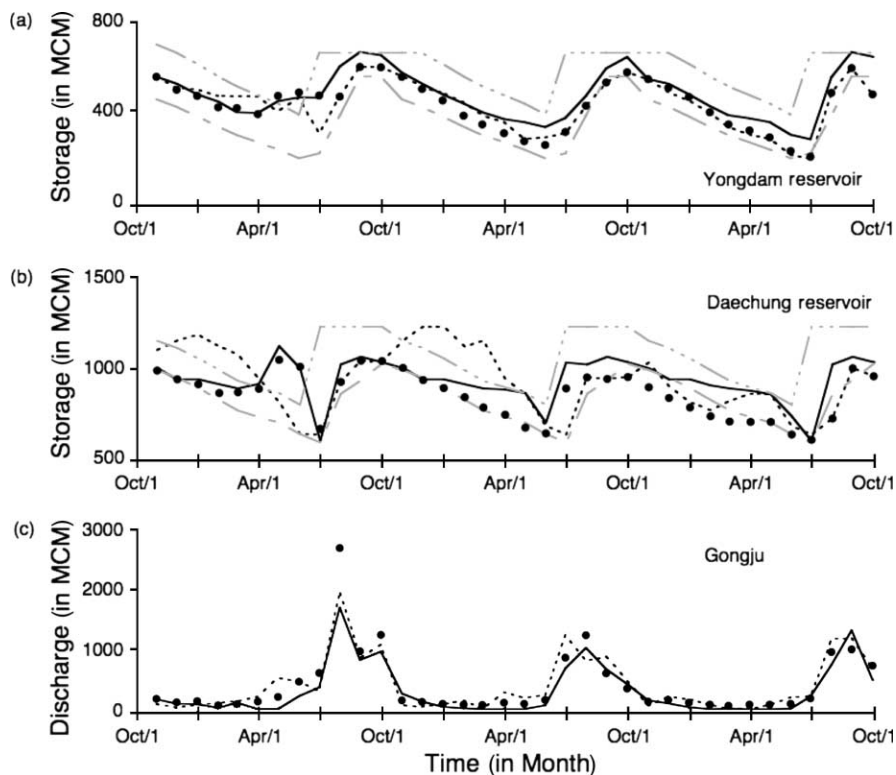
Figure 12 | Comparisons of channel routing results with observed data collected in the Geum River Basin; ○: without backrouting and ●: with backrouting.

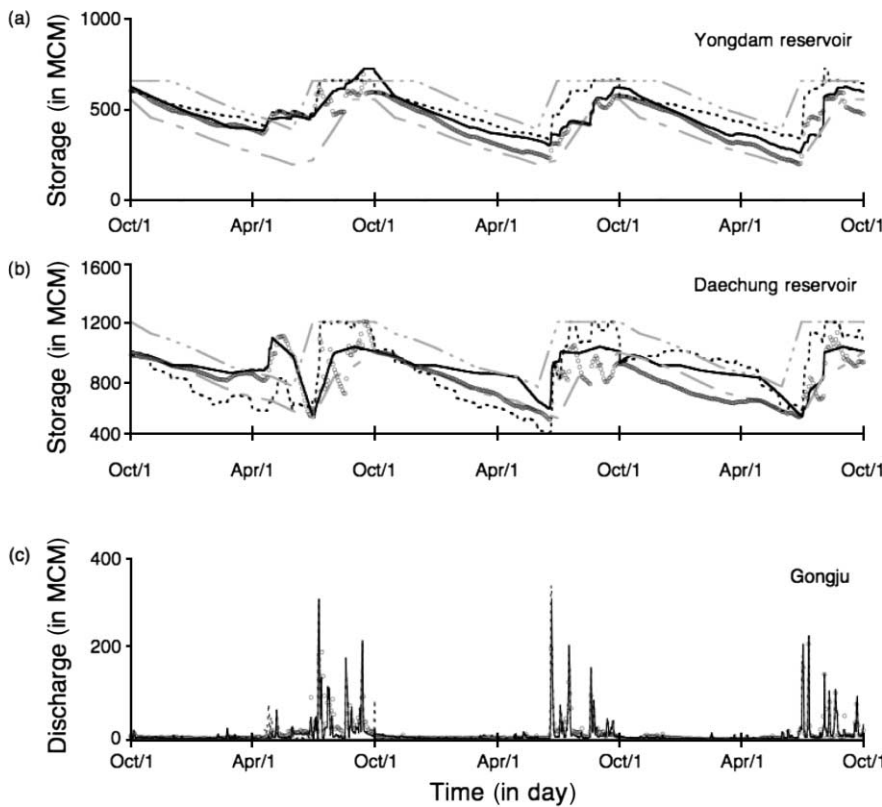
**Table 3** | Comparisons of statistics values calculated from measured and simulated both with backrouting method and without backrouting method (units: MCM/day)

Statistics	Sutong Point			KangKyung Point		
	Measured	Without backrouting	With backrouting	Measured	Without backrouting	With backrouting
Minimum	123.0000	40.00000	502.0000	1791.0000	511.00000	514.00000
Maximum	68948.00	40782.00	59942.00	319103.00	262418.00	262426.00
Mean	2638.921	1619.813	2640.852	14944.640	13933.373	15010.496
Median	1319.000	903.0000	1337.500	7085.5000	6848.0000	7326.0000
RMS	6699.331	3852.363	6420.556	30028.430	26456.688	28083.133
Std. Dev.	6159.572	3496.337	5854.084	26053.360	22497.230	23742.176
Variance	37,940,362	12,224,377	34,270,338	$6.781 \times 10^8$	$5.062 \times 10^8$	$5.632 \times 10^8$
Std error	152.0072	86.28330	144.4683	642.95012	555.19108	585.91392

are indicative of hydrologic conditions in the Geum River basin. The simulation results are compared with the actual storage data, results from SSDP for monthly data (Figure 13) and results from the SSDP-CoMOM for daily data (Figure 14). Figures 13 and 14 show that hydrologic states generate the actual ending storage well. The ending storages calculated from the hydrologic states are located between the guideline boundaries.

The simulation results show both the ending storage of SSDP and hydrologic states for the monthly simulation are greater than the actual storage operated in the Yongdam and the Daecheong reservoirs. During the simulation length, the mean storage and power energy results from the SSDP target simulation are increased by 15.2% and 24.6%, respectively. The mean storage and power energy results from the hydrologic states based on the operating rules

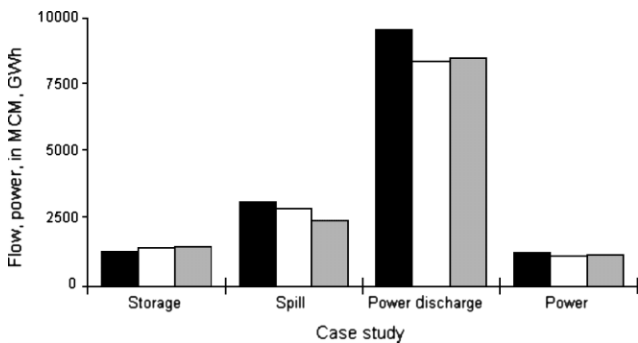
**Figure 13** | Comparison of the KModSim simulated results with measured data for three years (2002 October–2005 September); ●: actual storage target and measured flow at the Gongju Station; —: developed operation rules; - - - -: the SSDP storage target; ·····: Lower Reference Storage; - · - ·: Upper Reference Storage.



**Figure 14** | Comparison of the KModSim simulated results with measured data for three years (2002 October–2005 September); ●: actual storage target and measured flow at the Gongju Station; —: developed operation rules; - - - -: the SSDP storage target; ·····: Lower Reference Storage; - · - ·: Upper Reference Storage.

developed in this study are increased by 52.0% and 10.1%, respectively. The hydrologic state results have the biggest storage in the Yongdam reservoir and the SSDP results have the biggest storage in the Daechung reservoir (Figure 15). The SSDP-CoMOM target simulation results and the hydrologic state results for daily simulation show that storage simulation results with both targets are greater than the actual storage operated in the Yongdam and the

Daechung reservoirs. During the simulation length, the mean storage from the SSDP-CoMOM target simulation is increased by 9.4% and power energy results from the SSDP-CoMOM target simulation are decreased by 12.3%. The mean storage from the hydrologic state simulation are increased by 13.1% and power energy results from the hydrologic states simulation are decreased by 3.0%.



**Figure 15** | Comparisons of simulated results with measured data in which ■: actual storage target; □: the SSDP-CoMOM storage target; ▒: a new operation rule.

## CONCLUSIONS

A KModSim simulation model that can serve as the basin simulation component in the Geum River Basin DSS was developed. Both monthly and daily versions of the networks have been developed and extensively refined so that numerous issues of data inconsistencies have been resolved. A set of optimal operation rules for the Geum River basin considering the integrated operation of the Daechung and the Yongdam reservoirs using a dynamic programming approach was developed in the study. Both monthly and

daily networks were developed and each time step network was individually calibrated. Calibration was accomplished by a set of input data to simulate the river basin and compare the simulation results with measured gauge flows at the Gongju point and reservoir storage levels at both the Yongdam and the Daecheong reservoirs. Calibration and testing of the monthly and daily models show that the models and refined datasets are able to represent very well the actual operation of the system. Developing well-calibrated models was a major achievement of this study. The new routing procedure demonstrated that considering routing in the daily model improved the ability of the KModSim daily model to represent the actual flow situation in the basin. Developing the actual and integrated operation rules was another major achievement of the study. The additional work to develop a reservoir operational rule for the Daecheong reservoir that accurately reflects the actual situation should prove very useful in the evaluation of proposed operational strategies. This can become a baseline condition for comparison of proposed new operational strategies. The optimal integrated reservoir operation rules that were developed to evaluate potential operational scenarios for testing in the KModSim model should prove useful in a comparison to other methods. Also the developed daily operational rules should prove useful in daily operational decision-making for the basin. The developed KModSim model should provide a tool that water managers in Korea can use to help improve the operation of their reservoir systems. The KModSim provides a flexible river basin simulation model that can work at time scales of one month to one day in which the model now includes an innovative routing procedure for daily simulation. The KModSim model than can simulate a variety of operational scenarios through the use of scripting. This is an extremely important characteristic of the model since it will be used as part of the decision support system for the Geum River basin.

## ACKNOWLEDGEMENTS

This research was supported by a grant (code 1-6-3) from the Sustainable Water Resources Research Center of 21st Century Frontier Research Program.

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First received 24 June 2008; accepted in revised form 27 January 2009. Available online 14 November 2009