

Evaluating joint operation rules for connecting tunnels between two multipurpose dams

Ji-Woo Jeong, Young-Oh Kim and Seung Beom Seo

ABSTRACT

This study aims to provide a practically efficient approach for determining the most efficient joint operation rule for two reservoirs connected by a waterway tunnel. For this purpose, the connecting tunnel's effect was assessed and three heuristic joint operation rules accounting for the connecting tunnel were evaluated. A standard operation policy with the connecting tunnel led to positive effects on the water resource system of the target basin with regard to a reliable water supply.

The connecting tunnel provides an additional water supply of 12.4 million m³/year to the basin, and the reliability of the two reservoirs increased. Among the three rules, the equivalent reservoir (ER) rule led to the most positive effect on water supply. We found that the ER rule could maximize the positive effects of the connecting tunnel by maintaining the effective water storage rates of the two reservoirs. Moreover, the effects of hydrologic uncertainty on the joint operation rules were discussed using the synthetically generated multiple streamflow traces.

Key words | connecting tunnel, joint operation, reservoirs in parallel, synthetic streamflow generation, water supply

Ji-Woo Jeong
Nakdonggang Weir Office,
K-water,
Daegu 42917,
South Korea

Young-Oh Kim
Department of Civil & Environmental Engineering,
Seoul National University,
Seoul 08826,
South Korea

Seung Beom Seo (corresponding author)
Division for Integrated Water Management,
Korea Environment Institute,
Sejong 30147,
South Korea
E-mail: sbseo7@kei.re.kr

INTRODUCTION

At present, the construction of new dams is difficult in many developed countries, and there is an increasing need for efficient operation of the existing dams. Joint operation between adjacent dams can be employed as an alternative to constructing new dams, by improving the functioning and efficiency of existing dams. This strategy can be particularly valuable in monsoon areas where there is a very distinct seasonal pattern in rainfall and streamflow. For example, in Korea, approximately 2/3 of the annual rainfall occurs during the three-month flood season. Therefore, there is only 400 mm of rainfall available for water supply during the remaining nine months.

Numerous studies are available on the heuristic joint operating rules of multiple reservoirs (Oliveira & Loucks 1997; Labadie 2004; Park & Lee 2005; Paredes & Lund 2006; Chang & Chang 2009; Liu *et al.* 2011; Peng *et al.* 2015; Zhang *et al.* 2016). Among these, the following studies include cases of reservoirs in parallel for the operational objective of the water supply. Sand (1984) showed that the well-known space rule and New York City (NYC) rule presented by Clark (1950) and Bower *et al.* (1962), respectively, behave optimally for reservoirs in parallel with a single source of downstream demand. Later, Johnson *et al.* (1991) described various heuristic operating rules, including the space rule as a one-period optimization model, and applied the developed model to the Central Valley Project in Northern California to prove the efficacy of the developed model. Lund & Guzman (1999) reviewed several existing (such as the space and NYC rules) and new heuristic rules having

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (<http://creativecommons.org/licenses/by/4.0/>).

doi: 10.2166/nh.2020.053

rigorous mathematical derivations for various single operational objectives. [Revelle \(1999\)](#) revised the space rule to propose another allocation rule that simply calculates the water supply from downstream reservoirs in parallel as a function of storage capacity and reservoir inflow. Recently, these space rules, based on the hedging mechanism, have been proposed by several studies ([Draper & Lund 2004](#); [You & Cai 2008](#); [Zhao et al. 2011, 2014](#)). Furthermore, [Peng et al. \(2015\)](#) proposed a joint operation rule based on the hedging rule curves of each equivalent reservoir (ER).

There are some good examples of using connecting tunnels between two existing dams in Japan. One is the Ikari-Kawaji connecting tunnel, which has enabled efficient reservoir operation by sending up to 20 m³/s of water from the Ikari Dam, where spillway discharge occurs frequently in the flood season, to the Kawaji Dam, which has a smaller storage-to-inflow ratio ([Kinugawa Integrated Dam Control Office 2012](#)). The other example is the joint operation of five dams (Fukuchi Dam, Arakawa Dam, Aha Dam, Hungawa Dam, and Benoki Dam) located in the northern part of Okinawa ([Takeuchi 1998](#)). Water obtained from the intake dams with small storage capacities is sent to two detention dams (Fukuchi Dam and Aha Dam) to secure the reservoir space in the intake dams, save additional water of 43,000 m³/day, and reduce the spillway discharge from the reservoir system ([Korea Water Resources Corporation 2011a, 2011b](#)).

Motivated by the above-mentioned successful precedents in Japan, Korea launched the Andong-Imha Connecting Tunnel (AICT) project in 2011 and completed it in 2015. Therefore, developing an efficient operation plan for the new system was required. The processes in this study were divided primarily into two stages. First, using previous hydrological data, we simulated the operation of the reservoirs before and after the two dams were connected; this was done to quantify the water supply increment as the effect of tunnel connection. Second, we tested several heuristic joint operating rules to propose the most efficient operating plan for the connecting tunnel. The existing joint operation rules were modified to incorporate the connecting tunnel module. If there is not yet a proper joint operation rule for the two reservoirs connected by a waterway tunnel, the preference would be to focus on incorporating the connecting tunnel module into the existing joint operation rules developed by advanced countries rather than developing a

completely new rule. Although some studies have proposed heuristic optimization algorithms, such as genetic algorithm ([Afshar et al. 2010](#); [Ahmadianfar et al. 2017](#)) and particle swarm algorithm ([Afshar 2013](#)), for obtaining multiple reservoir operation rules, traditional but widely applied and efficient methods were modified in this study so that people can apply them practically with ease.

Based on the results of these previous studies, we decided to test the existing joint operating rules, such as the space rule, the Revelle's allocation (RA) rule, and the ER rule, for the case study. These rules were also compared with the standard operating policy (SOP), which is the simplest policy aiming to release a quantity of water demand if possible. We used SOP as a benchmark scheme as it is a fundamental operating rule that is currently being used. Besides releasing the target demand, SOP does not consider any joint operating concept; thus, it provides information only on the bottom-line performance of reservoir systems. The software package HEC-5, in which the ER rule was embedded, was used because this well-known simulation package has been officially used in the operation of other multipurpose dams in Korea. Each of the candidate operating rules is described in the Methods section, and the results of their application to the case study are presented in the Applications and Results section, followed by the Conclusions of the study.

METHODS

Standard operating policy

SOP is the most basic method used for reservoir operation, whose primary objective is to meet the target water demand ([Ministry of Land Transport and Maritime Affairs 2011](#)). According to SOP, if the available water (current storage + incoming inflow) is less than the target water demand, all available water is discharged. If the available water exceeds the target water demand, the required amount for the target water demand is delivered and the remaining water is stored in the reservoir ([Korea Water Resources Corporation 2013a](#)). Furthermore, if the stored water, remaining after discharging the amount required for the target water demand, exceeds the maximum capacity of the reservoir, it is discharged through the spillway. We implemented two different

versions of SOP to assess the effect of a joint operation with the connecting tunnel: (i) SOP-O, which does not consider the connecting tunnel, and (ii) SOP-W, which considers the connecting tunnel. SOP-O and SOP-W can be expressed using the following equations:

SOP-O:

$$\text{if } (S_{i,t-1} + I_{i,t}) < D_{i,t} \text{ then } R_{i,t} = (S_{i,t-1} + I_{i,t}) \quad (1)$$

$$\text{else if } (S_{i,t-1} + I_{i,t}) < (K_i + D_{i,t}) \text{ then } R_{i,t} = D_{i,t} \quad (2)$$

$$\text{else } R_{i,t} = S_{i,t-1} + I_{i,t} - K_i \quad (3)$$

SOP-W:

$$\text{if } (S_{i,t-1} + I_{i,t} + T_{\text{div}_i}) < D_{i,t} \text{ then } R_{i,t} = (S_{i,t-1} + I_{i,t} + T_{\text{div}_i}) \quad (4)$$

$$\text{else if } (S_{i,t-1} + I_{i,t} + T_{\text{div}_i}) < (K_i + D_{i,t}) \text{ then } R_{i,t} = D_{i,t} \quad (5)$$

$$\text{else } R_{i,t} = S_{i,t-1} + I_{i,t} + T_{\text{div}_i} - K_i \quad (6)$$

where $S_{i,t-1}$ is the storage of reservoir i at the end of time $t - 1$, $I_{i,t}$ is the inflow to reservoir i at time t , $D_{i,t}$ is the water demand from reservoir i at time t , $R_{i,t}$ is the discharge from reservoir i at time t , K_i is the maximum capacity of reservoir i , and T_{div_i} is the amount of water passed through the connecting tunnel from Imha to Andong Dam at time t . As the connecting tunnel is designed to send water in one direction from Imha Dam to Andong Dam (i.e., send the surplus water of Imha Dam to Andong Dam), T_{div_i} is always more than or equal to zero for Andong Dam but less than or equal to zero for Imha Dam.

Space rule

Bower et al. (1962) proposed the space rule, which is an operation plan to minimize spillway discharge. The space rule seeks to retain larger amounts of space in reservoirs where greater inflows are expected or where greater potential energy of inflows is expected in the case of energy storage (Bower et al. 1962). The space rule was developed for water supply storage and energy storage purposes; it is a special case of the NYC rule, seeking to minimize the total volume of spills (Lund & Guzman 1999). It is not efficient if spillway discharge occurs in the other reservoirs when a reservoir in the parallel reservoir group is not full. For the purpose of

water supply, the space rule sets a target storage in each reservoir so that the ratio of the space remaining at the end of the current period to the expected value of the remaining refill season inflow for each reservoir is identical (Johnson et al. 1991). All reservoirs are then balanced in terms of minimizing the expected spill and maximizing the current inflows (Lund & Guzman 1999). This is expressed as:

$$\frac{K_i - S_{i,t}}{E[CI_i]} = \frac{\sum_{i=1}^n K_i - V_t}{\sum_{i=1}^n E[CI_i]}, \forall i \quad (7)$$

$$\text{with } V_t = \sum_{i=1}^n (S_{i,t-1} - I_{i,t}) - D_t$$

where $E[CI_i]$ is the expected cumulative inflow to reservoir i from the end of the current period to that of the flood season, D_t is the total water demand in the parallel reservoir group at time t , and V_t is the total storage of the reservoir group at time t .

The space rule can be alternately expressed, as seen in Equation (8). The ratio of the residual space of reservoir i to the sum of the residual spaces of the reservoirs in the parallel reservoir group is the same as that of the future inflow in reservoir i to the sum of the future inflows in the parallel reservoir group.

$$\frac{K_i - S_{i,t-1} - I_{i,t} + R_{i,t}}{\sum_{i=1}^n (K_i - S_{i,t-1} - I_{i,t}) + D_t} = \frac{CI_i}{\sum_{i=1}^n CI_i} \quad (8)$$

RA rule

ReVelle (1999) presented a water supply allocation rule that simply calculates the water supply based on storage capacities and inflow to reservoirs in parallel. Following are the three empirical allocation rules proposed by ReVelle (1999):

- (1) RA-A allocates the target water supply depending on the ratio of storage at the end of the previous unit period of reservoir i in a reservoir group parallel to the total storage of the reservoir group. The discharge from reservoir i at time t ($R_{i,t}$) is estimated as:

$$R_{i,t} = \left(\frac{S_{i,t-1}}{\sum_{i=1}^n S_{i,t-1}} \right) \times D_t \quad (9)$$

- (2) RA-B is the allocation method depending on the ratio of the available water storage of reservoir i at the end of the previous period (i.e., sum of storage of reservoir i at the end of the previous time period and current inflow to reservoir i) to the total available water in the parallel reservoir group. $R_{i,t}$ is estimated as:

$$R_{i,t} = \left(\frac{S_{i,t-1} + I_{i,t}}{\sum_{i=1}^n S_{i,t-1} + I_{i,t}} \right) \times D_i \quad (10)$$

- (3) RA-C distributes the water supply according to the ratio of the water reserve rate, which is obtained by dividing the available water in reservoir i at time t by the maximum capacity of the reservoir. Thus, RA-A and RA-B are based on the storage, while RA-C is based on the water reserve rate. $R_{i,t}$ is estimated as follows:

$$R_{i,t} = \left(\frac{(S_{i,t-1} + I_{i,t})/K_i}{\sum_{i=1}^n (S_{i,t-1} + I_{i,t})/K_i} \right) \times D_i \quad (11)$$

ER rule

HEC-5 is a reservoir operation simulation model developed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE). To determine the discharge priority between reservoirs in parallel, HEC-5 uses the ER rule. The ER rule first releases water from the reservoir with the greatest effective water storage rate of all reservoirs in parallel, so that it can maintain the effective water storage rates of all reservoirs at the same level. USACE updated HEC-5 to HEC-ResSim, referred to as the balancing rule, but the concepts of the balancing and ER rules are similar. The ER rule is based on weighting the level of each reservoir in a subsystem by the storage in the reservoir to determine the storage-weighted level for the subsystem (U.S. Army Corps of Engineers 1998).

Figure 1 illustrates two reservoirs connected in parallel. For example, the effective water storage rates of reservoirs A and B become 0.875 and 0.625, respectively, if their reservoir storages are 35 and 12.5, given that their total capacities are 40 and 20, respectively. In this case, the ER rule releases water from reservoir A first, given that the

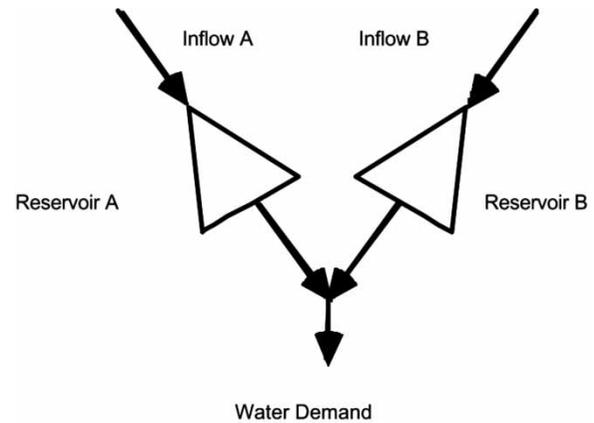


Figure 1 | Reservoirs in parallel (Lund & Guzman 1999).

effective water storage rate of reservoir A is greater than that of reservoir B. The ER rule then determines whether a release from reservoir B is required, based on the target water demand (US. Army Corps of Engineers 1996, 1998, 2007).

Synthetic streamflow generation

To address the effect of hydrologic uncertainty on the performance of the operation rules, a synthetic streamflow generation method can be used to generate multiple traces of inflow series for both dams. It is generally not enough to use only historical records in the reservoir operation analysis to test alternative designs and policies against the range of sequences that are likely to occur in the future (Loucks & Van Beek 2017; Yu et al. 2019). Therefore, in this study, the historical inflow data during 1989–2009 from both dams are applied to generate 50 traces of 20-year hydrologic series using the Thomas–Fiering model, which can be defined as follows (Loucks et al. 1981; Zhao et al. 2012):

$$q_{t+1} = f_{ave} + \rho_{flow}(q_t - f_{ave}) + \sqrt{1 - \rho_{flow}^2}(f_{ave}C_v)\tau \quad (12)$$

where q_t = streamflow in day t ; f_{ave} = mean generated streamflow, which is set as the historical average annual streamflow; ρ_{flow} = temporal correlation of the streamflow; C_v = coefficient of variability; and τ = random number with the standard Gaussian distribution.

The assumption of the stochastic simulation is originally based on the Markov process (Xu et al. 2017). It fixes the statistical characteristics of long-term streamflow data, such as mean flow and variance within a hydrologic year, for stochastic simulations (Matalas 1967; Xu et al. 2003).

APPLICATIONS AND RESULTS

Target basin

The target basin of this study is upstream of the Nakdong River Basin. Two reservoirs, Andong and Imha, are connected in parallel; the outflows from both reservoirs flow into the mainstream of the Nakdong River, as shown in Figure 2. The AICT project in Korea involved connecting the geographically adjacent Andong Dam and Imha Dam

with a tunnel having a diameter of 5.5 m and length of 1.925 km (Figure 2). The project was initiated to utilize the water resources more efficiently by moving water from the Imha Dam, which otherwise frequently overflows because of its relatively smaller storage capacity compared to the inflow, to the Andong Dam. Table 1 lists the operational characteristics of both dams. The AICT project was the first domestic project that involved connecting two dams in Korea, although most existing systems are one-directional water conveyance tunnels.

The Andong Dam is located upstream of the Nakdong River, and the Imha Dam is located at the Banbyeoncheon stream, a tributary of the Nakdong River. From the Banbyeoncheon confluence, the Andong Dam is located approximately 4 km upstream of the Nakdong River and the Imha Dam is located approximately 16 km upstream of the Banbyeoncheon stream (Kim et al. 2003). The

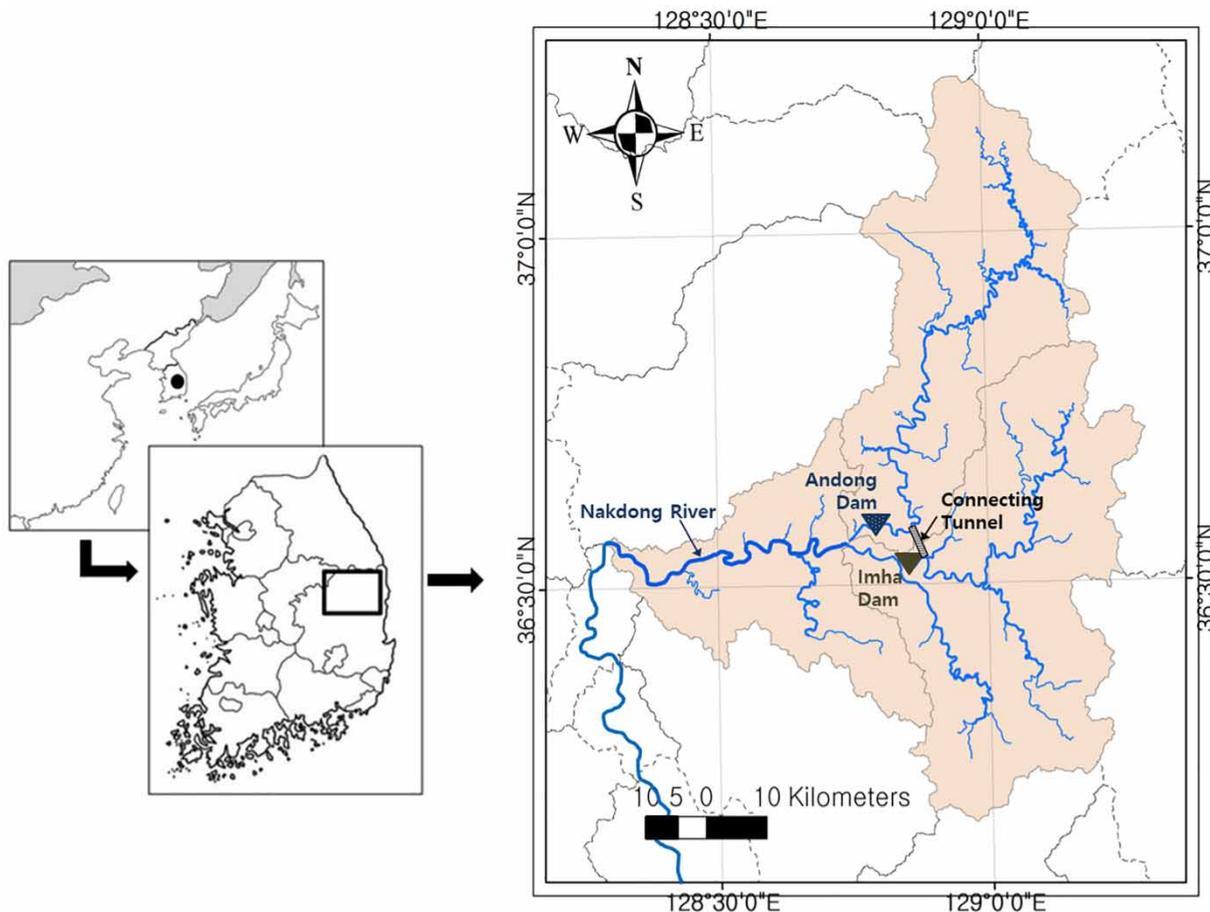


Figure 2 | Location of the target basin: Andong-Imha Connecting Tunnel.

Table 1 | Operational characteristics of Andong Dam and Imha Dam

Dam	Storage (million m ³)	Annual Inflow (million m ³)	Annual Supply (million m ³)	Storage/ Inflow	Supply/ Inflow
Andong	1,000	850	926	1.176	1.089
Imha	424	762	592	0.556	0.777

Andong Dam, built in 1976, is a central core-type rockfill dam with a height of 83 m, length of 612 m, total storage capacity of approximately 1.25 billion m³, and basin area of 1,584 km² (Korea Water Resources Corporation 2008a). The Imha Dam, built in 1993, is a multipurpose rockfill dam with a height of 73 m, length of 515 m, total storage capacity of approximately 595 million m³, and basin area of 1,461 km² (Korea Water Resources Corporation 2008b). There are two intake towers at both ends of the tunnel. The connecting tunnel is located 141 m above sea level.

Operational and hydrologic input data

Monthly water supply plan

The monthly water supply plan of the Andong Dam and Imha Dam follows the Dam Operation Practice Handbook (Korea Water Resources Corporation 2013b). The annual water supply from the Andong Dam is approximated at 926 million m³ (450 million m³ for industrial water demand, 300 million m³ for agricultural water demand, and 176 million m³ for instream flow requirements). The annual water supply from the Imha Dam is approximated to be 592 million m³. Approximately 25% of the annual water supply from the Imha Dam is sent to the Yeongcheon Dam through the Yeongcheon waterway in order to supply water to the Gyeongsangbuk-do southeastern area and river maintenance water for the Geumho River. This study also considers an additional instream flow requirement of 1 m³/s to prevent stream flow depletion.

Hydrologic input data

In this study, a historical daily inflow series, spanning 20 years from 1989 to 2009, of the Andong Dam and Imha Dam are used. The annual mean inflows to the Andong Dam and Imha Dam are 1,039 and 717 million m³,

respectively. Note that the Imha Dam's inflow is only 68% of the Andong Dam's inflow. Like other rivers in Korea, these two basins are characterized by strong seasonality; thus, more than 60% of the annual inflow occurs during the flood season from July to September, as illustrated in Figure 3(a). Figure 3(b) presents the annual inflow series of both dams. Examining 20 years of data on the inflow of the Andong Dam and Imha Dam, it is observed that severe droughts first occurred in the two dams from 1994 to 1996. During this period, the annual inflows to the Andong Dam and Imha Dam were 487 and 422 million m³ less than the mean annual inflows, respectively.

Hydrologic uncertainty representation

Fifty traces of 20 years' daily inflow series for the Andong Dam and Imha Dam were generated from the aforementioned synthetic streamflow generation method. Figure 4 shows ranges of the observed and generated streamflow hydrographs for both dams. It shows that the generated streamflow sequences can provide a similar range of observed streamflow. The statistical characteristics of the generated streamflow were also similar to the observed streamflow. The percent bias of mean flow of all generated streamflow traces ranged from -0.09 (-9%) to 0.07 (7%).

Simulation overview

We used Excel to assess and compare the performances of various operating rules for AICT because the system comprises only two dams. As mentioned before, the inflow time series were entered to test each operating rule. The SOP rule consists of two versions, the SOP-O rule and the SOP-W rule, to examine the bottom-line effect of the joint operation with a connecting tunnel. All other joint operating rules were then applied to the system with a connecting tunnel and expected to perform better than the SOP-W rule.

The system performance was assessed using three well-known measures: reliability, resiliency, and vulnerability (Hashimoto et al. 1982). Conceptually, reliability, resiliency, and vulnerability represent the number of times a system does not fail, how quickly the system recovers from a failure, and how large each failure is on an average, respectively. Here, reliability is described by the probability that a

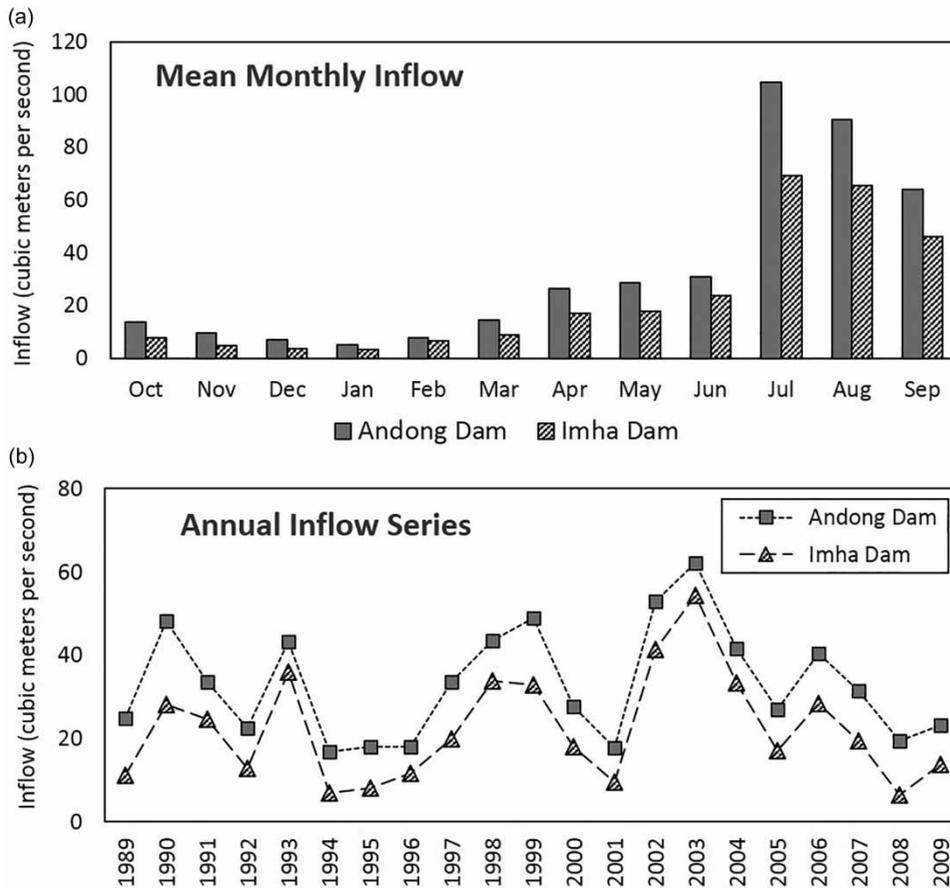


Figure 3 | Series of mean monthly and annual inflows to the Andong Dam and Imha Dam: (a) mean monthly inflow to the Andong Dam and Imha Dam, (b) annual inflow to the Andong Dam and Imha Dam.

system is in satisfactory state. Resiliency describes how quickly a system is likely to recover from failure. Vulnerability is defined as the expected water deficit from a single failure for a given period.

For reliability and resiliency ranging from 0 to 1, higher values indicate better performance and smaller values indicate better performance in case of vulnerability, which does not have an upper limit. The equations for reliability, resiliency, and vulnerability are expressed as:

$$\begin{aligned} \text{reliability} &= 1 - P(wd(i) > 0) \\ &= 1 - \frac{\text{the total number of failures}}{\text{the total number of the time intervals}} \end{aligned} \quad (13)$$

$$\text{resiliency} = \{\text{the average length of time which a system's status remains failure}\}^{-1} \quad (14)$$

$$\text{vulnerability} = \frac{1}{M} \sum_{i=1}^N wd(i) \quad (15)$$

where M is the total number of failures, N is the total number of time intervals, and $wd(i)$ is the amount of water deficit in time i .

Simulation results

Connecting tunnel effects

The effects of the connecting tunnel are first assessed by comparing SOP-O and SOP-W. Note that the SOP-O and SOP-W rules follow Equations (1) and (2), respectively.

In terms of water supply performance, Figures 5(a) and (b) present the number of days with water shortage

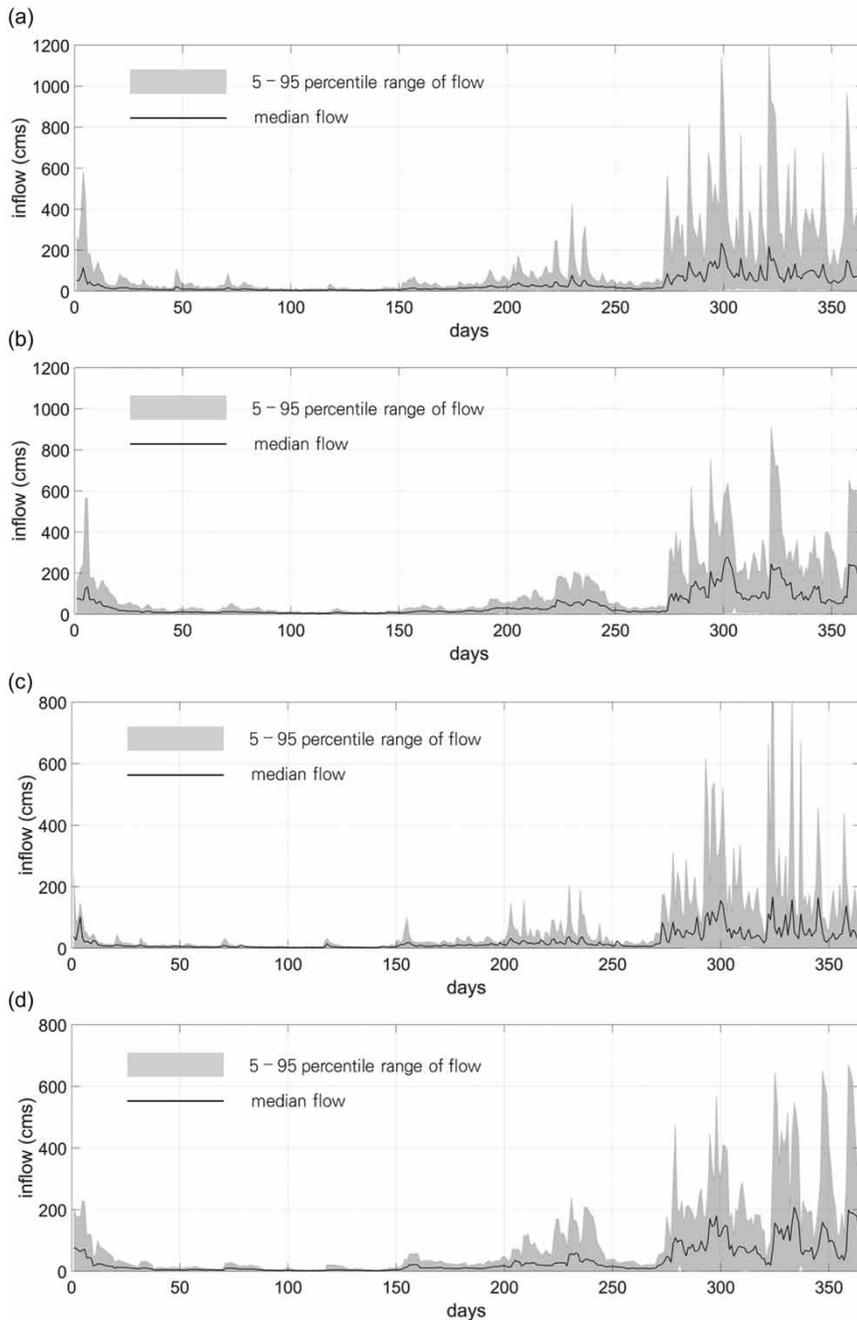


Figure 4 | Range of the observed and generated streamflow hydrographs: (a) observed streamflow hydrographs of the Andong Dam, (b) generated streamflow hydrographs of the Andong Dam, (c) observed streamflow hydrographs of the Imha Dam, (d) generated streamflow hydrographs of the Imha Dam.

and the amount of water shortage per year, respectively. As shown in the figure, SOP-W outperforms SOP-O in that the number of days with water shortage and the amount of water shortage are notably decreased in the overall system. Although SOP-O slightly outperforms SOP-W in the case

of the Andong Dam, significant improvement in the Imha Dam leads to an enhancement in the overall water supply capabilities. This is the main advantage of utilizing the joint operation of multiple reservoirs. Although there is some probability that a single reservoir's operation

performance temporally drops, the overall performance of the system can be improved noticeably.

Figures 5(c) and (d) present the three performance criteria: reliability, resiliency, and vulnerability. Similar to the results of water supply performance, SOP-W increases reliability in the Imha Dam so that the overall system reliability also increases, given that the water shortage in the Imha Dam dominates the overall water shortage in the system. Furthermore, the resiliency increases in both dams and in the overall system. Note that the resiliency in the Andong Dam increases even though the reliability decreases slightly. It is inferred that conveyance of water from the Imha Dam can enable the Andong reservoir to rapidly recover from the water shortage. In terms of vulnerability, on the contrary, SOP-O outperforms SOP-W. Hashimoto *et al.* (1982) stated that the efforts for improving reliability can cause a deterioration in vulnerability. As the number of days with water shortage can be decreased by canceling out the smaller event preferentially, a trade-off between reliability and vulnerability occurs as a natural consequence.

Overall, the connecting tunnel's effects on the water resource system of the Andong and Imha dams are noticeably positive for water shortage prevention.

Comparison of joint operating rules

The three joint operating rules – the space, RA, and ER rules – for the AICT project are simulated using a historic inflow series, and then assessed with the performance measures used in the previous section. The space rule determines the discharges of the two dams by considering their future inflow. The RA rule comprises three versions, as described in the RA rule section: RA-A, RA-B, and RA-C. RA-A employs the ratio of the current effective storage between the two dams, RA-B employs the ratio of the potential supply (the current effective storage + the future inflows) between the two dams, and RA-C employs the ratio of the relative effective storage (effective storage/storage capacity) between the two dams. The ER rule determines the discharges of the two dams to ensure that the current relative effective storages of the two dams are equal.

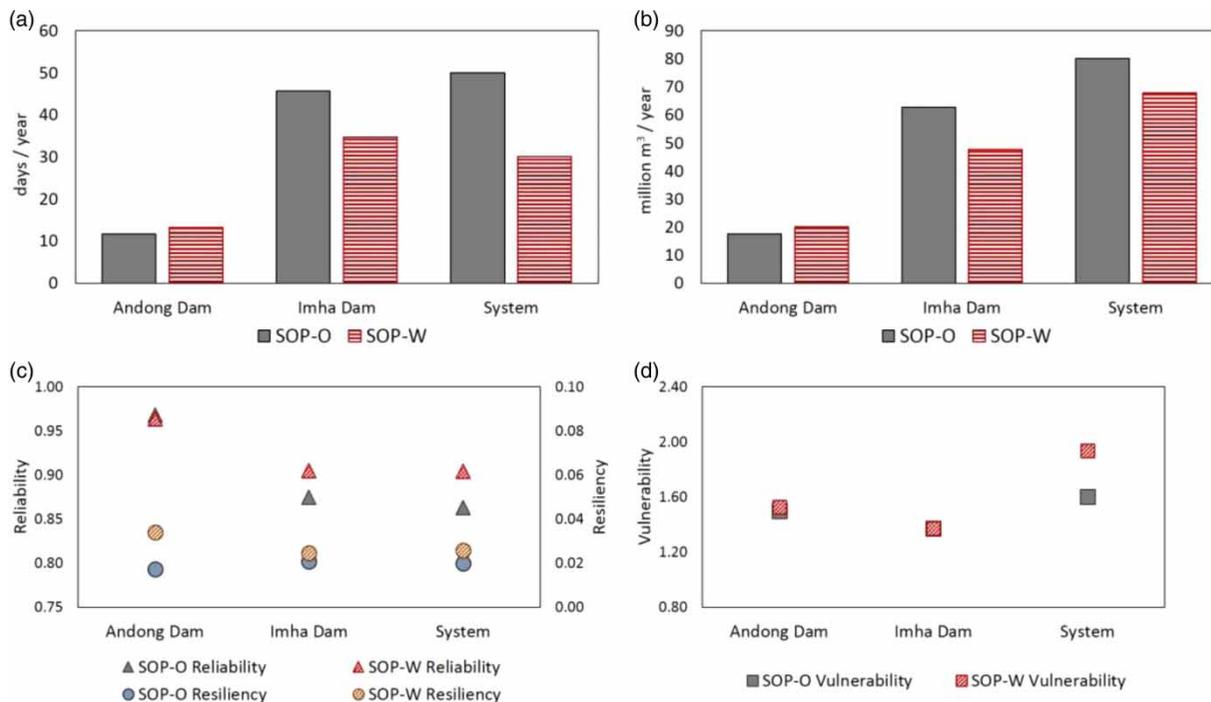


Figure 5 | Connecting tunnel effects on the water resource system of the Andong Dam and Imha Dam: (a) number of days with water shortage per year, (b) amount of water shortage per year, (c) reliability (left y-axis) and resiliency (right y-axis), and (d) vulnerability.

Figures 6(a) and (b) present the number of days with water shortage and the amount of water shortage per year, respectively. When compared to SOP-W, all other joint operation rules notably decrease the number of days with water shortage as well as the amount of water shortage. Among the joint operating rules, the ER rule outperforms the others. Specifically, the ER rule decreases the water shortage by approximately 2 million m^3/year (unlike the other rules that decrease the water shortage by less than 1 million m^3/year). This indicates that an effective storage of both dams should be preserved at the same rate during most of the operational period, to reduce the risk of water shortage of the entire system. The ER rule enables both dams to continue supplying water as long as possible under the drought condition, as it prevents a single dam from drying out before the other dam dries.

Figures 7(a)–(c) present the three performance criteria (reliability, resiliency, and vulnerability, respectively) of the joint operation rules. As expected, all joint operation rules can increase the reliability. On the other hand, the vulnerability of all rules is increased. As discussed above, there is a trade-off between reliability and vulnerability. While all joint operation rules show very close levels of improvement in reliability, only the space rule can increase resiliency. As

the space rule determines the reservoir discharge by considering the subsequent inflow (i.e., a day-ahead inflow forecast), the space rule apparently has the advantage of quick restoration over the other rules. Although the average length of the water shortage events was decreased by the space rule, the total number of days and total amount of water shortage driven by the space rule were greater than the ER rule. Overall, the advantages of the joint operation rules are confirmed by the evaluation of this study. Nonetheless, it seems difficult to identify which rule is superior to the others, as the values of the performance metrics are similar. It is noted that the ER rule is determined as the most effective joint operation rule with regard to both aspects, reliability and vulnerability, while the space rule is the best model if the ability of the system's restoration is solely considered.

In the practical operation of reservoirs for water supply, the ability of a reliable water supply, i.e., reliability, is usually considered as the first priority. Therefore, based on the performance criteria of the joint operation rules, the ER rule can be considered the best operation rule for the AICT project in that its performance in terms of water supply is greater than that of the other rules, although the difference is not large. In this regard, it can be inferred that

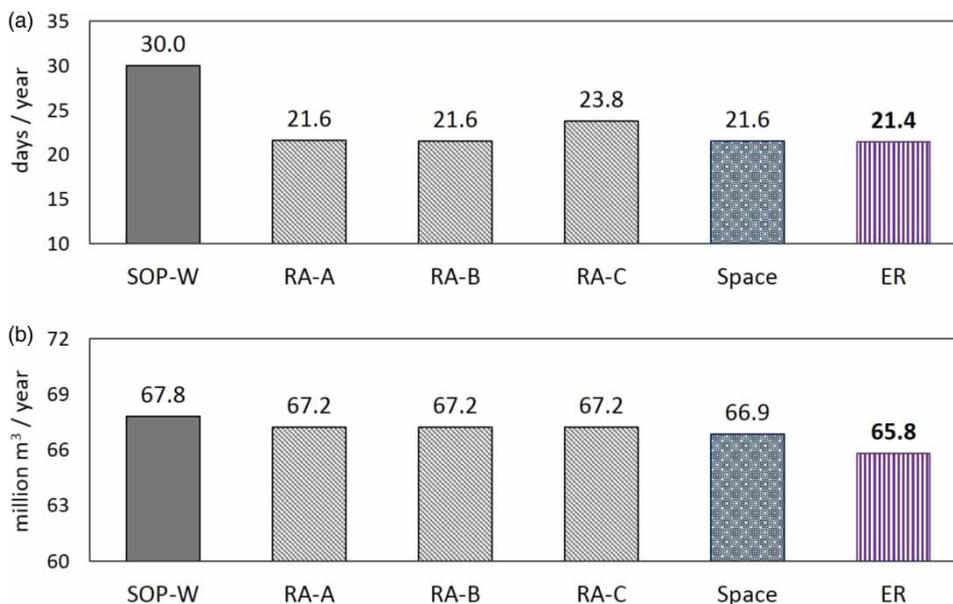


Figure 6 | Comparison of joint operation effects on water resource systems of the Andong Dam and Imha Dam: (a) number of days in water shortage per year, (b) amount of water shortage per year.

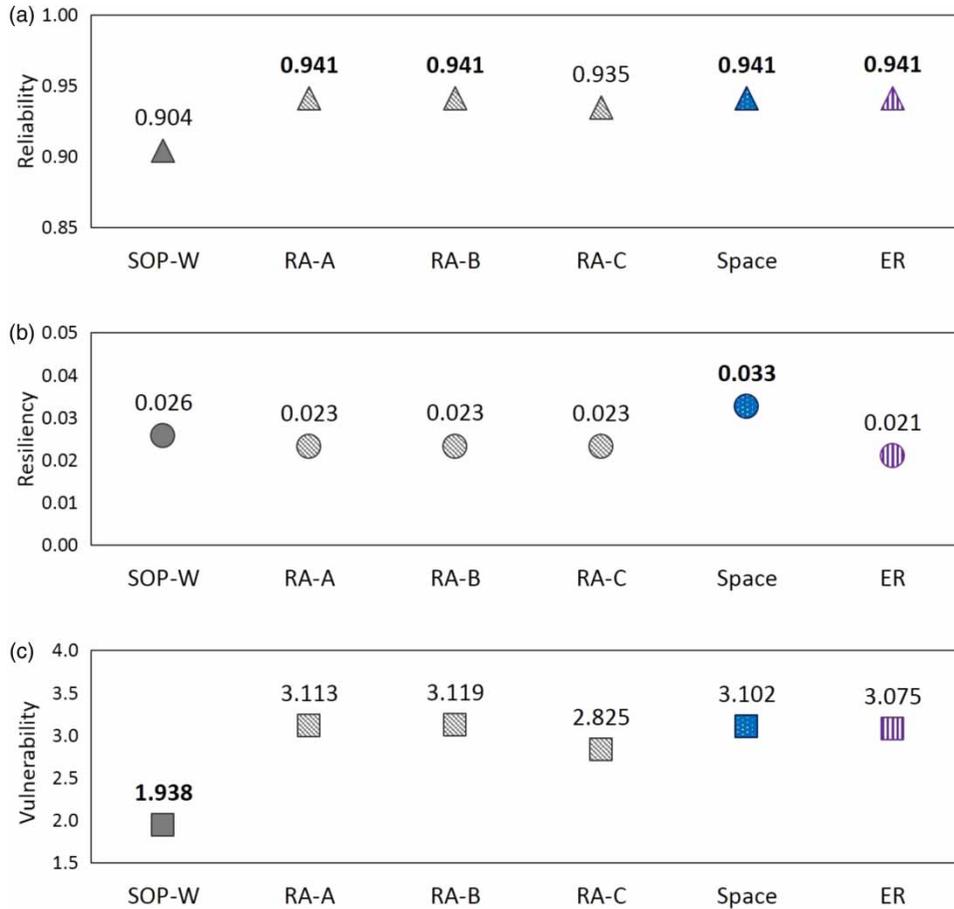


Figure 7 | Comparison of joint operation effects on water resource systems of Andong and Imha dams: (a) reliability, (b) resiliency, (c) vulnerability.

maintaining effective water storage rates of multiple reservoirs in parallel at the same level is an important regulation for reservoir operation in the AICT project.

Impact of hydrologic uncertainty

To evaluate the variability and range of possible effects of hydrology uncertainty on operation performance, a broader range of streamflow traces generated by the synthetic generation method is applied to SOP-W and the ER rule. Fifty groups of 20-year hydrologic sequences are evaluated based on the three performance criteria.

Figures 8(a)–(c) present the boxplots of reliability, resiliency, and vulnerability, respectively, for both SOP-W and the ER rules driven by the 50 synthetic streamflow traces. While reliability ranges from 0.86 to 0.95 with SOP-W, it ranges from 0.88 to 0.96 with the ER rule. Both rules are

affected by a range of synthetic streamflow series, and the overall performance of the ER rule is better than that expected from SOP-W. Similarly, in terms of resiliency, both rules are affected by a range of synthetic streamflow series. The ranges of reliability and resiliency outputs, i.e., impacts of hydrologic uncertainty, are very similar between the SOP-W and ER rule as well. Their values do not change drastically under the effect of hydrologic uncertainty. In contrast, there is a huge difference in the ranges of vulnerability between the two rules. Unlike SOP-W, the value of vulnerability with the ER rule varies considerably under hydrologic uncertainty. Although the overall performance in vulnerability is better with SOP-W, in most cases of synthetic streamflow, the vulnerability values of the ER rule are decreased over the performance driven by the observed inflow. It is inferred that the system operated by the ER rule is susceptible under hydrologic uncertainty.

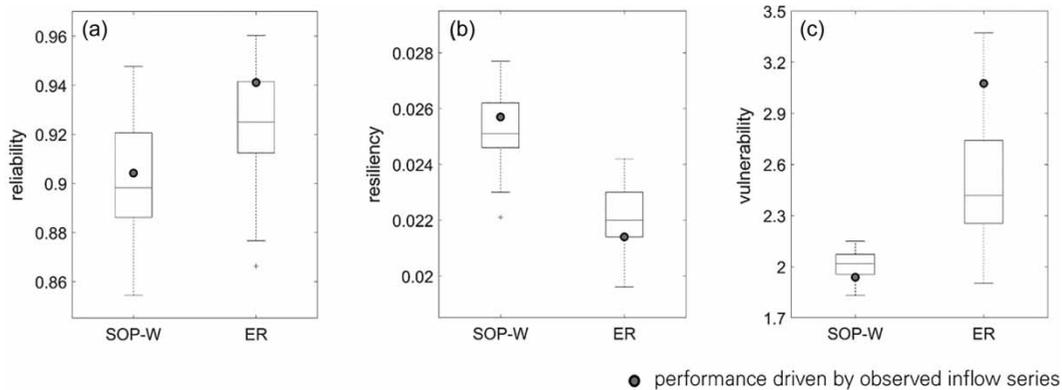


Figure 8 | Joint operation performance of water resource system of Andong and Imha dams under hydrologic uncertainty: (a) reliability, (b) resiliency, (c) vulnerability.

The ER rule is determined as the best method for joint operation in terms of reliability index. Besides, across the effect of hydrologic uncertainty, its superiority over SOP-W is confirmed. Nonetheless, it turns out that the ER rule is quite sustainable to hydrologic uncertainty. As there is a trade-off between reliability and vulnerability, it seems very difficult for a single method to outperform other methods across all performance indexes. Thus, the best possible option always differs depending on which criterion is required to be analyzed and evaluated.

CONCLUSIONS

This study provides a simple yet practically efficient approach to determine the optimal joint operation rule for parallel reservoirs that are linked by a connecting tunnel. First, the effect of the connecting tunnel was evaluated by comparing the results of the two operations driven by the SOP with and without a connecting tunnel (SOP-W and SOP-O, respectively). Subsequently, the existing joint operation rules were evaluated by comparing the joint operation results with SOP-W. From our experience in practical reservoir operation, selecting the optimum predeveloped models can often be better than developing a new one as per the circumstances.

Furthermore, the effects of hydrologic uncertainty on the joint operation performance were discussed using the synthetically generated multiple streamflow traces. This is significant because a broad range of potential streamflow

sequences should be comprehensively considered when testing an alternative policy.

As the connecting tunnel was built for drought mitigation, an optimal operation rule is required to maximize the advantage of using the tunnel. It was found that the reliability of the water supply system increased by passing approximately 12 million m³/year of additional water from the Imha Dam to Andong Dam. Additionally, the number of days with water shortage decreased with the help of the connecting tunnel. The connecting tunnel's effects were notably positive from a water supply and drought management perspective.

These positive effects of the connecting tunnel were further enhanced by the optimal joint operation rules. On comparison of the three different joint operation rules in terms of reliability and vulnerability of the reservoir system, the ER rule was found to be the most suitable operation rule for the AICT project. When both dams operated using the ER rule, there was approximately 2 million m³/year of additional water supply; the number of water shortage days per year also decreased from 30 to 21.4 days. Thus, maintaining effective water storage rates in the Andong Dam and Imha Dam at the same level resulted in the most efficient operation rule for the target basin. Besides, hedging rules can improve reservoir performance especially under drought conditions (Seo et al. 2019). Further application of the hedging rules on the joint operation might be able to produce effective operation rules for drought management.

To address the effect of hydrologic uncertainty, a wide range of possible streamflow series, which were

synthetically generated, were tested for the operation rules. This did not result in a drastic impact on the performance metrics. However, when the ER rule was applied, the vulnerability of the water supply system was found to be susceptible to the natural variability of hydrologic inputs, while the reliability and resiliency were relatively robust. This indicates that preserving the effective water storage rates of all reservoirs at the same level can reduce the possibility of water shortage but lead to larger water shortage once the water supply fails.

On the other hand, the performance results of the joint operating rules can change if the inflow patterns change due to anthropogenic or climate change effects on the streamflow. Furthermore, the order of priorities can vary across different watersheds due to changes in geographical features and climate regimes. Thus, we cannot conclude that the ER rule will outperform the other rules in other case studies. To extend this study to other watersheds considering a joint operation of the reservoirs, the proposed comparative study needs to be implemented to evaluate the performance of each joint operation rule, which would be affected by some external conditions such as topography and climate regime.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ACKNOWLEDGEMENTS

This research was supported by a grant (18AWMP-B083066-05) from the Advanced Water Management Research Program funded by the Korea Environmental Industry and Technology Institute. The authors are grateful for the support from the Institute of Engineering Research, Seoul National University.

REFERENCES

- Afshar, M. H. 2013 [Extension of the constrained particle swarm optimization algorithm to optimal operation of multi-reservoirs system](#). *Int. J. Elec. Power* **51**, 71–81.
- Afshar, A., Shafii, M. & Haddad, O. B. 2010 [Optimizing multi-reservoir operation rules: an improved HBMO approach](#). *J. Hydroinform.* **13** (1), 121–139.
- Ahmadianfar, I., Adib, A. & Taghian, M. 2017 [Optimization of multi-reservoir operation with a new hedging rule: application of fuzzy set theory and NSGA-II](#). *Appl. Water Sci.* **7** (6), 3075–3086.
- Bower, B. T., Hufschmidt, M. M. & Reedy, W. W. 1962 *Operating Procedures: Their Role in the Design of Water-Resource Systems by Simulation Analyses*. Design of water resource systems, Harvard University Press, pp. 443–458.
- Chang, L. C. & Chang, F. J. 2009 [Multi-objective evolutionary algorithm for operating parallel reservoir system](#). *J. Hydrol.* **377** (1–2), 12–20.
- Clark, E. J. 1950 New York control curves. *J. Am. Water Works Assoc.* **42** (9), 823–827.
- Draper, A. J. & Lund, J. R. 2004 [Optimal hedging and carryover storage value](#). *J. Water Res. Plan. Man.* **130** (1), 83–87.
- Hashimoto, T., Stedinger, J. R. & Loucks, D. P. 1982 Reliability, resilience and vulnerability criteria for water resources system performance evaluation. *Water Resour. Res.* **18** (1), 489–498.
- Johnson, S. A., Stedinger, J. R. & Staschus, K. 1991 [Heuristic operating policies for reservoir system simulation](#). *Water Resour. Res.* **27** (5), 673–685.
- Kim, Y.-O., Eum, H.-I., Lee, E. G., Lee, K. S. & Kim, S. W. 2003 Development of an Integrated Operation System for the Nakdong River Basin. In: *2003 KSCE Annual Conference*, pp. 1984–1989.
- Kinugawa Integrated Dam Control Office 2012 *The Roles of the Group of Dams in the Upstream Area of Kinugawa River*. MLIT, Japan.
- Korea Water Resources Corporation 2008a *The Investigation of Andong Dam Sediment*. K-water.
- Korea Water Resources Corporation 2008b *The Investigation of Imha Dam Sediment*. K-water.
- Korea Water Resources Corporation 2011a *Andong-Imha Dams Connecting Tunnel Construction Feasibility Study Report*. K-water.
- Korea Water Resources Corporation 2011b *Andong-Imha Dams Connecting Tunnel Construction Working Design Report*. K-water.
- Korea Water Resources Corporation 2013a *Dam Management Regulation*. K-water.
- Korea Water Resources Corporation 2013b *Dam Operation Handbook*. K-water.
- Labadie, J. W. 2004 [Optimal operation of multi reservoir systems: state-of-the-art review](#). *J. Water Res. Plan. Man.* **130** (2), 93–111.
- Liu, P., Guo, S., Xu, X. & Chen, J. 2011 [Derivation of aggregation-based joint operating rule curves for cascade hydropower reservoirs](#). *Water Resour. Manag.* **25** (13), 3177–3200.
- Loucks, D. P. & Van Beek, E. 2017 *Water Resource Systems Planning and Management: An Introduction to Methods, Models, and Applications*. Springer, Cham, Switzerland.

- Loucks, D. P., Stedinger, J. R. & Haith, D. A. 1981 *Water Resource Systems Planning and Analysis*. Prentice-Hall, Englewood Cliffs, NJ, USA.
- Lund, J. R. & Guzman, J. 1999 Some derived operating rules for reservoirs in series or in parallel. *J. Water Res. Plan. Man.* **125** (3), 143–153.
- Matalas, N. C. 1967 Mathematical assessment of synthetic hydrology. *Water Resour. Res.* **3** (4), 937–945.
- Ministry of Land, Transport and Maritime Affairs. 2011 *Criteria of Dam Design MLTM*.
- Oliveira, R. & Loucks, D. P. 1997 Operating rules for multi-reservoir systems. *Water Resour. Res.* **33** (4), 839–852.
- Paredes, J. & Lund, J. R. 2006 Refill and drawdown rules for parallel reservoirs: quantity and quality. *Water Resour. Manag.* **20** (3), 359–376.
- Park, K. B. & Lee, S. T. 2005 Parallel reservoirs system operation using nyc-space allocation-rule. *J. Environ. Sci.* **14** (6), 533–542.
- Peng, A., Peng, Y., Zhou, H. & Zhang, C. 2015 Multi-reservoir joint operating rule in inter-basin water transfer-supply project. *Sci. China Technol. Sci.* **58** (1), 123–137.
- ReVelle, C. 1999 *Optimizing Reservoir Resources: Including A New Model for Reservoir Reliability*. Wiley, New York, NY, USA.
- Sand, G. M. 1984 *An Analytical Investigation of Operating Policies for Water-Supply Reservoirs in Parallel*. PhD Dissertation, Cornell University.
- Seo, S. B., Kim, Y.-O. & Kang, S. W. 2019 Time-varying discrete hedging rules for drought contingency plan considering long range dependency in streamflow. *Water Resour. Manag.* **33** (8), 2791–2807.
- Takeuchi, K. 1998 *Sustainable Reservoir Development and Management*. No. 251. International Association of Hydrological Sciences.
- US. Army Corps of Engineers 1996 *Developing Seasonal and Long-Term Reservoir System Operation Plans Using HEC-PRM*. Hydrologic Engineering Center, U.S. Army Corps of Engineers.
- US. Army Corps of Engineers 1998 *HEC-5 User's Manual Version 8.0*. Hydrologic Engineering Center, U.S. Army Corps of Engineers.
- US. Army Corps of Engineers 2007 *HEC-ResSim, Reservoir System Simulation, User's Manual*, Hydrologic Engineering Center, U.S. Army Corps of Engineers.
- Xu, Z., Schumann, A. & Li, J. 2003 Markov cross-correlation pulse model for daily streamflow generation at multiple sites. *Adv. Water Resour.* **26** (3), 325–335.
- Xu, C., Hu, C., Liu, X. & Wang, S. 2017 Information entropy in predicting location of observation points for long tunnel. *Entropy* **19** (7), 332.
- You, J.-Y. & Cai, X. 2008 Hedging rule for reservoir operations: 1. A theoretical analysis. *Water Resour. Res.* **44** (1), 1–9.
- Yu, Y., Zhao, J., Li, D. & Wang, Z. 2019 Effects of hydrologic conditions and reservoir operation on transboundary cooperation in the Lancang-Mekong River Basin. *J. Water Resour. Plan. Manag.* **145** (6), 04019020.
- Zhang, X., Yu, X. & Qin, H. 2016 Optimal operation of multi-reservoir hydropower systems using enhanced comprehensive learning particle swarm optimization. *J. Hydro-Environ. Res.* **10**, 50–63.
- Zhao, J., Cai, X. & Wang, Z. 2011 Optimality conditions for a two-stage reservoir operation problem. *Water Resour. Res.* **47** (8), 1–16.
- Zhao, T., Yang, D., Cai, X., Zhao, J. & Wang, H. 2012 Identifying effective forecast horizon for real-time reservoir operation under a limited inflow forecast. *Water Resour. Res.* **48** (1), W01540.
- Zhao, T., Zhao, J., Lund, J. R. & Yang, D. 2014 Optimal hedging rules for reservoir flood operation from forecast uncertainties. *J. Water Res. Plan. Man.* **140** (12), 04014041.

First received 3 April 2019; accepted in revised form 30 December 2019. Available online 22 January 2020