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Development and Evaluation of the Hydropower Reservoir Rule Curve for a Sustainable Water Supply

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Abstract: The Seoul metropolitan area in the Han River basin is searching for sustainable water supply options after recently experiencing an extreme drought. Building a new reservoir is a common way to alleviate water shortage, but this comes at a great environmental cost. The South Korean government granted permission to add on a water supply function for the Hwacheon Reservoir, the largest hydropower reservoir in Korea, for the first time in the history. This study develops a new rule curve for the Hwacheon Reservoir to supply water and generate energy at the same time, considering the status of other reservoirs in the Han River basin. The simulation model uses two scenarios, with scenario 1 simulating historic operation and scenario 2 applying the deficit supply method. The new rule curve was formulated based on the results from scenario 2. Time-based and volumetric reliability increased by 33% and 4%, respectively, and resiliency more than doubled compared to the historic reservoir operation. This is the first case study in South Korea that demonstrates how to successfully integrate a water supply function into an existing hydropower reservoir. This study can be applied and extended to other river basins in an attempt to alleviate water shortages by adding new functions to existing reservoirs.

Keywords: rule curve; deficit supply method; hydropower reservoir; sustainable water supply

1. Introduction

In large river basins, water resources are often managed by reservoir systems [1,2]. Reservoir systems play key roles in water supply [3], power generation [4], flood control [5], and instream water supply [6]. In South Korea, reservoir systems are vital for water resource management, as most rainfall is concentrated from June to September. The role of reservoir systems has become more significant as climate change has advanced. Climate change has recently caused more extreme weather events like floods and droughts [7,8] as well as significant changes in reservoir inflow due to an increase in the spatiotemporal variability of rainfall [9–17]. These changes impact water availability in reservoirs [18]. New reservoirs were proposed in the Han River basin to meet the increasing water demand beginning in 1998, but they were never built, for environmental reasons [19–21].

The Han River basin is the largest basin in South Korea. The Seoul metropolitan area, with a population of more than 20 million people, is located in this basin. Water resources in the Han River basin are managed by a reservoir system consisting of nine reservoirs. The Paldang Reservoir, located downstream of the Han River, supplies water to the Seoul metropolitan area. Eight reservoirs lie upstream of the Paldang Reservoir, of which three multipurpose reservoirs in particular (Chungju, Soyanggang, and Hoengseong Reservoirs) have the greatest impact on the water supply of the Paldang Reservoir. Due to the recent spatiotemporal changes in rainfall, the stability of reservoir operations in the Han River basin have been affected. South Korea endured a drought from 2014 to 2016, which lasted longer than usual. The rainfall during this three-year period was only 55–68% of the long-term average. The three-year drought resulted in an insufficient water supply to the Seoul metropolitan area. During this period, the Paldang Reservoir could not meet the planned water supply for the Seoul metropolitan area.

Each reservoir is part of a complex reservoir system in which every reservoir significantly affects the operation of all other reservoirs. Integrated reservoir system operation is essential for the sustainable water management of the entire basin. However, it is difficult to integrate a reservoir system, as numerous agencies manage different types of reservoirs (i.e., multipurpose, hydropower, irrigation, etc.) in South Korea. For example, K–water, which is the largest water company in South Korea, operates and manages multipurpose reservoirs, while Korea Hydro and Nuclear Power (KHNP) operates and manages hydropower reservoirs.

In 2020, the South Korean government made an exception for the Hwacheon Reservoir to not only generate hydropower but also to supply water to alleviate the damage caused by severe drought. This decision was made for the Hwacheon Reservoir, as it is the largest hydropower reservoir with sufficient water capacity to supply water. The Hwacheon Reservoir is missing a rule curve, as it was only used for hydropower generation purposes and not for water supply purposes. This study developed a new rule curve for the Hwacheon Reservoir to help two separate agencies integrate their reservoir system operations.

A reservoir rule curve is an ideal curve of storage or release based on inflow, water supply, and power generation [22]. In Taiwan, Chen developed and verified a rule curve for the Fei-Tsui Reservoir using a multipurpose genetic algorithm [23]. Rule curves for multipurpose reservoirs were developed, considering the environmental water supply, using the integrated adaptive optimization model (IAOM) [24]. In Sweden, Bosona et al. developed a rule curve using reservoir simulation to improve the performance of hydropower reservoirs [25]. In the United States, a study was conducted on the use of historical water level data to evaluate reservoir rule curves [26]. Previous studies developed and evaluated a rule curve for a single reservoir, while this study developed a rule curve for the Hwacheon Reservoir while considering the status of other reservoirs in the Han River basin.

Two scenarios and evaluation cases were simulated. In scenario 1, the existing reservoir system operation was presented. Scenario 2 was constructed to develop the rule curve for the Hwacheon Reservoir. The rule curve was developed using the deficit supply method and historical release data of the Hwacheon Reservoir. The deficit supply method is a reservoir operations method in which the streamflow is observed at a point downstream, and the releases from the upstream reservoirs are adjusted to meet the streamflow required at the downstream point. This study applied the deficit supply method to three multipurpose reservoirs (Chungju, Soyanggang, and Hoengseong Reservoirs) and a hydropower reservoir (Hwacheon Reservoir) to improve the water supply capability of the entire Han River reservoir system. The evaluation case was simulated to analyze the effects of the Hwacheon Reservoir rule curve on the water supply of the entire Han River reservoir system. The time-based reliability, volumetric reliability, and resiliency of the Chungju, Soyanggang, Hoengseong, and Paldang reservoirs were calculated and compared to evaluate the water supply capability, since the releases from these reservoirs have great effects on the water supply to the Seoul metropolitan area. This study also evaluated the amount of water released from the Hwacheon Reservoir for the production of hydropower in order to check if the main function of power generation would still be maintained even after adding the water supply function.

2. Study Area

The Han River basin is the largest basin in South Korea, with an area of 34,428 km^2. The basin consists of the South Han River and the North Han River. There are nine reservoirs in the Han River basin, including three multipurpose reservoirs and six hydropower reservoirs (Figure 1). The Paldang Reservoir is located at the junction of the South and North Han Rivers and is essential, as it supplies water to the Seoul metropolitan area. The operation of the Paldang Reservoir depends on the operation of five upstream reservoirs (four hydropower and one multipurpose reservoir) in the North Han River as well as three upstream reservoirs (one hydropower and two multipurpose reservoirs) in the South Han River (Table 1).

Figure 1. Reservoir system in the Han River basin.

Table 1. Physical characteristics of reservoirs in the Han River basin.

Reservoir	Type	River	Total Storage (MCM)	Effective Storage (MCM)
Chungju	Multipurpose reservoir	South Han River	2750.0	1789.0
Hoengseong			86.9	73.4
Soyanggang		North Han River	2900.0	1900.0
Hwacheon	Hydropower reservoir		1018.4	658.0
Chuncheon			150.0	61.0
Uiam			80.0	57.5
Cheongpyeong			185.5	82.6
Goesan		South Han River	15.3	5.7
Paldang		Han River (Junction of South Han and North Han Rivers)	244.0	18.0

3. Methodology

3.1. Simulation for Reservoir Operation

Most reservoirs in South Korea are operated based on the firm supply method, which supplies a predetermined amount of water, regardless of the current downstream streamflow condition (Figure 2a). The firm supply method enables sustainable reservoir operations when a reservoir has enough water, but it cannot meet the downstream water demand when reservoir storage is insufficient. The deficit supply method determines the streamflow required at a downstream point in advance and reduces release from the reservoirs when natural streamflow exceeds the predetermined streamflow (Figure 2b) [27]. For example, Paldang Reservoir, which has a predetermined streamflow of 174 m^3/s, sits at a downstream point. This method allows the reservoir to store water when the natural streamflow is abundant and to supply water only when the natural streamflow is insufficient.

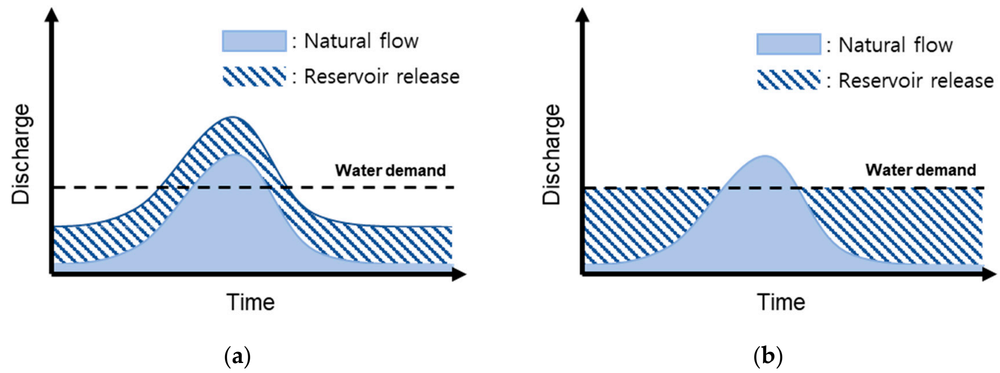

Figure 2. Examples of firm supply and deficit supply methods. (**a**) The firm supply method supplies a certain amount of water, regardless of the situation downstream. (**b**) The deficit supply method supplies additional water in the event of downstream water shortage.

The Han River reservoir system was analyzed using the simulation model [28–33]. This study used the Hydrologic Engineering Center–Reservoir Simulation (HEC–ResSim) developed by the U.S. Army Corps of Engineers [34]. The HEC–ResSim can simulate the complex operations of reservoirs in detail. Input data for the simulation model were 33 years (1987–2019) of daily inflow.

This study simulated two scenarios and one evaluation case for nine reservoirs, including three multipurpose reservoirs and six hydropower reservoirs (Figure 3). Scenario 1 is a basic scenario that demonstrates the current Han River reservoir system. In this scenario, the multipurpose reservoirs released the planned amount of water (firm supply method) and the hydropower reservoirs released the water that is above the normal high-water level (run-of-river reservoir). In scenario 2, this study applied the deficit supply method to three multipurpose reservoirs and the Hwacheon reservoir, which is the largest hydropower reservoir in Korea. The downstream point was the Paldang Reservoir. The rest of the hydropower reservoirs released the water when it was above the normal high-water level. Originally, the main function of the Hwacheon Reservoir was power generation; the water supply function was added in 2020. The model maintains the historic power generation release, as the generation of power from this reservoir is still essential. The Hwacheon Reservoir's power generation release was analyzed by comparing its monthly average historical release data with its monthly average simulated release data.

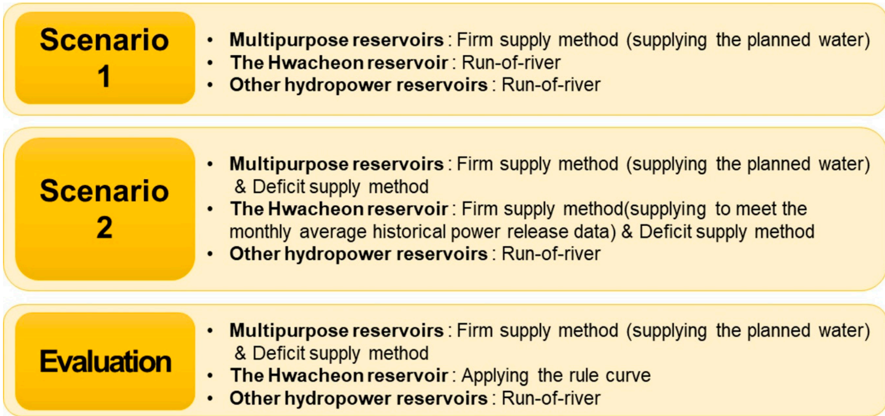

Figure 3. Reservoir operation methods for the study. Multipurpose reservoirs include the Chungju, Soyanggang, and Hoengseong reservoirs. Other hydropower reservoirs include the Chuncheon, Uiam, Cheongpyeong, and Goesan reservoirs. All reservoirs are located upstream of the Paldang Reservoir.

This study ultimately developed a rule curve for the Hwacheon Reservoir based on the results from scenario 2 (Figure 4). Reservoirs aim to increase storage to the normal high-water level by the end of September such that the stored water can be used for a year. The storage level at the end of September has the greatest influence on the reservoir operation.

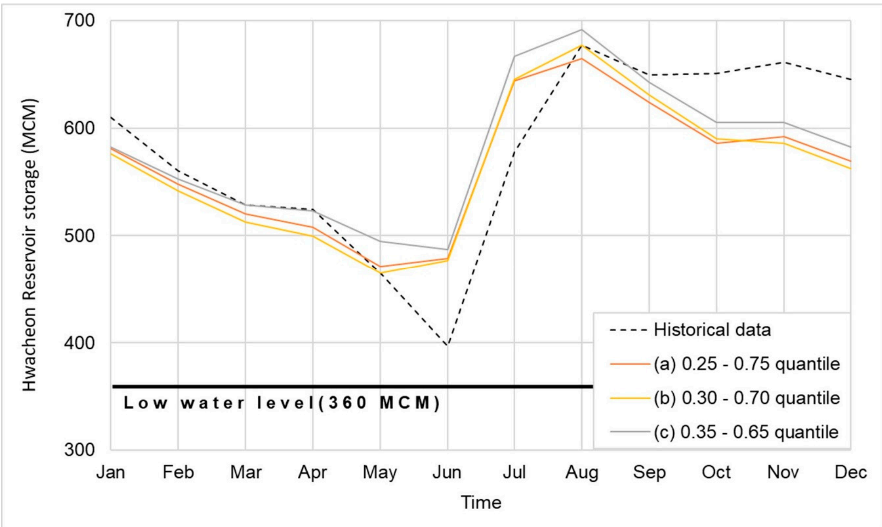

Figure 4. Rule curves for the Hwacheon Reservoir. Correlation coefficients by each curve were (**a**) 0.84; (**b**) 0.82; and (**c**) 0.82. Curve (**a**) was selected as the rule curve of the reservoir. The Hwacheon Reservoir's dead storage is 360 MCM, and the effective storage, including dead storage, is 1018 MCM.

The years that reflected the storage quantiles of 0.3–0.7, 0.25–0.75, and 0.35–0.65 at the end of September were selected to develop the three rule curves. Three rule curves were developed by averaging the monthly storage of the years selected for each quantile (Figure 4). Correlation analysis was conducted with the historical storage for the three rule curves to select the one most suitable for the actual operation of the Hwacheon Reservoir. If the water level is above the rule curve, a reservoir release is maximized to lower the water level based on the rule curve. If the water level is below a rule curve, the release is minimized to raise the water level to the rule curve. The evaluation case applied a newly developed rule curve to assess the Han River reservoir system.

3.2. Evaluation Indexes

This study evaluated the results of the simulation model using evaluation indexes (i.e., time-based reliability, volumetric reliability, resiliency) suggested by Hashimoto et al. (1982) [35]. Time-based reliability represents the probability of success in water supply over time, and it is the ratio of the period in which the planned amount of water supply was achieved during the whole period (Equation (1)). Volumetric reliability represents the probability of success in a quantitative water supply, and it is calculated as the ratio of the actual amount of supply to the total planned amount of water supply during the whole period (Equation (2)). The resiliency represents the recovery rate to the normal state after a water supply failure, and is calculated using Equation (3). In Equations (1) and (2), *TR* is time-based reliability, *Tt* is the whole period, *Ts* is the water supply failure period, *VR* is the volumetric reliability, *Qp* is the total planned amount of water supply during the whole period, and *Qs* is the shortage in water supply. In Equation (3), γ is the average resiliency, M is the number of water supply failure events, and *d*(*j*) is the duration of the water shortage.

This study calculated three indexes for the Chungju, Soyanggang, Hoenseong, and Paldang reservoirs. These indexes were not calculated for the Hwacheon, Chuncheon, Uiam, Cheongpyeong, and Geosan reservoirs, since they are hydropower reservoirs and do not have the planned amount of water supply.

$$TR\ (\%) = \left[1 - \frac{T_s}{T_t}\right] \times 100\ (\%) \tag{1}$$

$$VR\ (\%) = \left[1 - \frac{Q_s}{Q_p}\right] \times 100\ (\%) \tag{2}$$

$$\gamma = \left[\frac{1}{\mathrm{M}} \sum_{\mathrm{j}=1}^{\mathrm{M}} \mathrm{d}(\mathrm{j})\right]^{-1} \tag{3}$$

4. Results and Discussion

4.1. Scenario 1

In scenario 1, the model simulates the current operation of the Han River reservoir system. Multipurpose reservoirs supplied the planned amount of water, and hydropower reservoirs released the inflow when the reservoir water level was above the normal high-water level. All upstream multipurpose reservoirs supplied water based on the firm supply method, regardless of the status of the downstream Paldang Reservoir. The Paldang Reservoir failed to supply water in 38% of the operation period. The volumetric reliability was 93.8%, and the resiliency was 0.03 (Table 2). The Hwacheon Reservoir released only 60% of the historic power generation release (Table 3). The results showed that it is challenging to achieve both a sustainable water supply from the Paldang Reservoir and generate sufficient power from the Hwacheon Reservoir.

Table 2. Reservoir water supply capability indexes. The average resiliency of the Soyanggang Reservoir could not be calculated because there was no water supply failure event in scenario 1.

Index	Case	Chungju Reservoir	Soyanggang Reservoir	Hoengseong Reservoir	Paldang Reservoir
Time-based reliability (%)	Scenario 1	93.3	100.0	86.9	62.1
	Scenario 2	92.2	95.5	86.0	96.1
	Evaluation	95.8	85.8	92.3	95.1
Volumetric reliability (%)	Scenario 1	95.3	100.0	89.2	93.8
	Scenario 2	94.6	97.0	88.4	97.6
	Evaluation	97.1	88.3	94.7	97.8
Average resiliency	Scenario 1	0.027	-	0.018	0.030
	Scenario 2	0.027	0.030	0.019	0.048
	Evaluation	0.030	0.019	0.027	0.066

Table 3. The Hwacheon Reservoir monthly release for power generation. In scenarios 1 and 2, release amounted to 60% and 90% of the levels in the average historical data, respectively. In the evaluation model, the rule curve for the Hwacheon Reservoir was applied, and the release was 90% of that in the historical data.

Month	Scenario 1 (m^3/s)	Scenario 2 (m^3/s)	Evaluation (m^3/s)	Historical Data (m^3/s)
Jan	3.1	19.6	4.9	24.0
Feb	3.2	19.5	21.6	23.2
Mar	5.6	20.8	23.9	23.5
Apr	12.9	24.6	27.3	27.3
May	22.3	38.6	40.1	46.6
Jun	34.4	27.3	22.1	37.9
Jul	80.1	72.4	58.7	79.2
Aug	81.2	97.3	92.5	94.2
Sep	36.2	60.1	81.4	56.6
Oct	1.0	24.1	30.6	28.1
Nov	2.6	12.9	11.9	14.1
Dec	1.6	15.4	17.2	16.9
Average	23.68	36.05	36.02	39.30

4.2. Scenario 2

This scenario applied the deficit supply method to the three multipurpose reservoirs and the Hwacheon Reservoir. When the Paldang Reservoir could not supply the planned amount of water, these reservoirs supplied additional water to reduce the water shortage damage in the Seoul metropolitan area. However, if water scarcity occurred in both upstream and downstream reservoirs, the upstream reservoirs made a release to meet the planned amount of water. The deficit supply method enabled efficient reservoir system operation and sustainable water resource management, since upstream reservoirs were operated in consideration of the downstream reservoirs. Although a water supply function was added to the Hwacheon Reservoir, the power generation function should be maintained, as the reservoir is a hydropower reservoir.

The results of scenario 2 showed that the time-based reliability of the Paldang Reservoir increased by 34%, and its volumetric reliability increased by 3.8% compared to scenario 1. In the operation results of the multipurpose reservoirs, all the indexes (time-based reliability, volumetric reliability, and resiliency) decreased compared to scenario 1 (Table 2), as each multipurpose reservoir released additional water in addition to the planned amount of water supply in order to reduce the water shortage of the Paldang Reservoir. However, the increase in the reliability of the Paldang Reservoir was greater than the reduction in the reliability of the multipurpose reservoirs. Resiliency, which evaluates the rate of recovery to the normal state after a water supply failure period, increased by more than 50% in scenario 2 as compared to scenario 1. The results from scenario 2 were more efficient than the results from scenario 1 in terms of the entire reservoir system. In scenario 1, the release for power generation sharply decreased in non-flood periods because all inflow above the normal high-water level was released. The results from scenario 2 showed that the power generation release from the Hwacheon Reservoir was close to the historical release (92%) (Table 3). Compared to scenario 1, scenario 2 was also more efficient in terms of the power generation of the Hwacheon Reservoir. The operation method in scenario 2 could improve the water supply capability of the Paldang Reservoir while maintaining the power generation of the Hwacheon Reservoir. The rule curve of the Hwacheon Reservoir was developed based on the results of scenario 2.

This study looked at the correlation between three rule curves (0.3–0.7, 0.25–0.75, and 0.35–0.65 quantiles) at the end of September and the historical reservoir storage. The best rule curve was the 0.25–0.75 quantile, which had the highest correlation coefficient (Figure 4).

4.3. Evaltuation of the Rule Curve for the Hwacheon Reservoir

The model was constructed to evaluate the effect of the rule curve developed using the results of scenario 2 on the operation of the Han River reservoir system and the Hwacheon Reservoir. The deficit supply method was applied to the three multipurpose reservoirs and the rule curve of the Hwacheon Reservoir was also applied. Compared to the current operation (scenario 1), the time-based reliability and volumetric reliability of the Paldang Reservoir increased by 33% and 4%, respectively (Table 2). The water supply capability of the reservoir system was more efficient when the rule curve was applied to the Hwacheon Reservoir. The resiliency was more than doubled, indicating faster recovery from water supply shortage.

Compared to the results of scenario 2, time-based reliability decreased by 1% while the volumetric reliability and resiliency increased by 0.2% and 0.018, respectively. During a water shortage, scenario 2 would cause more severe damage than the evaluation case. The simulated power generation release of the Hwacheon Reservoir was 90% of the historical release data in the evaluation case (Table 3).

The reservoir storage was compared during a recent drought (2014–2017) between the results of the Hwacheon Reservoir in scenario 2 and the evaluation case (Figure 5). In scenario 2, the water level of the reservoir decreased at the beginning of the drought and did not recover as the drought continued. In the evaluation case, the water level did not reach the low-water level due to the reservoir operation based on the rule curve. Although the evaluation indexes between scenario 2 and the evaluation case did not have a significant difference, storage changes during the drought confirmed that the evaluation case enables more sustainable operations of the Hwacheon Reservoir.

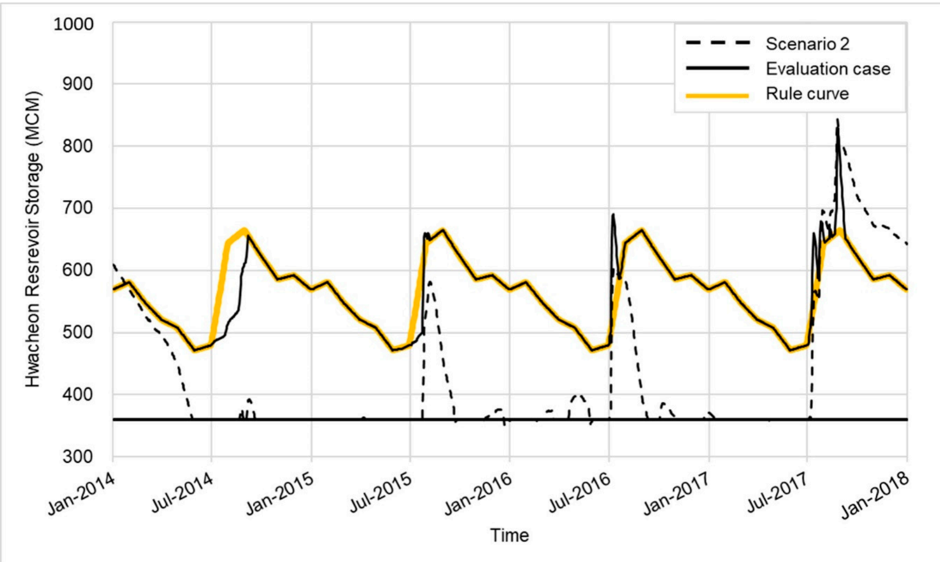

Figure 5. Storage change of the Hwacheon Reservoir (2014–2017). The water level reached the low-water level by continuously supplying the planned amount of water in scenario 2. However, in the evaluation case, the water level was maintained according to the rule curve.

5. Conclusions

Supplying enough water to the Seoul Metropolitan area became challenging as extreme weather events like droughts occurred more frequently. The Seoul metropolitan area is searching for stable water supply options. Building reservoirs is one of the most common approaches to stabilizing water availability, satisfying water demand, and alleviating water shortage. This approach has significant negative environmental impacts during the construction and operation of reservoirs. As an alternative, Korean government changed the function of the largest hydropower reservoir (Hwacheon Reservoir) and added a water supply function. Accordingly, it is necessary to develop a new rule curve for the Hwacheon Reservoir. This study developed a new rule curve for the Hwacheon Reservoir to consider the new water supply function. Applying the deficit supply method and considering the status of the other reservoirs in the Han River basin was key to developing a new rule curve for the Hwacheon Reservoir. The simulation model ran two scenarios and then developed a new rule curve based on the results from scenario 2 that applied the deficit supply method and the historical release data. The evaluation showed that it is possible to provide a sustainable water supply and generate almost the same amount of energy in the Hwacheon Reservoir using a newly developed rule curve.

Metropolitan areas like Seoul will continue to vigorously seek out additional sources of water supply under current exacerbating climate conditions. Building a new reservoir can cause negative environmental impacts. Alternatives to building new reservoirs do exist. The approach of adding a water supply function to an existing hydropower reservoir will bring additional water supply without needing to build a new reservoir and losing hydropower generation function. This work can be applied and extended to other river basins attempting to alleviate water shortage by adding a new function to an existing reservoir.

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