

Article

Assessing the Potential of Agricultural Reservoirs as the Source of Environmental Flow

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Abstract: Excessive nutrient loadings from drainage areas and resulting water quality degradation in rivers are the major environmental issues around the world. The water quality further deteriorates for the large seasonal variation of precipitation and water flow. Environmental decision makers have been exploring affordable and effective ways of securing environmental flow (EF) to improve the water quality, especially in dry seasons, and agricultural reservoirs have attracted the attention of policymakers as an alternative source of EF. This study proposed an analysis framework for assessing the EF supply potential of agricultural reservoirs as alternative sources of EF. A reservoir water balance model was prepared to mathematically represent the reservoir water balance and quantify temporal variations of the amount of water available for the EF supply. The simulation model was designed to explicitly consider inflow from the upstream drainage areas, irrigation water requirement, and hydrological processes happening in the reservoirs. The proposed framework was applied to four agricultural reservoirs located in South Korea to evaluate its efficiency. Results showed that the additional storage capacity added by the dam reinforcement enabled the study reservoirs to satisfy both needs, EF and irrigation water supply. The surplus capacity turned out to be enough to satisfy various EF supply scenarios at the annual time scale. However, the current operation plans do not consider the seasonal variations of reservoir hydrology and thus cannot supply EF without violating the original operational goal, irrigation water, especially in dry months. The results demonstrate that it is necessary to consider the temporal variations of EF when developing reservoir operation rules and plans to secure EF. This study also highlights the unconventional roles of agricultural reservoirs as resources for improved environmental quality. The methods presented in this study are expected to be a useful tool for the assessment of agricultural reservoirs' EF supply potential.

Keywords: irrigation; reservoir water balance; reservoir operation; hydrological modeling; Four Major Rivers Restoration Project; tank model

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1. Introduction

Reservoirs play an important role for water resources management by helping store rainwater received from their drainage areas and regulate downstream streamflow. Reservoir operation can alter downstream flow regimes and ecosystems [1–3]. Sustainable water resources management requires reservoirs to support both anthropogenic activities

and the environment; however, the hydrological and social complexity involved in reservoir decision-making processes makes it challenging to optimize the trade-off between multiple water use objectives [1,4,5]. Various reservoir operation models and strategies have been developed to guide reservoir-river management, but there is still substantial room for improvement in balancing between reservoirs' roles as the sources of water for agricultural water use and the environmental flow (EF) [1–3,6,7].

Rivers and reservoirs are important freshwater resources that serve many unique needs and demands [1–3,8]. In Korea, agricultural sectors use 48% of the water resources, and the Korean government has constructed more than 70,000 agricultural infrastructure facilities, including 17,240 reservoirs, to provide stable irrigation water since the early 20th century [9]. Recently, the government newly built 16 weirs along the four major rivers, Han, Nakdong, Geum, and Yeongsan Rivers, and heightened the dams of large agricultural reservoirs with the purpose of securing more water resources and mitigating floods, which is called the Four Major Rivers Restoration Project [10,11]. However, the construction of weirs inevitably slowed upstream water velocity and decreased downstream water volume, which resulted in unfavorable environmental consequences such as increases in nutrient concentrations and algal bloom frequency [12].

Agricultural reservoirs reinforced with additional dam heights are expected to help increase river flow discharge by diverting stored water into rivers [13–17]. Environmental flow is defined as water flows required to maintain ecosystem services and satisfy human needs, and it considers not only the quantity and quality of the flow, but also their temporal variations [2,8,18–21]. According to the Korea Design Standards (code names: KDS 51 and 67) [22,23] on stream and agricultural infrastructure, EF represents the amount of water required for conserving stream water quality, groundwater level recharge, and habitat for animals and plants. EF is usually determined considering a low flow condition, usually specified by 10-day low flow, which is commonly applied to reservoir design in Korea [24,25]. Stable stream EF can help improve water and ecosystem quality by reducing pollutant concentrations (dilution) and conserving wildlife habitats. It is now widely agreed that water demands must be balanced with environmental and ecological needs [8,26–28]

Reservoirs have been regarded as a source of water to satisfy both human and environmental demands simultaneously [1–3,29,30]. Wang et al. [5] proposed a framework to explicitly consider ecological flow requirements when operating reservoirs for water supply and hydropower generation. KhazaiPoul et al. [31] optimized reservoir operation schedule to meet downstream environmental water requirement while maximizing agricultural income from irrigated croplands. Gorgoglione et al. [32] proposed a scenario-based modeling framework to resolve environmental and socio-economic water conflicts in allocating water in transboundary watersheds. Huang et al. [4] explored hedging rules for two-objective reservoir operation based on the characteristics of economic and multi-level environmental water demands. Adams et al. [1] developed a framework for operating reservoirs to support the downstream ecology of regulated rivers with seasonal uncertainty while meeting human water demands. Many approaches and methods have been proposed for reservoir water allocation or operation rules optimization; however, there is no such unique standard method applicable to any cases; each may be suitable for different applications.

Lee and Noh [14] assessed the availability of EF supply from an agricultural reservoir by applying optional operation rule curves. Kim et al. [13] estimated the EF supply potential of agricultural reservoirs and developed EF supply scenarios based on the amount of daily water release of the reservoirs. Park et al. [16] calculated the water balances of four representative reservoirs considering their irrigation water and EF supply. Lee et al. [15] estimated the amount of EF available from four reservoirs located in the Nakdong River basin using the operation rules determined based on the water release criteria curves. Lee and Noh [33] investigated the potential impacts of climate changes on the irrigation water and EF supply capacity of an agricultural reservoir. The previous studies investigated the

potential of agricultural reservoirs as a source of EF, but they did not consider the seasonal variations of irrigation water requirement and EF but only their annual overall amount. Moreover, details of the reservoir operation rules, including restrictions applied to the level of stored water in rainy seasons and the rate of water release in drought, were rarely considered when calculating the amount of water available for EF. Thus, the EF estimates were likely to become biased and even unrealistic.

The Yeongsan River, one of the four major rivers in Korea, has 169 tributaries with two large weirs (and 1102 small dams and reservoirs) within its drainage watershed and an estuary dike at its outlet. Two new weirs were recently built, and the dams of 14 reservoirs were heightened as part of the four major rivers restoration project [34]. The river has been suffering from water quality degradation, and the issue now gets worse due to the construction of the new two weirs and resulting decrease in stream flow volume and velocity. The Korean government is trying to identify feasible and tangible ways to improve the river's water quality and ecosystems, especially in dry season. As part of such effort, the Ministry of Environment is looking for reliable water sources to secure stable EF for the river basin.

Several reservoirs in the Yeongsan River basin received the attention of policy makers as an alternative source of EF, since they believe that the reinforcement made for the dams may be able to provide the reservoirs with capacities to provide the amount of water required to keep "stable flow" of the river. Among them, four large agricultural reservoirs were expected to be the immediate option to help supply EF of the Yeongsan River because of their relatively large storage capacities. However, it is not clear how much water can be taken from the reservoirs to provide EF while meeting their original operational goals of supplying irrigation water to its downstream agricultural areas [1,4].

This study proposed an analysis framework to evaluate the capacities of reservoirs as the source of EF and explore advanced reservoir operation options that can balance the trade-off between irrigation water and environmental flow. The proposed methods were applied to developing EF supply plans for the Yeongsan River basin in South Korea to test the applicability. In this study, we explored efficient ways to release reservoir water to the river to meet both EF and irrigation requirements, considering the temporal variations of watershed hydrology and EF. To accomplish the goals, we prepared a simulation model that describes hydrological processes associated with the water balance of a reservoir and tested the effectiveness of plausible reservoir water release strategies using the model. This study demonstrates how the environment can be improved by integrating and maximizing the use of existing resources and facilities.

2. Framework Development and Materials

2.1. Reservoir Water Balance Model

There are many different models capable of describing the water balance of an agricultural reservoir. In this study, we used a reservoir water balance model consists of a three-layer tank (inflow) and irrigation (outflow) sub-modules. The reservoir water balance in the model is governed by the reservoir's storage continuity equation [6,35]:

$$\frac{dS}{dt} = R + RI - E - IWS - SO - EF, \quad (1)$$

where R is rainfall on the reservoir area (ML/day, where ML (megaliter) is 10^3 m^3), RI is reservoir inflow (ML/day), E is reservoir surface evaporation (ML/day), IWS is irrigation water supply (ML/day), SO is spillway overflow (ML/day), and EF is environmental flow (ML/day), which is governed by reservoir operations for supply plans and scenarios (Sections 2.3 and 2.4). Daily R and E were collected from weather stations for the water balance calculations. This study assumed that the reservoir-groundwater interaction is negligible because the reservoir groundwater outflow is known to have little effect on water balance in Korean reservoirs [6,36,37].

2.1.1. Reservoir Inflow

The reservoir water balance model employs a modified three-layer tank for reservoir inflow estimation, which is commonly used when the basin lag time is short, and the hydrograph recession slope is steep, especially in mountainous monsoon areas such as Korea and Japan [6,38–40]. Parameter calibration is often not an option due to the absence of reservoir inflow measurements. In such a case (ungauged areas), model parameter values can be estimated from the statistical relationships between watershed characteristics and parameter values derived from gauged watersheds, often called regionalization [41–44]. In this study, we selected 3-Tank models regionalized to the study areas (R-Tank). The R-Tank model is known to accurately predict streamflow of the Korean watersheds, and it has been widely used for reservoir water management and planning in ungauged watersheds [36,45,46]. Song et al. [44] showed the R-Tank models could provide acceptable prediction performance ($0.50 < NSE$, and $|PBIAS| < \pm 15$) at 9 of 10 watersheds in Korea. Song et al. [6] related streamflow simulation outputs of the R-Tank model [38] to a reservoir water balance equation and found the simulated reservoir water levels were in good agreement with the observed ones. The R-Tank model was employed to estimate reservoir inflow in the Four Major Rivers Restoration Project. Thus, the modeling and scenario analysis processes conducted in this study could be consistent with those of the project, and the new reservoir operation rules could be fairly compared with the original ones. A more detailed explanation of the three-layer tank model can be found in Song et al. [39].

2.1.2. Reservoir Outflow (or Irrigation)

Irrigation water supply (*IWS*) is the amount of water abstracted from the source, and its accurate quantification is important for improved agricultural reservoir operation efficiency [6,47,48]. Monitoring would be the most reliable way to quantify *IWS*, but it is often impractical to measure *IWS* released from reservoirs distributed at low densities across areas [48,49]. In the absence of *IWS* measurements, the irrigation water requirement (*IWR*) concept combined with a paddy water balance analysis can help estimate *IWS*, especially for irrigation facility design and water resources planning [48,50].

The *IWS* consists of the irrigation water requirement (*IWR*) and delivery management water requirement (*DMWR*) [48,51]. The irrigation efficiency (*Es*) is used to determine the *DMWR*. The *Es* represents the relative portion of the *IWS*, and it considers the combined efficiency of the water conveyance and distribution systems [48,52,53]. The *IWS* was calculated using the following equation [6,48,54]:

$$IWS_i = \frac{A_{rice}}{Es} \times \frac{IWR_i}{1000} \quad (2)$$

where A_{rice} is the irrigated area (km^2), *IWR* is the irrigation water requirement (mm/day), and *Es* is the irrigation efficiency (%). The *IWR* can be calculated using water balance in paddy fields [47,48,55]:

$$\frac{dPD}{dt} = RAIN + IWR - (DR + ET + INF), \quad (3)$$

where *PD* is the ponding depth (mm/day), *RAIN* is the rainfall on paddy fields (mm/day), *DR* is the surface drainage (mm/day), *ET* is the actual evapotranspiration (mm/day), and *INF* is the infiltration (mm/day). The *ET* is calculated by a modified Penman method [56,57] and the crop coefficient of paddy rice in each growth stage [37]. The *DR* occurs when the *PD* is greater than the height of the outlet weir (*LH*) [47,48,50,58,59]:

$$DR = PD - LH \text{ when } PD > LH, \quad (4a)$$

$$DR = 0 \text{ when } PD \leq LH, \quad (4b)$$

The *IWR* can be calculated by subtracting the *PD* from the recommended ponding depth (*PDrec*) when the *PD* drops below *PDrec* [47,48,50,58]:

$$IWR = PDrec - PD \text{ when } PD \leq PDrec, \quad (5a)$$

$$IWR = 0 \text{ when } PD > PDrec, \quad (5b)$$

The SO can be calculated simply from the following Equation (6):

$$SO = S - S_{so} \text{ when } S > S_{so}, \quad (6a)$$

$$SO = 0 \text{ when } S \leq S_{so}, \quad (6b)$$

where S_{so} is the reservoir storage corresponding to the normal pool level (m).

The reservoir water balance model has been widely employed in South Korea as a practical tool for agricultural reservoir planning and design. The modeling algorithms and computational procedures (Equations (1)–(6)) of the model were written in FORTRAN (V, Control Data Corporation, Bloomington, Minnesota, U.S.) to allow the standardized application in different cases, which is called the Hydrological Operation Model for Water Resources System (HOMWRS). The HOMWRS model is maintained by Korea Rural Community Corporation (KRC), responsible for agricultural reservoir design, construction, and operation in Korea [37] (Figure 1). Lee [60] applied the model to calculate irrigation water requirement with the consideration of EF supply. Woo and Kim [61] estimated the hydroelectric power generation capacity of an agricultural reservoir by calculating the amount of water available for power generation using the model. The HOMWRS model has also been used to evaluate the supply reliability of five agricultural reservoirs that were reinforced by the Four Major Rivers Restoration Project [62]. Besides, HOMWRS is being used by KRC to establish new operation and rehabilitation plans for existing agricultural reservoirs. The HOMWRS model was also used to analyze the water balance of agricultural reservoirs in the Four Major Rivers Restoration Project. We selected the model for this study to maintain the consistency and conduct comparative analysis of results with the Four Major Rivers Restoration Project. This study employed the same HOMWRS submodules and parameter values as those used in the Four Major Restoration Project for consistency. In this study, the interpretation of the HOMWRS outputs was prepared using Microsoft Excel and PowerPoint.

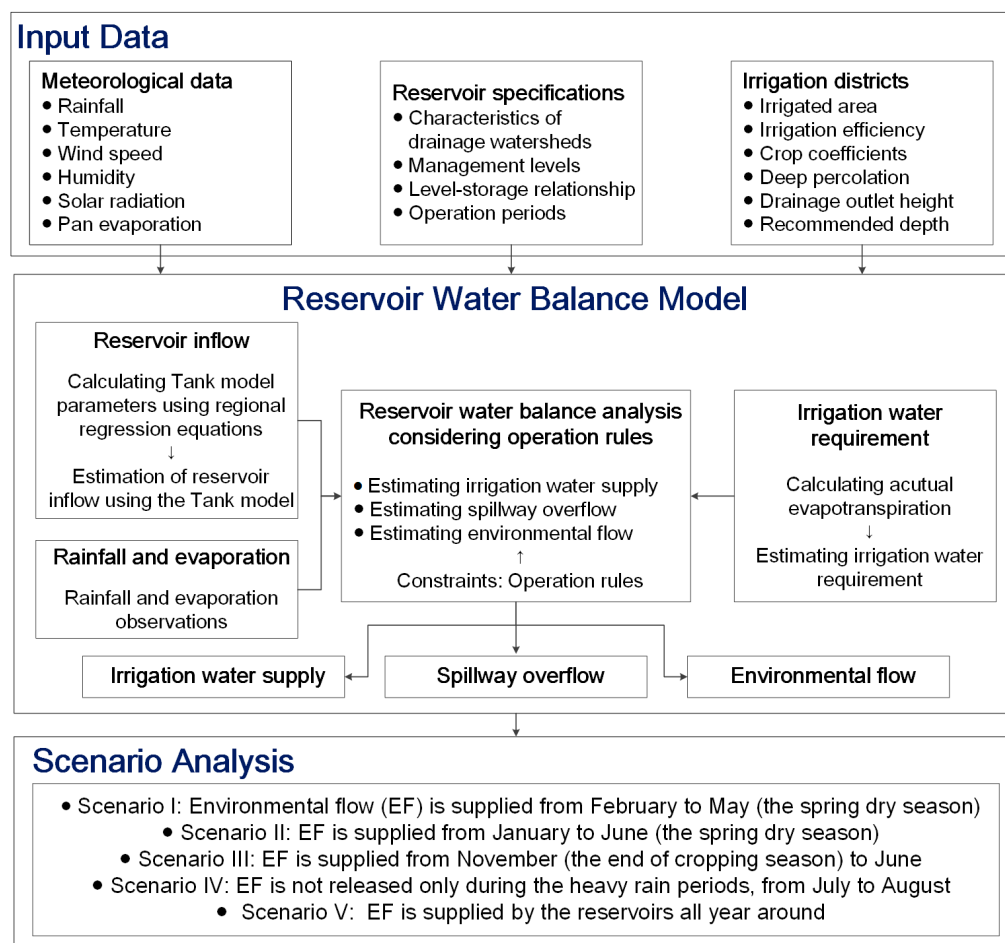


Figure 1. The procedure of the water balance analysis to evaluate the alternative environmental flow (EF) supply scenarios.

2.2. Study Reservoirs

This study focused on the four large agricultural reservoirs that have water storage capacity assumed to be able to provide EF: The Naju, Jangsung, Damyang, and Gwangju reservoirs (Figure 2 and Table 1). The reservoirs were originally constructed in 1970s with the purpose of providing irrigation water, and now they are expected to additionally serve as the sources of EF. The four study reservoirs had the total effective storage capacity of 256 Mm³ together, and the four major rivers restoration project increased the capacity up to 304 Mm³ through raising the dam heights by 2 m on average.

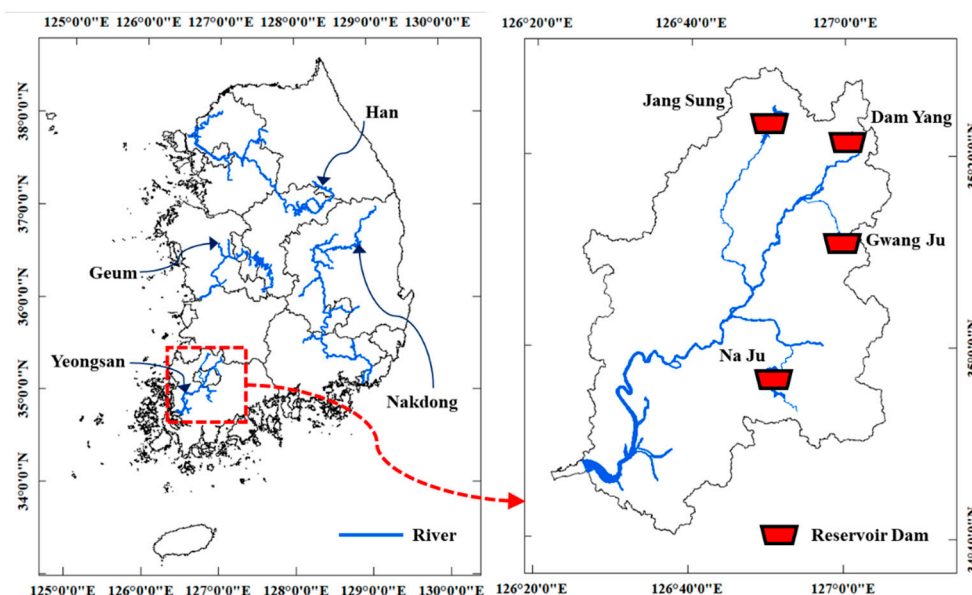


Figure 2. Locations of the study watersheds and the four major rivers in South Korea.

Table 1. Specification of the study reservoirs and their expected capacity for EF supply.

Items		Naju	Jangsung	Damyang	Gwangju	Total
Catchment Area (km ²)		104.7	122.8	65.6	41.3	334.4
Storage Capacity (ML)		107,810	103,883	77,608	23,256	312,556
Effective Storage (ML)		106,544	99,707	76,670	21,086	304,007
Surface Area (km ²)		7.8	7.4	4.4	2.2	21.8
Irrigation Area (km ²)		92.6	96.0	50.7	23.4	262.7
EF Supply Plan (ML)	Daily	34.0	39.6	29.2	23.6	126.4
	Annual	7550	7920	7250	5560	28,280
Actual EF Supply (ML)	2013	11,917	18,461	11,796	5170	47,344
	2014	7654	12,078	12,879	4299	36,910
	2015	12,857	14,472	12,600	6096	46,025
	2016	7456	10,983	3337	1670	23,444
	2017	4646	12,885	2759	4688	24,963
	2018	2440	5212	154	5390	13,196
Average		7828	12,349	7254	4552	31,983

In Korea, major (or large) agricultural reservoirs are constructed and operated by KRC, and reservoir operation and maintenance records are kept by the corporation. Data showing daily water supply (or reservoir outflow) from 2013 to 2018 were obtained from KRC and incorporated into the water balance modeling. The records of weather variables, including rainfall, evaporation, temperature, relative humidity, wind speed, and solar radiation, were collected from 1989 to 2018 (30 years) at the Gwangju weather station operated by Korea Meteorological Administration (Figure 3).

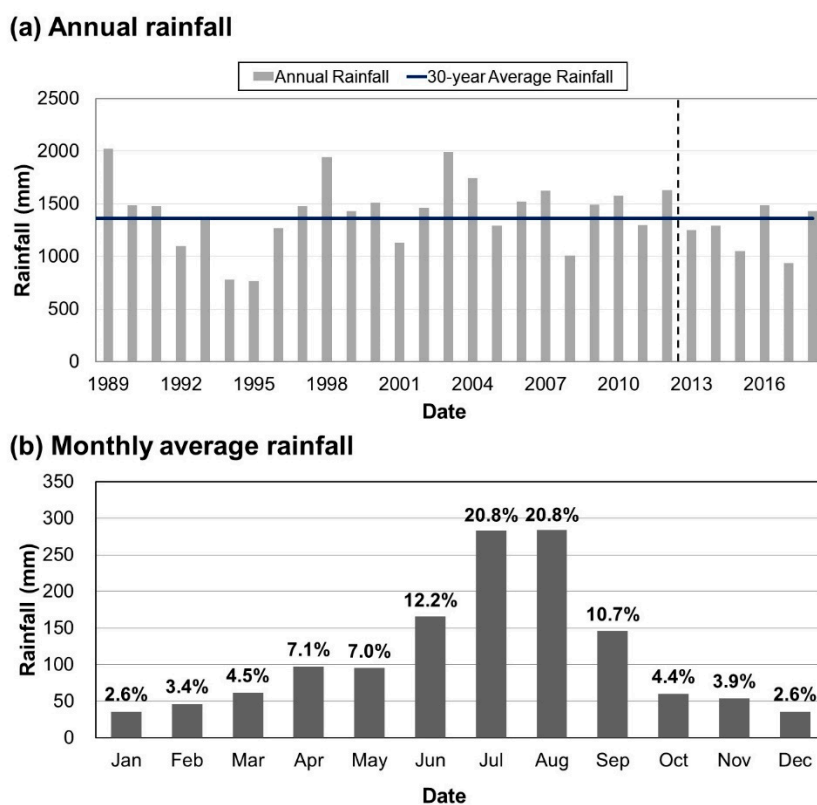


Figure 3. Annual (a) and monthly (b) variations of rainfall in the study areas.

2.3. Original, Current, and Additional Reservoir Operation Rules for EF Supply Plans

The Four Major Rivers Restoration Project planned to take 28 Mm³/year from the four study reservoirs and their watersheds to the Yeongsan River (Table 1). The EF supply plan of 28 Mm³/year was determined using the HOMWRS model conditioned with the hydro-meteorological status observed from 1989 to 2009, assuming the completion of the Four Major Rivers Restoration Project (the current plan in Table 2). Recently, the reservoir operation rule has been changed due to the repetitive drought in the past 10 years (Figure 3) after the Four Major Rivers Restoration Project plan was completed. Thus, it is necessary to re-evaluate the EF supply potentials of the four reservoirs (the additional plan in Table 2). The water release of the reservoirs for the EF supply is made only once the irrigation requirement is satisfied, as the original operation goal of irrigation water supply is expected to come first before the planned EF supply (the original plan in Table 2). Reservoir water is released to secure EF for its downstream only when the daily amount of water stored in the reservoirs exceeds the threshold of the day. The threshold (or irrigation requirement) was determined based on the long-term (30 years) average of reservoir storage before the storage capacities were enhanced by the Four Major Rivers Restoration Project in the original and current EF supply plans (Table 2 and Figure 3).

Table 2. Comparison of the original, current, and additional reservoir operation rules for EF and irrigation water supply.

Plans	Original	Current	Additional
Operation rules	Reservoir water is released for EF supply only when the amount of water stored is greater than 110% of the 30-year average. When	Reservoir water is released for EF supply only when the amount of water stored is greater than 100% of the 30-year average. When the	This study proposes an additional rule to the current plan to protect the irrigation water supply, which does not allow EF supply when the

the amount of less than the 110%, there will be no EF supply.	amount of less than the 100%, there will still be EF supply as much as drought flow.	amount of water stored is less than 40% of the 30-year average.
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Drought is the major factor to be considered when determining the amount and timing of reservoir water release for EF. As shown in Figure 3, for instance, the annual depths of rainfall were smaller than the 30-year long-term average in 4 years out of the recent 6 years. Such hydrologic drought dropped the amount of water stored in the reservoirs and threatened the irrigation water supply. In this study, we added another reservoir operation rule to project the irrigation water supply at an annual scale, which does not allow reservoir water release for EF supply when the storage drops below the 40% of the 30-year average (The additional plan in Table 2). The threshold of 40% was adopted from the manual (“On-site Action Manual for Drought Disaster”) of Korean Rural Community Corporation for drought management [63,64]. Such an additional rule was expected to help meet the original reservoir operation goal.

2.4. Development of Alternative EF Supply Scenarios

This study developed five alternative EF supply scenarios based on the information of monthly precipitation variations (Figure 3) and local irrigation practices, including water application rates and timings. Using the HOMWRS model, this study estimated the amount of water available for EF supply from the study reservoirs and evaluated the effectiveness of the five EF supply scenarios. Scenario 1 (or S1) represents four months of water supply for EF from February to May, which corresponds to the spring dry season. Scenario 2 (S2) releases reservoir water for EF during the first half of a year, January to June, before the wet season begins. In Scenario 3 (S3), reservoir water is provided for EF for eight months, from November (the end of the cropping season) to June. Scenario 4 (S4) assumes that reservoir water is not released only during the heavy rain periods, from July to August, and Scenario 5 (S5) supposes that EF is provided by the reservoirs all year round. Such scenarios considered the fact that agricultural reservoirs need to secure enough water for irrigation water supply in spring, the driest but the most water demanding season. In addition, the reservoirs should release the amount of stored water enough to protect the dams from being overtopping before the wet summer season begins.

In the scenario analysis, a higher priority is given to water supply for agricultural irrigation over EF to make the scenarios feasible. The EF calculation counts only water that is released from the reservoirs when there is no spillway overflow to downstream areas; outflow through the spillway or water gate of a reservoir is not considered as EF supply. In addition, EF is assumed to be minimized to the level as much as drought flow when the amount of water stored in the reservoirs remains below a threshold, the 30-year average, which means that the reservoirs has performed the minimum function for environmental purpose. When the stored water amount exceeds the threshold, on the other hand, the amount of EF flow provided by each reservoir will be increased as much as its potential evaluated in this study.

3. Results and Discussion

3.1. Evaluation of the Reservoir Storage and Historical EF Supply Practices

The historical reservoir operation records showed that EF supply lasted throughout the year, and often it was evenly distributed over the seasons (Figure 4). However, the time-constant EF supply might not be a desirable way to achieve the primary operational goal of the reservoirs, irrigation water supply. The amount of streamflow including reservoir inflow and the Youngsan river flow is substantially low in the dry seasons (spring and winter), compared to that of the wet season (summer); thus, it is necessary to account

for the seasonal variations of the reservoir hydrology when determining the timing of EF supply.

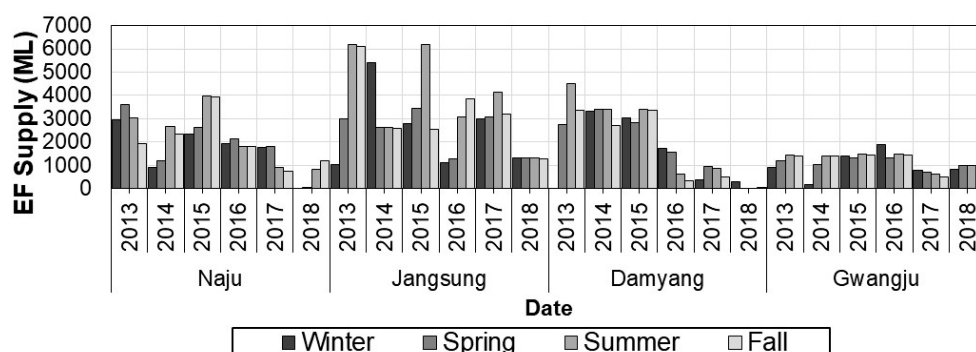


Figure 4. Seasonal variation of historical EF supply from the four reservoirs.

From the reservoir operation records, this study found that the amount of water of 32 Mm³/year was released from the four reservoirs to stabilize the streamflow of the Yeongsan River (or to provide EF for the river) from 2013 to 2018 even though the drought condition persisted (Figures 4 and 5). Compared to the current EF supply plan prepared based on the 30-year historical water use data (Table 2), two of the reservoirs were over drained: Naju (7828 Mm³/year drained on average, 104% of the planned amount) and Jangsung (12,349 Mm³/year drained on average, 156%) (Table 1). The Gwangju reservoir was able to provide part of EF without breaking the primary operational goal (irrigation water supply). However, the EF contribution of the Gwangju reservoir was attributed to the fact that the reservoir had been operated based on the outdated high-water level (HWL) determined before the storage enhancement of the Four Major Rivers Restoration Project. In the waterside areas of the Gwangju reservoir, there are ecological parks and trails newly constructed as part of the Four Major Rivers Restoration Project, and the previous HWL was kept (rather than being updated) to reduce the risk of flooding in the areas even after the dam height increase. Thus, the enhanced storage capacity is not being used currently due to the flooding concern. Daily results of relative error (RE) between the actual and planned EF showed that percentages of the periods that satisfy the daily RE less than 30% were only 4% to 45% for the four reservoirs, which indicates the EF supply must have been partially over-drained or under-drained in actual operations because of weather conditions or outdated rules.

Overall, the amount of water released for EF supply was as large as 113% of the current plan in the past 6 years (2013–2018), which demonstrated that the irrigation water supply capacity could be compromised by reservoir operation rules toward EF (Figure 5). This overuse has resulted in a continuous decrease in annual EF supply. For example, the recorded amount of EF supply carried by the four reservoirs in 2018 was the smallest among them of the recent 6 years even though the annual depth of rainfall was greater than the average (Figures 3–5).

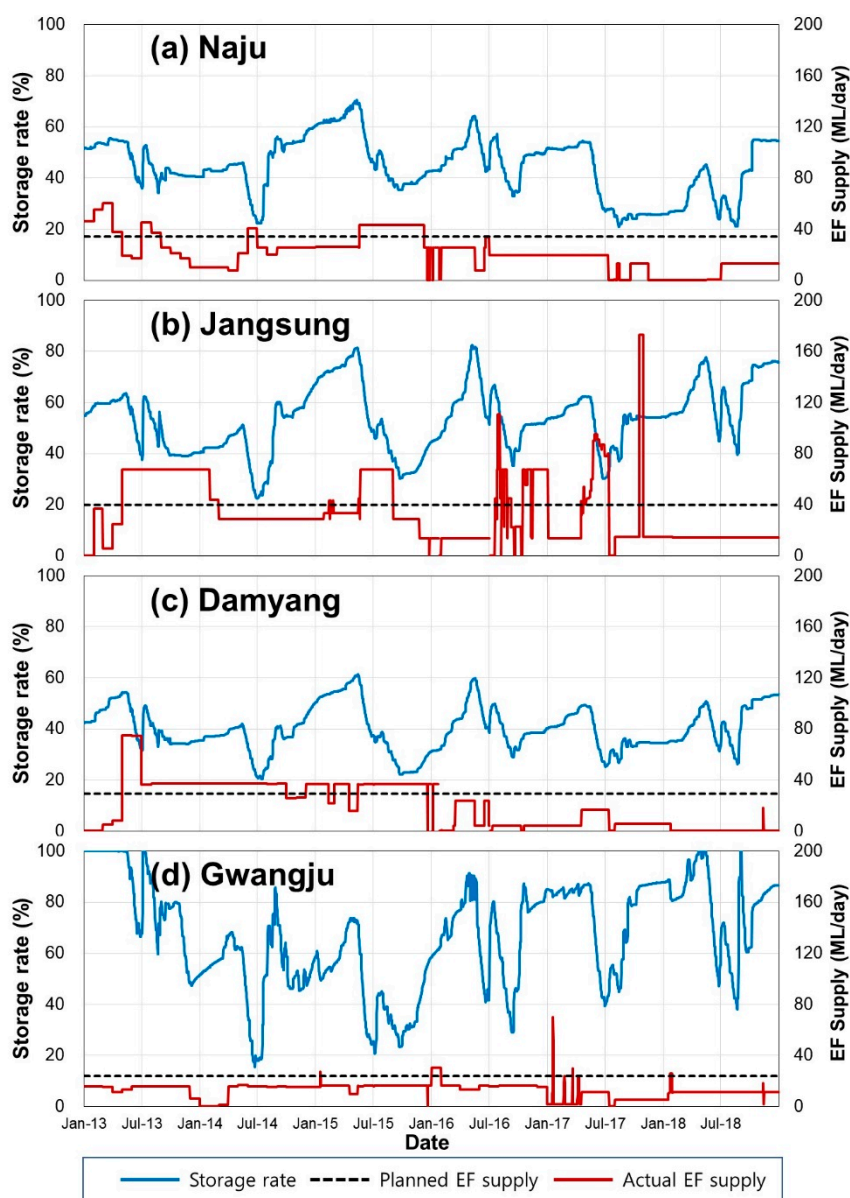


Figure 5. Daily variations in the amount of water stored in the reservoirs, planned and actual EF supply.

The HOMWRS modeling results showed that, when considering 10-year frequent drought specified in the Korean agricultural reservoir design standard [65], the study reservoirs need to collectively secure additional 227 Mm³ of storage capacity so that the main operation goal (irrigation water supply) of the reservoirs can be met (Table 3). The current effective storage capacity was estimated to 304 Mm³ including 48 Mm³ that was newly added by the dam height increases; thus, it turns out that the reservoirs have 77 Mm³ of surplus storage capacity that can be used for purposes other than irrigation (Tables 1 and 3).

Table 3. The estimated amount of water that each of the reservoirs can store after the dam enhancement.

Reservoir	Previous Storage Capacity (ML) (A)	Newly Added Storage Capacity (ML) (B)	Current Storage Capacity (ML) (C) = (A) + (B)	Irrigation Requirement (ML) (D)	Surplus Storage Capacity (ML) (C) - (D)
Naju	89,945	16,599	106,544	81,613	24,931
Jangsung	85,543	14,164	99,707	81,152	18,555
Damyang	65,741	10,929	76,670	49,214	27,456
Gwangju	15,198	5888	21,086	15,520	5566
Total	256,427	47,580	304,007	227,499	76,508

3.2. Evaluation of the EF Supply Plans

The scenario analysis showed that the annual EF supply potential of the study reservoirs varied from 27 Mm³/year to 30 Mm³/year depending on the scenarios (Table 4). In the case of supply periods equal to or shorter than eight months (S1, S2, and S3), the supply potential of the scenario was slightly larger than that (28 Mm³/year) of the current plan of the Four Major Rivers Restoration Project. The simulated potential of the five scenarios varied from 95% to 110% of the planned, and such modelling results showed that the current plan had reasonable estimates of the potential EF. However, EF supply (32 Mm³/year) records made from 2013, when the Four Major Rivers Restoration Project was completed, were greater than the simulated potential (27 to 30 Mm³/year) by more than 10%. None of the simulated potentials exceeded the current supply records. Such a result should be attributed to the regional drought that the four reservoirs had experienced since 2013. The results also demonstrated that the current level of EF supply (32 Mm³/year) is likely to fail to achieve the original goal of the reservoirs as the sources of irrigation water. Such finding suggests that it is necessary to reduce EF supply for reliable irrigation water supply, or supplementary irrigation water sources such as aquifers should be explored to secure agricultural water to keep both the current EF supply level and the original operation goal.

Table 4. Simulated EF supply potential of the study reservoirs.

Scenarios		S1	S2	S3	S4	S5
		130	181	242	303	365
Supply Period (days)		(February to May)	(January to June)	(November to June)	(September to June)	(January to December)
Daily Supply (ML/day)	Naju	67.8	49.3	40.1	34.6	30.9
	Jangsung	78.4	55.3	45.4	39.1	34.2
	Damyang	73.6	51.0	39.5	32.5	27.9
	Gwangju	39.8	29.0	24.2	20.1	17.2
Average Annual Supply (ML/year)	Naju	8964	8850	8762	8599	8375
	Jangsung	9719	9287	9256	8913	8120
	Damyang	7398	7386	7337	7143	6873
	Gwangju	4330	4342	4381	4048	3639
Total		30,411	29,865	29,736	28,703	27,007

The EF supply potential increased with decreases in the supply periods, which should be attributed to the fact that the scenarios with short supply periods more efficiently focus on dry seasons and thus could increase their supply efficiency compared to others, demonstrating the trade-off relationship between irrigation water and EF supplies. The lengths of periods when reservoir water was available for EF supply corresponded to 60% to 70% of the planned supply periods (Table 4 and Figure 6). Such finding indicates that EF may not be available during 30% to 40% of the planned supply periods because of

spillway-overflow or low storage rate. The length of spillway-overflow period was relatively small in the scenarios that have short EF supply periods such as S1 and S2 (Table 4 and Figure 6). Considering that the EF supply potential increased with decreases in the supply periods, it could be said that the relatively short supply period scenarios are able to more effectively manage the reservoir outflow as they can reduce uncontrolled water release. The results also suggest that an effective reservoir management plan and practices can increase the amount of water available for EF by using the surplus storage capacity that can help to control the water release schedule [1,4]. Ineffective water release during the heavy rain season can be converted to effective EF supply during the dry season by controlling water release timing.

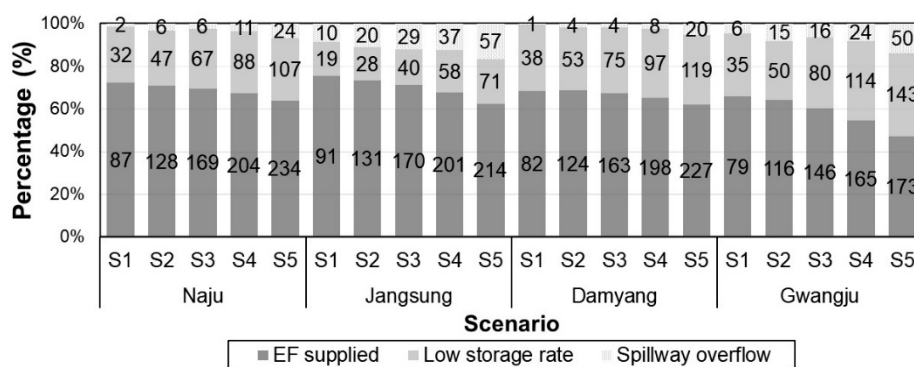


Figure 6. Lengths of periods when water is available from the reservoirs.

The alternative plans were compared with each other and that of the current EF supply plan in terms of the EF supply potential to evaluate their efficiency (Table 4). Although S1 has the shortest supply period of 130 days, it provided the greatest supply potential among the scenarios. On the other hand, Scenario 5 has the longest supply period and a water supply pattern similar to that of the current, but it turned out the least efficient (Table 4). The difference between the EF supply potential of Scenario 5 and the current plan was about 1 Mm³/year on average, showing no efficiency improvement. Such findings emphasize the need for a detailed investigation of reservoir hydrology and its temporal variations and highlight the importance of water supply timing (Figure 7). The monthly variations of EF supply potential provided by the scenarios show that EF supply can be concentrated in the dry season (or spring). For instance, the EF supply potential of S1 is substantially larger than those of the other scenarios and two times as large as that of S5 from February to May. In the wet season, on the other hand, S1 provides the least amount of EF supply potential, which can be compensated by uncontrolled spillway excess water release to the downstream river. Considering that the condition of streamflow and water quality in spring Korea is relatively poor, S1 should be preferred.

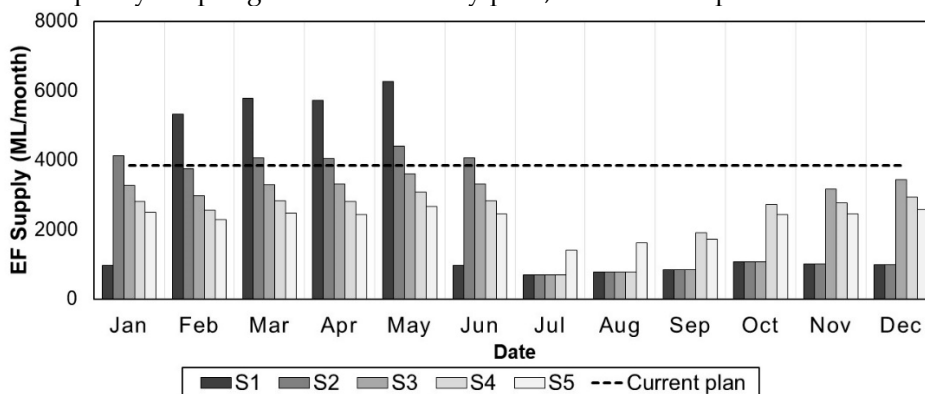


Figure 7. Variations of monthly EF supply by the scenarios.

We investigated the agricultural reservoirs' capacities of providing EF flow and found that the dam height enhancement could not guarantee the reservoirs secure the amount of water as much as they can (i.e., HWL). Such a finding suggests that simply increasing the reservoir water storage cannot necessarily increase the water supply capacity, highlighting the fact that the capacity is largely controlled by the hydrological characteristics of a reservoir and its temporal variations. In this aspect, groundwater that is relatively constant compared to surface water can be an effective alternative to the source of EF. In addition, an irrigation network equipped with advanced pumping, water level sensing, and control capabilities are expected to help secure EF by relaxing the irrigation supply requirement of the reservoirs.

This study investigated the amount and timing of water available for EF supply using the hydrological reservoir operation model (HOMWRS) with reservoir operation scenarios. The determination of EF requires multifactorial considerations relating to existing water rights and conflicts and the unique eco-hydrological characteristics of watersheds. Thus, time- and location-invariant streamflow index- or threshold-based approaches may be too simple to handle the complexity involved in decision-making processes for EF [2,66,67]. Previous studies evaluated the impacts of changes in EF on river ecosystem by transforming hydrological data into ecologically relevant information using modeling and scenario approaches [66]. Bovee [68] developed a habitat simulation method to understand how EF affects habitats and biota. Arthington et al. [69] proposed a scenario-based EF assessment framework to predict the biophysical, social, and economic consequences of altering a streamflow regime. Stamou et al. [2] combined hydrological, hydrodynamic, and habitat modeling for the identification of ecologically optimal discharge ranges and the selection of a minimum acceptable discharge.

The results demonstrated the trade-off between agricultural activities (i.e., irrigation) and the environmental flow is crucial in reservoir operation. However, balancing the two water uses are challenging, especially in dry periods. Environmental and agricultural water demands simultaneously reach their maximum levels sometimes, especially in the early stages of the growing season (April to May), because rivers are usually dried up due to the winter and spring drought (Figures 3 and 5). Given the complexity of reservoir operation, additional detailed modeling might be needed to consider all ecological, environmental, hydrological, and legal factors in decision making. Future efforts to determine the environmental flow in rivers and streams will need to combine hydrological, hydrodynamic, and habitat modeling based on a more detailed understanding of relationships between flows and ecosystem health [2].

This study showed that the current EF supply plans for the agricultural reservoirs could not satisfy both requirement for EF and irrigation water supply with the existing storage capacity (even after the storage enhancement) when considering the temporal variations of reservoir water balance. The scenario analysis demonstrated that the EF supply could be increased by strategically focusing on vulnerable (or dry) periods, suggesting that reservoir operation plans should be determined through investigating the seasonal variations of EF needs rather than taking a supply-oriented operation approach. In addition, the seasonal variations of water quality in reservoirs should be considered and understanding the seasonal biogeochemical changes in reservoirs is critical for determining environmental flow releases and the ecological trajectory of both the reservoir and river systems [3].

4. Conclusions

This paper proposed an analysis framework to evaluate the capacity of an agricultural reservoir as the source of EF and identify effective reservoir operation scenarios that can meet both reservoir operation goals, irrigation water, and EF supplies. The HOMWRS model was used to mathematically represent the water balance and operation of the study reservoirs. Reservoir operation scenarios for EF supply were evaluated using the model. The results showed that the scenario that concentrates on dry seasons or spring (S1: From

February to May) could provide the overall largest annual amount of EF from all study reservoirs. The annual EF supply potential tends to increase with the decreases of the supply period, and the difference among the supply potentials estimated from the scenarios was significant. Such a finding indicates that annual and monthly EF supply potential can be efficiently secured by considering the seasonal variations of hydrology and reservoir water balance when determining the amount of EF supply and timing. The results also showed that the study reservoirs had supplied EF more than their simulated potential, suggesting the revision of the current EF supply plan so that both reservoir operation goals can be met. This study demonstrated that the reservoir water could be more efficiently secured by improving the reservoir operation schedule rather than simply increasing the storage capacity. The detailed investigation on the reservoir water balance and its temporal variations showed how the trade-off between the different uses of reservoir water could vary depending on hydrological conditions and reservoir operation schedules and how the overall benefits of using the reservoir water resources could be maximized by considering seasonal hydrological variations. The analysis framework proposed in this study will help improve the water use efficiency of the existing reservoirs under multiple operations objectives, improved agricultural and environmental sustainability. The proposed framework is based on simulation and scenario analysis implemented using a hydrological model, 3-Tank, which is known as applicable to a wide range of watersheds and thus expected to help explore the trade-off between irrigation and EF in other areas [36,44,45,70,71]. Reservoir operation scenarios for ET supply were evaluated using a 3-Tank model regionalized to the study areas in the analysis.

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