Assessment of Future Climate Change Impact on an Agricultural Reservoir in South Korea

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Abstract: Drought has been frequently occurring in South Korea due to climate change. Analyzing the water supply capacity of the water resource system provides essential information for water resource management. This study evaluates the future water supply capacity of the Gwanghye (GH) agricultural reservoir based on the representative concentration pathways 4.5 and 8.5 climate change scenarios. We performed a reservoir simulation by reflecting the full water level of the reservoir before and after reservoir heightening. Climate change is expected to decrease the GH reservoir's future available water resources due to the overall reduction in the reservoir's runoff. After the reservoir-heightening project, an overall improvement was observed in the stability of the future irrigation water supply. Moreover, the remaining water after the supply of the irrigation water could supply 0.6–7.2×10^3 m³ of daily instream water. Thus, flexible reservoir operations are necessary according to climate change scenarios and the reservoir operation period. The use of climate change information should be expanded to establish reasonable water management policies for future climate change scenarios.

Keywords: climate change; heightened reservoir; reservoir water balance; water supply evaluation

1. Introduction

Frequent droughts caused by climate change have led to global water shortage issues [1]. Moreover, the fast pace of climate change is expected to cause various social problems, including environmental pollution and food shortages [2]. In South Korea, the water shortage crisis caused by recent extreme weather conditions has been continuously reported [3]. Accordingly, numerous studies have investigated climate change issues, such as insufficient water storage in water resource facilities, algae occurrence, and agricultural productivity changes [4–6].

As climate change increases the water cycle variability, it is critical to identify the impact of climate change on water supply and demand in dams and reservoirs. Many researchers worldwide have studied the impact of climate change on water resource facilities. Payne et al. [7] researched the effect of climate change on a reservoirs' operation in the Columbia River watershed in the United States. Gohari et al. [8] predicted a future agricultural water shortage due to climate change in the Chadegan reservoir in the Zayandeh-Rud River watershed in Iran. Fujihara et al. [9] demonstrated that an increase in farmland would cause water shortages in the Seyhan and Catalan dams in the Seyhan River watershed in Turkey due to inflow reduction by climate change. In South Korea, Kim [10] evaluated the water supply of the Yongdam and Daecheong dams taking into account the impact of climate change. Chung et al. [11] analyzed the influence of future inflow changes on water storage and discharge for a group of multipurpose dams in the Han River.

South Korea receives concentrated rainfall in summer under the influence of the monsoon climate. Because of this seasonal impact, water resource facilities, such as reservoirs and dams, have been developed to accommodate seasonal variations in precipitation.

These facilities are essential for managing South Korea's water supply. Agricultural water represents 61% of the total water resources used (25.1 billion m^3), excluding instream water [12]. As agricultural water is sensitive to climate change, the water supply of agricultural reservoirs is also influenced by climate change [13].

In South Korea, agricultural reservoirs supply agricultural water only during the irrigation period (April–September). During the non-irrigation period, it is a common practice for reservoirs to secure maximum water inflow for the following year's agricultural water supply. As water is not supplied to the downstream areas of reservoirs, stream ecosystems in these areas are negatively affected. In 2009, the Korean government started a project to secure water resources by increasing the embankment height of agricultural reservoirs for supplying instream water during the dry season and address the future water shortage problem [14]. This prompted various studies on embankment-heightened reservoirs since 2010. The researchers in South Korea analyzed the effects of water management and flood management before and after the reservoir embankment-heightening project and researched reservoir operation after the project. The downstream flood control effect before and after the project was analyzed by Lee et al. [15] for the Bonghak reservoir, and by Hwang et al. [16] for the Jangseong, Suyang, Yutang, and Wangdong reservoirs. Regarding the studies on reservoir operation considering flood control, Lee [17] proposed that appropriate water levels should be maintained at each agricultural reservoir. Noh [18] analyzed the water storage change at the end of the year, according to the flood-limit water-level scenario for agricultural reservoirs, and determined a negligible influence of the limited water level. Regarding the operation of embankment-heightened reservoirs, Lee and Noh [19] reported that the application of water management regulations of agricultural reservoirs would enable a flexible water supply. Kim et al. [20] evaluated the applicability of reservoir operation regulations based on past operation data, and Park et al. [21] formulated reservoir operation regulations using the water balance analysis results that considered water supply.

The reservoir embankment-heightening project implemented by the Korean government applied a design method reflecting only past meteorological data, wherein data from the past was analyzed without performing future climate change impact assessment. Other studies [15–21] on heightened reservoirs also analyzed past meteorological data, instead of future climate change impact assessment. Therefore, it is necessary to establish a water supply plan of agricultural reservoirs based on future climate change scenarios. The objective of this study was to assess the future water supply capacity of an agricultural reservoir in South Korea based on representative concentration pathway (RCP) climate change scenarios. The Gwanghye (GH) reservoir, which underwent embankment heightening, was selected as the target agricultural reservoir. First, the irrigation water supply capacity was analyzed before and after the embankment project. Second, after the completion of the project, the irrigation water supply was prioritized, and instream water that can be supplied using the remaining water storage was quantified.

2. Materials and Methods

We applied a water balance method using the RCP 4.5 and RCP 8.5 climate change scenarios to evaluate the water supply capacity of agricultural reservoirs. The calibration and validation of the reservoir operation simulation were conducted using observed reservoir storage data. Climate change scenarios were also constructed for future-period reservoir simulation operations. We analyzed the stability of the irrigation water supply according to changes in reservoir water levels before and after the heightening and estimated the appropriate instream water supplies under adequate irrigation supply by performing a simulation.

2.1. Study Area

The target reservoir of this study is the GH reservoir in central South Korea (Figure 1). The GH reservoir is situated in Dugyo-ri, Juksan-myeon, Anseong-si, Gyeonggi-do (127°25 E,

37°00 N). The main river of the reservoir is the Chiljang River, which supplies water to the downstream irrigation area of the reservoir and then joins the Miho River, the Geum River's first tributary. Forest areas account for 88.5% of the reservoir watershed area, followed by paddy (6.0%), water surface (3.2%), upland (2.0%), and land areas (0.3%). The watershed area is 1040 ha, and the irrigation area is 446 ha. The 2011 embankment-heightening project increased the reservoir embankment height by 2.0 m. This increase resulted in a full water-level increase from EL.127.5 m to EL.129.5 m. The effective water storage also increased from 3,166,000 m^3 before the reservoir-heightening project to 4,198,000 m^3 after the project, thereby securing an additional water storage space of 1,032,000 m^3.
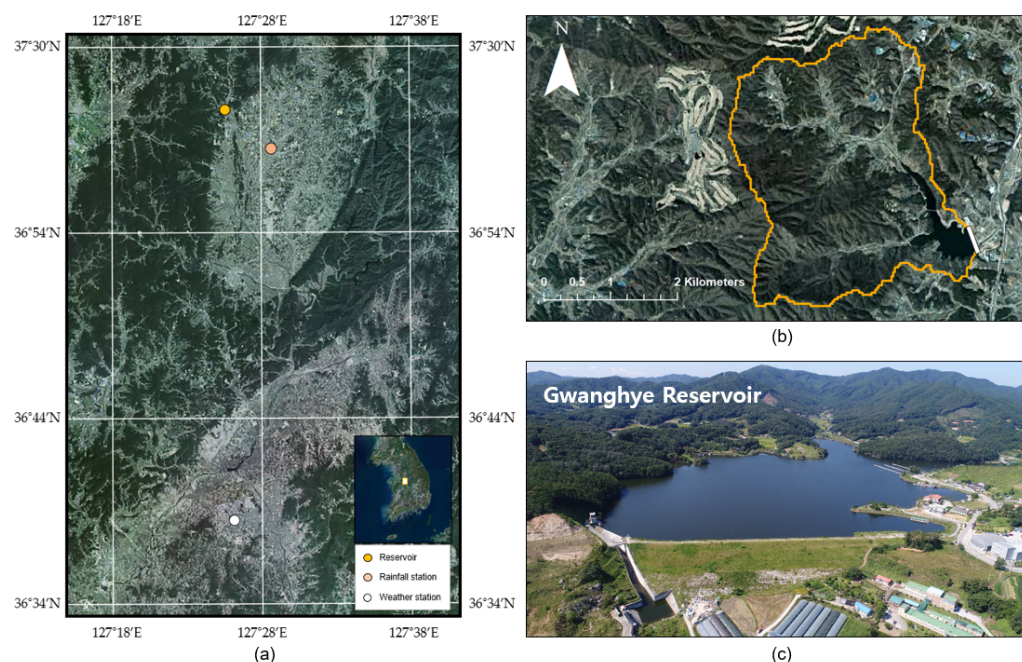

Figure 1. The location (**a**), watershed (**b**), and aerial view (**c**) of Gwanghye (GH) agricultural reservoir in the study area.

2.2. Data Collection

2.2.1. Meteorological and Hydrological Data

In this study, we obtained meteorological data for the period from 1980 to 2010: rainfall data from the Oryu rainfall station, and temperature, relative humidity, and wind speed data from the Cheongju weather station near the GH reservoir (Figure 2). The data were provided by the Water Resources Management Information System [22]. Figure 2 indicates an annual average rainfall of 1182.9 mm, an average temperature of 12.4 °C, relative humidity of 67.9 %, and an average wind speed of 1.8 m/s for the study area. The water-level storage curve data and the GH reservoir's water-level data required for the water balance analysis were obtained from the Korea Rural Community Corporation [23]. The reservoir storage rate data from 1991–2010, a year before the start of the embankment-heightening project, were used to validate and calibrate the reservoir simulation operation. For the climate change scenario, which includes future climate change information, RCP daily data for the Korean Peninsula with a 12.5 km resolution was simulated with the global climate model (HadGEM2-AO) at the Meteorological Agency Hadley Centre, the United Kingdom. These data are provided to the public by the Climate Change Information Center [24] for establishing national-level climate change adaptation measures in South Korea.
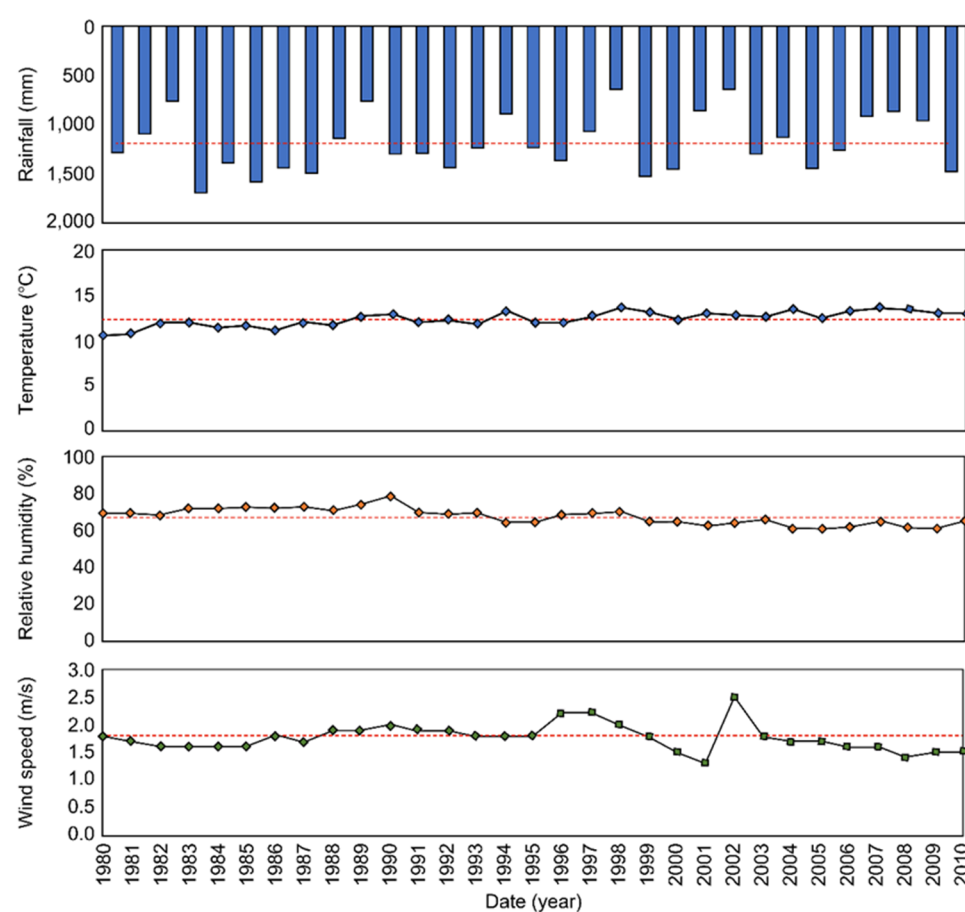
Figure 2. Thirty-year rainfall data for the GH watershed area obtained from the Oryu rainfall and the Cheongju weather station.

2.2.2. Future Climate Data Selection

In this study, RCP greenhouse gas (GHG) scenarios were selected for future climate data construction. The RCP scenarios were introduced in the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) [1]. They are classified into RCP 2.5 (a case which demonstrates the recovery of the earth from the effects of human activities), RCP 4.5 (a case in which GHG reduction policies are substantially realized), RCP 6.5 (a case in which GHG reduction policies are marginally realized), and RCP 8.5 (a case in which GHGs are discharged without reduction) according to radiative forcing. Figure 3 shows the trend of radiative forcing in the RCP scenarios [25]. The carbon dioxide concentrations for RCP 2.6, 4.5, 6.0, and 8.5 are 420, 540, 670, and 940 ppm, respectively. RCP 4.5 and RCP 8.5, with different GHG reduction policies, were selected for this study.
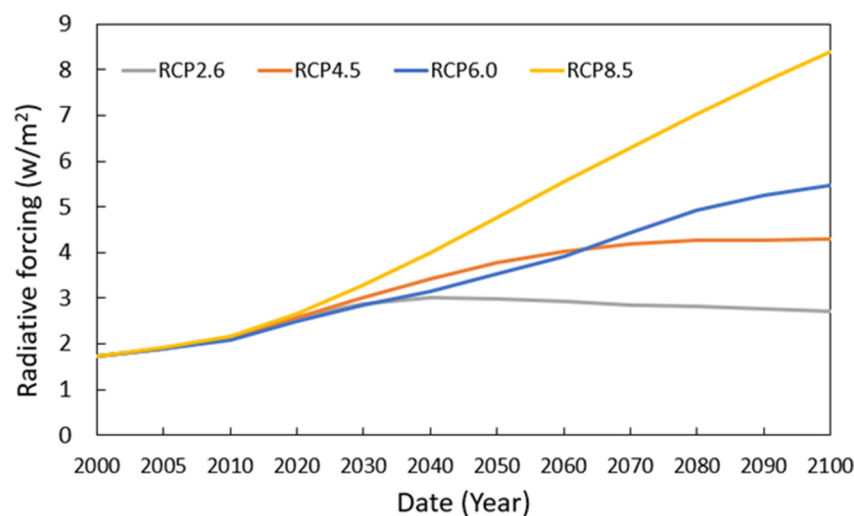
Figure 3. Trends in radiative forcing according to representative concentration pathway (RCP) scenarios.

2.3. Research Analysis Method

2.3.1. Construction of RCP Climate Change Data

We extracted daily rainfall and temperature data in the RCP scenario corresponding to the Oryu rainfall station and Cheongju weather station, respectively. The bias correction method was applied to remove bias between observation and the RCP data. First, the rainfall data were corrected using the local intensity scaling technique suggested by Schmidli et al. [26]. The average rainfall and number of rainy days were corrected in the past simulation period (1979–2005) of the RCP scenario using the local intensity scaling technique suggested by Schmidli et al. [26]. The RCP rainfall data and the observed rainfall data for the same period were sorted in descending order by each month, respectively. The RCP rainfall value of the array in which the observed rainfall value was zero was defined as the local threshold (L_{th}) for monthly correction of rainfall day frequency. The local rainfall factor (L_o) was calculated monthly using Equation (1). Herein, the RCP scenarios' rainfall data above the local threshold (L_{th}) value were used to calculate the average rainfall in the RCP scenario ($\bar{P}_{rcp}$). Then the RCP future rainfall data was constructed using Equation (2).

$$L_o = \frac{\bar{P}_{obs}}{\bar{P}_{rcp} - L_{th}} \tag{1}$$

$$P_{fut} = L_o \left(P_{rcp} - L_{th} \right) \tag{2}$$

$$P_{fut} = 0, \text{ if } P_{fut} < 0 \tag{3}$$

Second, the method proposed by Lenderink et al. [27] was applied to the temperature data to correct the difference between the average value of the past simulation period (1979–2005) and the observation data for the same period in the RCP scenarios as shown in Equation (3). Herein, the RCP scenarios' temperature data were used to calculate the potential evapotranspiration for the estimation of future agricultural water supply. The temperature data were corrected by the deviation of the average value for the past simulation period of the RCP scenario and the average value of the observed data for the same period.

$$T_{fut} = T_{rcp} + \left(\bar{T}_{obs} - \bar{T}_{rcp} \right) \tag{4}$$

where T_{fut} is the future temperature after bias correction, T_{rcp} is the daily temperature of the RCP scenario before bias correction, $\bar{T}_{rcp}$ is the average temperature during the RCP

scenario's past simulation period, and $\overline{T}_{obs}$ is the average observed temperature during bias correction period.

2.3.2. Irrigation Water Requirement Calculation

The irrigation water calculation process considers the evapotranspiration, infiltration, and effective rainfall in a paddy field. In this study, the amount of water required in a unit rice paddy was calculated by applying the rice paddy water balance method as shown in Equations (4) and (5) [28,29]. The irrigation water requirement for the reservoir was calculated by considering 15% of the irrigation canal loss and 20% of the distribution management water suggested in the field and multiplying them by the irrigation area.

$$D = \Delta D + Re - ET - Inf \tag{5}$$

$$Req = RD - D \tag{6}$$

where D is the ponding depth, ΔD is the remaining ponding depth, Re is the effective rainfall, ET is the evapotranspiration, Inf is the infiltration volume, Req is the irrigation water requirement of a unit rice paddy, and RD is the water management height according to the rice paddy growth period.

When calculating the irrigation water requirement, 60 mm of ponding depth was applied for the available potential rainfall in a paddy field and 5.45 mm, a value obtained from a field survey, was applied for the infiltration volume. The reference evapotranspiration was calculated using the Penman–Monteith method [30] as shown in Equation (6), and the crop evapotranspiration was calculated by considering the empirical formula obtained in a local study [31].

$$ETo_{PM} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2(e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)} \tag{7}$$

where ETo_{PM} is the potential evapotranspiration calculated using the Penman–Monteith method (mm/day), Rn is the net solar radiation (MJ/m^2/day), $e_a - e_d$ is the difference between the saturated water vapor pressure and the actual average vapor pressure (kPa), T is the average temperature (°C), U_2 is the wind speed measured at a height of 2 m from the ground (m/s), Δ is the slope of the saturated water vapor pressure and temperature curve (kPa/°C), G is soil heat flux density (MJ/m^2/day), and γ is the humidity constant (kPa/°C).

The selected RCP scenarios for the Korean Peninsula do not provide solar radiation data, and thus, the direct application of the Penman–Monteith method (ETo_{PM}) is not possible. Therefore, we calculated the future potential evapotranspiration using the Hargreaves method (mm/day), which uses the temperature data, as shown in Equation (7). This method calculates evapotranspiration by applying the past observation data, and a technique that uses the derived relationship was also applied [29], as shown in Figure 4.

$$ETo_{Harg} = 0.0023(T_{mean} + 17.8)\sqrt{(T_{max} - T_{min}) \times R_a} \tag{8}$$

where ETo_{Harg} is the potential evapotranspiration calculated using the Hargreaves method (mm/day), T_{max} is the daily maximum temperature (°C), T_{min} is the daily minimum temperature (°C), T_{mean} is the daily average temperature (°C), and R_a is the radiant heat outside the atmosphere (MJ/m^2/day).
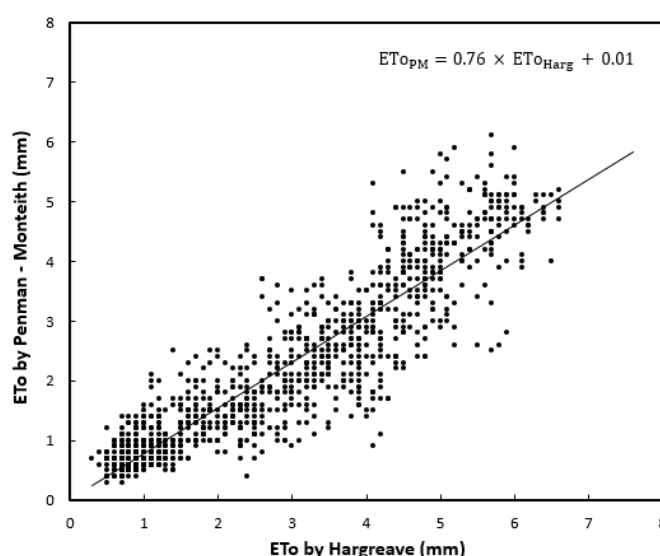
Figure 4. Relationship between evapotranspiration by the Hargreaves and Penman–Monteith method.

2.3.3. Reservoir Simulation Operation

In South Korea, agricultural reservoirs are ungauged watersheds, and thus, the amount of discharge is not measured. Therefore, the reservoir inflow is calculated by the rainfall-runoff analysis method using the empirical formula for the reservoir watershed. In this study, the reservoir water balance was analyzed by calculating the amount of irrigation water supply, which was then compared with the observed water storage to calculate the runoff. The water storage was calculated using a water balance equation, as shown in Equation (8). Water storage is increased by reservoir inflow and decreased by surface water evaporation and water supply quantity (agricultural water and instream water). The overflow was assumed to occur when the water storage exceeded the full water level, as shown in Equation (9).

$$V = \Delta V + IQ - SE - SQ \tag{9}$$

$$OV = V - FV \tag{10}$$

where V is the water storage, ΔV is the remaining water storage, IQ is the inflow, SE is the water surface evaporation, SQ is the water supply quantity, OV is the overflow, and FV is the water storage at the full water level.

We applied an empirical formula for the reservoir inflow that derived the watershed runoff based on multipurpose dam inflow data in South Korea [32]. The runoff (Q) is calculated based on a nonlinear change relationship depending on the soil moisture storage (S), as shown in Equation (10). Herein, the soil moisture storage is increased by rainfall and decreased by evapotranspiration and runoff. We calculated the initial soil moisture storage by comparing observed and simulated reservoir' water storages through trial and error and applied the value of 65 mm for this study.

$$Q = \left(1 - e^{-0.003 \times S}\right)^{\left(0.2 + e^{-0.001 \times S \times 4.5}\right)} \times S \tag{11}$$

Before applying future climate change information, the reservoir simulation operation was calibrated and validated to ensure the reliability of the past simulation results. In terms of the period setting, the calibration period was from 1994 to 2001, and the validation period was from 2001 to 2009. The suitability of the reservoir simulation operation results was evaluated by the determination coefficient (R^2) of the observed and simulated water

storages, the Nash and Sutcliffe model efficiency (NSE), and the percent error (PE), as shown in Equations (11)–(13) [33,34].

$$R^2 = \left(\frac{\sum \left(O - \bar{O} \right) \left(S - \bar{S} \right)}{\sqrt{\sum \left(O - \bar{O} \right)^2 \sum \left(S - \bar{S} \right)^2}} \right)^2 \tag{12}$$

$$NSE = 1 - \frac{\sum \left(O - S \right)^2}{\sqrt{\sum \left(O - \bar{O} \right)^2}} \tag{13}$$

$$PE = \frac{\left| \bar{O} - \bar{S} \right|}{\bar{O}} \times 100 \tag{14}$$

where O and S are the observed and simulated water storage, respectively; $\bar{O}$ and $\bar{S}$ are the average observed and simulated water storage, respectively.

2.3.4. Future Water Supply Capacity Evaluation

To evaluate the GH reservoir's future irrigation water supply capacity, the results of the reservoir simulation operation based on the RCP 4.5 and 8.5 scenarios were analyzed. The future period was divided into the following three sections: 2025s (2011–2040), 2055s (2041–2070), and 2085s (2071–2100). In the reservoir simulation operation, the full water levels were set to El. 127.5 m and El. 128.5 m for the periods before and after the reservoir embankment-heightening project. Before the project, the water supply was assumed to exclusively supply irrigation water. After the project, it was assumed that both irrigation water and instream water were supplied. For the instream water, the appropriate supply amount was calculated when water was left after the supply of irrigation water.

In addition, a method of evaluating the reliability of water supply safety was applied as a standard index for determining the possibility of reservoir water supply [35]. Water supply reliability is an index used to evaluate the stability of an irrigation facility's water supply capacity. This parameter was analyzed annually and calculated using Equation (14). As the water storage of an agricultural reservoir is determined based on the drought frequency for ten years in South Korea, water shortages were evaluated based on whether 90% of the water supply safety was satisfied.

$$WSR = \left(1 - \frac{n}{N} \right) \times 100 \tag{15}$$

where WSR is the water supply reliability (%), N is the total number of years during the analysis period, and n is the number of years in which the water supply failed

3. Results and Discussion

3.1. Validation and Calibration of Reservoir Simulation Operation

The water storage change during the past period was calibrated and validated to perform future reservoir simulation operations. The calculated irrigation water requirements and reservoir inflow were estimated. Table 1 lists the statistical analysis results for the validation and calibration periods of the reservoir simulation operation, and Figure 5 displays these results in graphs.

Table 1. Summary of calibration and validation for GH reservoir.

	Calibration (1994–2001)			Validation (2001–2009)		
R^2	PE(%)	NSE	R^2	PE(%)	NSE
0.67	2.4	0.66	0.76	0.5	0.67
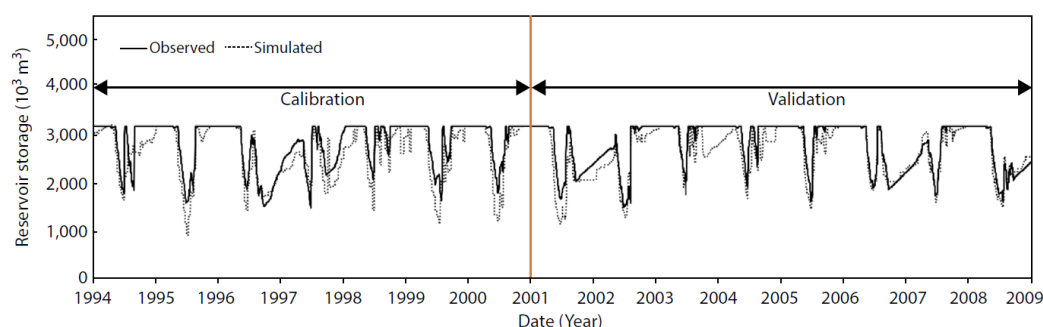
Figure 5. Calibration and validation results for the GH reservoir.

The applicability of the water storage simulation operation was evaluated using the R^2, NSE, and PE. In this study, R^2 was 0.67 or higher, NSE was 0.66 or higher, and PE was 2.4% or less. The validation result was better than the calibration result because appropriate setting reservoir modeling in the calibration process was considered appropriate by minimizing errors between the observed and simulated reservoir storage. R^2 has a value of 1 when the measured and simulated values are in strong correspondence. The NSE ranges from $-\infty$ to 1, and the value of 1 indicates that the observed and simulated values are in correspondence. Furthermore, PE exhibits better results, as it is closer to zero. After validating the reservoir simulation operation results' reliability, we performed reservoir simulation operations for future periods by applying the climate change scenarios.

3.2. Hydrological Changes in the Reservoir Watershed by Climate Change

A runoff analysis was conducted to examine the future hydrological changes of the GH reservoir watershed due to climate change by applying the RCP scenarios. The future runoff simulation results were divided into three periods: 2025s (2011–2040), 2055s (2041–2070), and 2085s (2071–2100), and compared with the results of the past 30 years (1981–2010). Table 2 details the hydrological changes of the GH reservoir watershed forecasted by each RCP scenario.

Table 2. Predictions of the GH reservoir watershed's hydrological elements by representative concentration pathway (RCP) scenarios.

Reservoir	Baseline (1981–2010)	RCP 4.5			RCP 8.5		
		2025s	2055s	2085s	2025s	2055s	2085s
Precipitation (mm)	1206.1	1093.2 (−112.9)	1384.7 (+178.6)	1218.2 (+12.1)	1131.4 (−74.7)	1172.1 (−34.0)	1288.4 (+82.3)
Temperature (°C)	14.5	15.9 (+1.4)	16.6 (+2.1)	16.9 (+2.4)	15.7 (+1.2)	17.3 (+2.8)	19.2 (+4.7)
Evapotranspiration (mm)	536.4	583.7 (+47.3)	608.5 (+72.1)	606.1 (+69.7)	581.3 (+44.9)	618.6 (+82.2)	647.5 (+111.1)
Runoff (mm)	703.2	577.64 (−125.6)	838.65 (+135.5)	685.85 (−17.4)	615.59 (−87.6)	613.55 (−89.7)	710.84 (+7.6)
Runoff ratio (%)	56.7	49.1 (−7.6)	59.5 (+2.8)	53.8 (−2.9)	52.1 (−4.6)	50.5 (−6.2)	52.9 (−3.8)

The average annual precipitation variation ranged from −112.9 to +178.6 mm in the RCP 4.5 scenario and from −74.7 to +82.3 mm in the RCP 8.5 scenario. The variation range of RCP 8.5 was smaller than that of RCP 4.5. The temperature increased by up to 2.4 °C in RCP 4.5 whereas up to 4.7% in RCP 8.5. RCP 8.5 expected a 2.0 °C higher increase than RCP 4.5. The evapotranspiration increased by 47.3–69.7 mm in RCP 4.5 whereas it increased between 44.9–111.1 mm in RCP 8.5. RCP 8.5 exhibited the largest value at the end of the 21st century, which appears to be due to the temperature increase. The runoff variation ranged from −125.6 to +135.5 mm in RCP 4.5 whereas it ranged from −87.6 to +7.6 mm in RCP 8.5. The run-off change exhibited a tendency similar to that of the precipitation change; however, RCP 8.5 predicted a larger runoff decrease than precipitation change at the end of the 21st century. This may be because the increase in the watershed's evapotranspiration affected the decrease in run-off caused by rainfall. The variation in the GH reservoir's runoff ratio ranged from −7.6% to +2.8% when GHG emissions maintained the current trend (RCP 4.5). An increase in emissions compared to the current trend (RCP 8.5) produced a runoff ratio variation ranging from −6.2 to −3.8%. In RCP 4.5, the future run-off ratio due to climate change exhibited a decreasing tendency, except for the middle part of the 21st century. Based on the above results, we expect that the GH reservoir's water management will be difficult in the future because of the decrease in the available water resources.

In a study in Korea [36], future temperature predictions were similar to our results. However, compared to our results, there was a tendency for decreased evaporation or increased rainfall. Climate change showed a common phenomenon of increasing future temperature on the Korean Peninsula, but rainfall and evaporation were expected to vary according to regions within the same country. On the other hand, another study [37] predicted that precipitation, evapotranspiration, and runoff would increase in the future, although this study did not mention temperature. The results of RCP 8.5 predicted an increase more than those of RCP 4.5. Therefore, the results of climate change showed a significant difference in the future, which means that there is a need to prepare different water resource response policies for each region even in the same country.

3.3. Evaluation of Future Irrigation Water Supply Capacity by Reservoir Embankment Heightening

In this study, climate change scenarios were applied to evaluate the future irrigation water supply capacity of the reservoir-heightening project. Table 3 lists the simulated water storage results under the condition of supplying only irrigation water from the GH reservoir before and after the dam heightening project.

Figure 6 compares the irrigation water supply capacity before and after the project for each RCP scenario. For the reservoir's water supply capacity, the water supply stability was evaluated based on the ten-year drought frequency (90% of water supply safety) of the Korean agricultural reservoir design standard.

Before the reservoir-heightening project, the water supply safety was the lowest at the beginning of the 21st century under RCP 4.5. However, it was equal to the design criterion or higher in the middle and end of the 21st century. In RCP 8.5, the overall irrigation water supply capacity was lower than the design criterion in all periods. In particular, the irrigation water supply was the lowest in the 2025 period of RCP 4.5. This is because the future runoff was higher than in the past.

After the reservoir-heightening project, the GH reservoir's future irrigation water supply capacity increased by up to 3.4% in RCP 4.5 and up to 13.3% in RCP 8.5. These increases indicate that the overall agricultural water supply capacity was improved compared to the period before the project because water resources were secured due to embankment heightening. However, finding a change in the supply capacity of irrigation water was challenging during the 2085s period in RCP 4.5 despite reservoir-heightening, as an extreme drought was predicted during this period.

Table 3. Water balance analysis results before and after dam heightening under RCP scenarios (supplying irrigation water only).

| Project	Scenario	Period	Inflow	Irrigation Water	Overflow	Water Storage	Instream Water	Water Supply Reliability
			(10³ m³/year)					(%)
Before	RCP 4.5	2025s	5724.2	4327.9	2402.6	2003.8	-	63.3
		2055s	8356.4	3290.5	5233.7	2815.8	-	96.7
		2085s	6835.3	3714.1	3643.2	2593.6	-	90.0
	RCP 8.5	2025s	6042.7	3861.9	2690.0	2290.5	-	83.3
		2055s	6033.2	4195.6	2586.0	2313.6	-	80.0
		2085s	7022.2	3741.3	3643.5	2550.7	-	86.7
After	RCP 4.5	2025s	5724.2	4464.6	1982.2	2443.5	-	66.7 (+3.4)
		2055s	8356.4	3823.7	4649.6	3614.8	-	100 (+3.3)
		2085s	6835.3	3980.7	3106.3	3293.0	-	90 (+0)
	RCP 8.5	2025s	6042.7	4012.6	2284.0	2946.6	-	90 (+6.7)
		2055s	6033.2	4203.2	2149.4	3013.7	-	93.3 (+13.3)
		2085s	7022.2	3998.3	3205.8	3265.2	-	96.7 (+10)
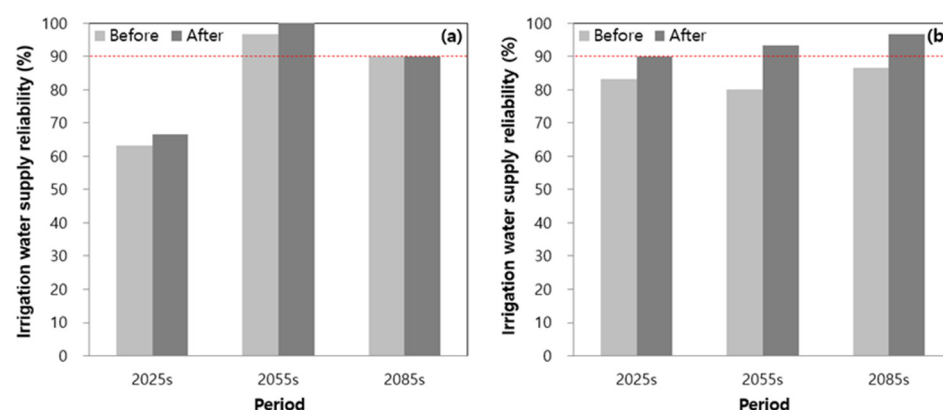
Figure 6. Comparison of the future irrigation water supply reliability before and after the reservoir-heightening project based on RCP 4.5 (**a**) and RCP 8.5 (**b**) scenarios. The red dot line is the standard for evaluating reservoir′ water supply safety. The periods of 2025s, 2055s, and 2085s include 2011–2040, 2041–2070, 2071–2100, respectively.

Figure 7 shows the comparison of the annual average storage and water shortage quantity before and after embankment heightening in the 2085s in RCP 4.5. The water balance analysis that applied the full water level and climate change data only affected the lack of water storage. The water shortage quantity after heightening tended to decrease, which highlights the inability of the reservoir-heightening project to prevent reservoir depletion completely.

A study from Cambodia [38] predicted that a decrease in runoff would reduce water availability in the future, and that water shortage would be more pronounced when considering instream water supply other than irrigation water. Accordingly, it is argued that reservoir construction is more effective in adapting to climate change than managing water supply. In our study, similar results were obtained as the water supply capacity could be improved through the construction project to secure reservoir capacity in preparation for climate change. On the other hand, another study [39] suggested that the increase in water demand in the future due to climate change would reduce by water management. In the current study, we confirmed the water supply effect of the reservoir-heightening project, and we found the need for proper reservoir operation because the construction due to the embankment-heightening project cannot provide sufficient water supply alone.
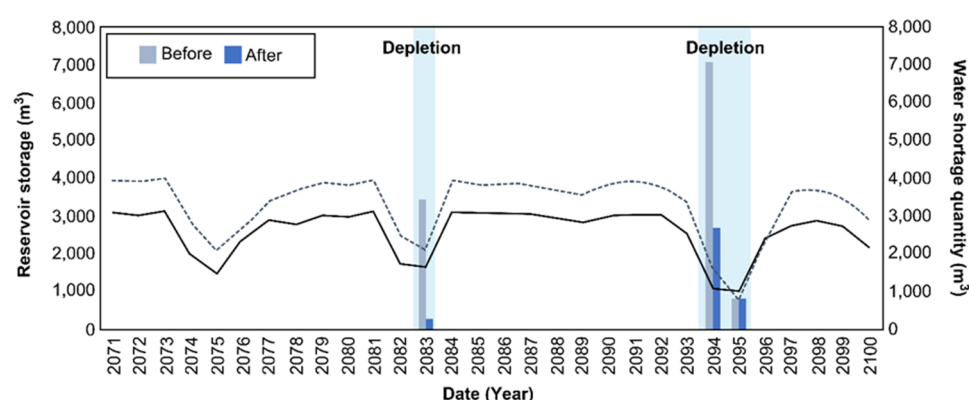
Figure 7. Comparison of the future GH reservoir' annual average water storage following the embankment-heightening project.

3.4. Evaluation of Future Instream Water Supply

As mentioned above, irrigation water was supplied, and the remaining water resources were analyzed to determine whether it is possible to supply the remaining water resources as instream water. Based on the future climate change scenario, the appropriate instream flow with 90% of the water supply safety from the GH reservoir was calculated. Therefore, the instream flow was presented under the condition of supplying a constant amount of instream water during the non-irrigation period. Table 4 lists the simulation operation results of the embankment-heightened reservoir under future RCP scenarios.

Table 4. Water balance analysis results before and after dam heightening under the RCP scenarios (supplying the irrigation water and instream water).

Scenario	Period	Inflow	Irrigation Water	Overflow	Water Storage	Instream Water	
		$(10^3 \text{ m}^3/\text{year})$				$(10^3 \text{ m}^3/\text{year})$	$(10^3 \text{ m}^3/\text{day})$
RCP 4.5	2025s	5706.2	4584.6	1927.5	2391.1	109.4	0.6
	2055s	8342.1	3934.5	3414.8	3085.8	1312.1	7.2
	2085s	6821.0	4180.9	2663.0	3086.0	510.3	2.8
RCP 8.5	2025s	6017.5	4078.8	2179.3	2884.8	127.6	0.7
	2055s	6005.4	4220.5	2071.9	2969.1	91.1	0.5
	2085s	6999.6	4082.4	2667.5	3048.1	637.8	3.5

The future instream flows were 0.6, 7.2, and $2.8 \times 10^3 \text{ m}^3$ for the 2025s, 2055s, and 2085s under RCP 4.5, respectively, and 0.7, 0.5, and $3.5 \times 10^3 \text{ m}^3$ under RCP 8.5, respectively. Herein, the result of the 2025s period in RCP 4.5 was calculated in the water supply safety condition range of the period before reservoir embankment heightening for which no decrease occurred. Consequently, the instream water supply range was 0.6–$7.2 \times 10^3 \text{ m}^3/\text{day}$ in RCP 4.5 and 0.5–$3.5 \times 10^3 \text{ m}^3/\text{day}$ in RCP 8.5.

Figure 8 compares the instream water supplied with the extra water after the irrigation water supply under the RCP scenario. The appropriate future instream water was a minimum of $0.6 \times 10^3 \text{ m}^3$ in RCP 4.5 and $0.5 \times 10^3 \text{ m}^3$ in RCP 8.5, indicating similar values for the two scenarios. However, the maximum instream water that can be supplied varied significantly depending on the reservoir watershed runoff change. In particular, as shown in Table 4, the reservoir inflow was high in the 2055s period under RCP 4.5. In this instance, the instream water shows the maximum value. During this period, the overflow also had the highest value, indicating that reservoir water storage increased because the irrigation water required from the reservoir decreased with the supply of water by rainfall in the irrigation area.
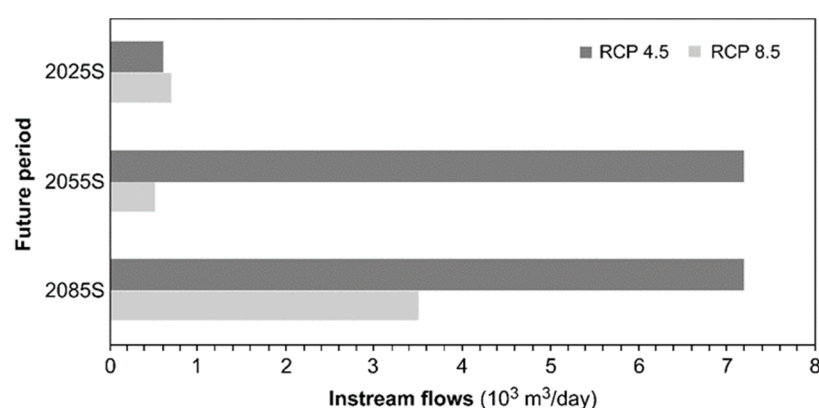
Figure 8. Comparison of the future instream water by the climate change scenario.

　　　Figure 9 compares the irrigation water portions and instream water supplied from the reservoir under the RCP scenarios. In the RCP 4.5 scenario, the future instream water supply ratios were 2.3%, 25%, and 10.9% in the 2025s, 2055s, and 2085s, respectively, and 3.0%, 2.1%, and 13.5% in the RCP 8.5 scenario, respectively. As the agricultural reservoir was built to supply irrigation water, there was no instream water supply, and therefore, this study compares the total water supply ratio. It was possible to quantitatively compare the amount of reservoir water secured by the embankment height as instream water. The instream water supply ratio was estimated to have large variability according to the set period for each climate change scenario. Our results reveal that timely and flexible operation is necessary to instream the water supply.
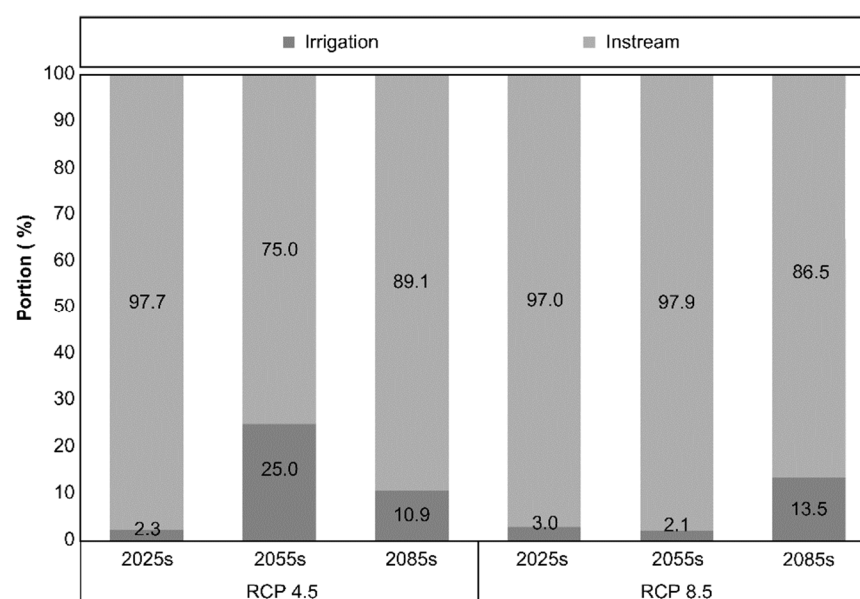

Figure 9. Comparison of the portions of irrigation and instream water by the climate change scenario.

　　　In a previous study [40], downstream hydrological changes were not significant despite the influence of construction on the water resource facility. This is because the facility was operated under the same parameters as before construction to prevent changes in the hydrological condition. Similarly, our study showed that supplying instream water additionally while the reservoir was operating the same way maintained sufficient irrigation water supply. Another study [41] analyzed that the use of the existing reservoir was more efficient in the economic analysis of the instream water supply of the existing reservoir and the new reservoir. A quantitative comparison is difficult due to insufficient research on the future supply of instream water for agricultural reservoirs. The results from our study will

serve as basic data that can minimize the impact on downstream ecosystems by supplying instream water and can be used as a reference for future reservoir operation.

4. Conclusions

The purpose of this study was to evaluate the future water supply capacity of an agricultural reservoir based on the RCP 4.5 and 8.5 climate change scenarios. For the GH reservoir, a reservoir-heightened in South Korea, a reservoir simulation operation was performed before and after the reservoir-heightening project. Before the project, the conditions for supplying irrigation water in the future were simulated. After the project, it was assumed that the water remaining after the irrigation water supply was distributed as instream water, and the water supply capacity was evaluated as follows.

For the future hydrological changes of the GH reservoir watershed, the average annual temperature increased by up to 4.7 °C until the end of the 21st century compared to the past period (1981–2010). The runoff ratio changed from −7.6% to +2.8% in RCP 4.5, whereas by −6.2% to −3.8% in RCP 8.5. Climate change is expected to decrease the GH future available water resources of the reservoir due to the overall reduction in the reservoir's runoff ratio compared to the past. The GH reservoir's future irrigation water supply capacity due to the reservoir-heightening project was analyzed. Before the project, the future water supply safety ranged from 63.3% to 97.6% under RCP 4.5, and from 80.0% to 86.7% in RCP 8.5, indicating that the overall future water supply capacity was not sufficient. After the project, the future water supply safety increased by up to 3.4% in RCP 4.5 and up to 13.3% in RCP 8.5. This indicates that the project improved the overall future irrigation water supply capacity.

After the reservoir-heightening project, the available instream flows from the GH reservoir due to sufficient water storage ranged from 0.6 to 7.2 $\times$ 10^3 m^3/day in RCP 4.5 and from 0.5 to 3.5 $\times$ 10^3 m^3/day in RCP 8.5. Among the total supply, the instream water represented up to 25% in RCP 4.5 and 13.5% in RCP 8.5.

Our results reveal that it was possible to quantitatively estimate the capacity of an agricultural reservoir in South Korea to supply irrigation water and instream water using the water secured through reservoir embankment heightening. In South Korea, water balance is analyzed in the reservoir design process under the assumption that the past meteorological data will be the same in the future. This assumption is expected to have limitations in operating facilities in future water shortage conditions. If climate change information is also utilized to analyze the water balance of water resource facilities, it would facilitate the formulation of appropriate water management policies under climate change scenarios.

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