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Climate change impacts on water storage requirements of an agricultural reservoir considering changes in land use and rice growing season in Korea

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ABSTRACT

Agriculture is directly affected by climate conditions and changes. It is necessary to understand the effects of climate change on agricultural water resources and to minimize its negative effects in order to achieve stable and sustainable crop production. Climate change affects not only crop water requirements but also various aspects of rice cultivation systems, including cultivation land and crop-growing season. This study aimed to analyze the impact of climate change on the water requirements of agricultural reservoirs using a reservoir water-balance model that includes climate change data, the paddy rice growing season and changes in land use. The results showed that due to increasing temperature, transplanting and heading dates were delayed 5–25 days and 0–10 days, respectively, in comparison to the baseline. The average decreasing rates of irrigation water requirements (IWRs) in eight districts were 7.0% (2025s), 9.2% (2055s) and 12.9% (2085s). The major causes of this decrease in IWRs were crop evapotranspiration and percolation followed by a shortened growing period. The average decreasing rates for yearly maximum water storage requirements in all reservoirs were 19.1% (2025s), 23.1% (2055s), and 26.9% (2085s). The decrease in rates could be the result of IWR and increasing watershed runoff (average 10.7% to 27.0%). The results of this study can be used to estimate the capacity and capability of agricultural water resources. Our results also contribute to the establishment of countermeasures against possible risks and the development of policies for future agricultural water management.

1. Introduction

Korea experienced an average temperature increase of 1.5 °C between the years of 1904 and 2000 (KMA, 2008), about twice the world average. The average temperature in Korea was 14.1 °C, an increase of approximately 0.6 °C, and the average annual rainfall was 1485.7 mm, which represents approximately a 10% increase between 1904 and 2000. There were, on average, 28 rainy days, eight more than the previous average. Korea has been reported to have experienced the effects of climate change more than the global average (KMA, 2008). Rising temperatures and changing rainfall patterns (both amount and frequency) due to global warming have affected agricultural water resources which account for 47% of the total water resources in Korea (MCT, 2006; IPCC, 2007). The management and development of agricultural water resources in South Korea have been focused mainly on the protection of paddy rice fields from drought, because rice self-sufficiency has been a priority. Approximately 80% of the paddy fields in Korea are irrigated from over 63,000 agricultural water structures. Reservoirs are the main sources, although others, including pumping stations and head works, provide approximately half of the supply. It is necessary to understand the effects of climate change on agricultural water resources and to minimize its negative effects for stable and sustainable crop production.

Fig. 1 shows how human activities (particularly changes in population, lifestyle, economy, technology and food demands) affect freshwater resources (both quantitatively and qualitatively) and their management (Oki, 2005; IPCC, 2007). When irrigation, which is globally the largest water-use sector, is affected by climate change, all aspects of agriculture, including water requirements, systems of cultivation, land use and seasonal characteristics, need to be reviewed. To assess change in agricultural water requirements due to climate change, various factors should be simultaneously considered (e.g., evapotranspiration and effective rainfall). Like the timing and duration of the water supply, climate change occurring during the planting and growing seasons of a crop affect

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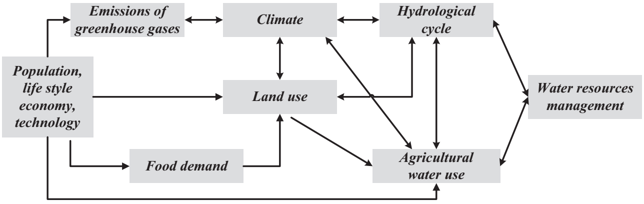


Fig. 1. Impact of human activities on freshwater resources and management, with climate change being only one of multiple pressures.
Source: Modified after Oki (2005); IPCC (2007).

not only its water requirement but also the overall design water requirements and management. Runoff and agricultural water requirements are also affected by changes in land use and cultivation area, respectively. Therefore, a comprehensive approach to the problems associated with climate change will provide more meaningful answers.

Various studies (Fischer et al., 2007; De Silva et al., 2007; Rodriguez Diaz et al., 2007; Thomas, 2008; Shahid, 2011) on the water requirements of paddy rice under climate change have been performed locally and globally. In Korea, Chung (2009) projected volumetric increases of the IWRs by 5.3% (2020s), 8.1% (2050s) and 2.2% (2080s) in the Nakdong River Basin using MM5 (Fifth-Generation Penn State/NCAR Mesoscale Model) by KMA (2008) outputs for the A2 scenario. Chung et al. (2010) estimated total volumetric decreases of the IWRs by 4–10% in eight regional provinces using HadCM3 (Hadley Centre Coupled Model, version 3) outputs by the Hadley Centre for Climate Prediction and Research (Gordon et al., 2000) for the A2 and B2 scenarios. Yoo et al. (2012) estimated the paddy water demand (PWD) and unit duty of water based on high-resolution climate change scenarios (A1B scenario) by KMA (2012); the average change in the PWDs of eight irrigation districts was estimated to be −2.4% (2025s), −0.2% (2055s), and 3.2% (2085s). Previous studies have also concentrated on changes in evapotranspiration and the irrigation water requirements (IWRs) of paddy fields, based on the assumption that there were no changes in the growing period or paddy area. Various studies (Park et al., 2009a, 2009b; Kim et al., 2011) on the impacts of climate and land use changes on an agricultural reservoir watershed and its water balance have been performed. These studies also focused on changes in land use and climate variables, while assuming that there were no changes to the water supply period and paddy area.

In this study, the impact of climate changes on the water storage requirements of agricultural reservoirs was analyzed using the reservoir water-balance model, in which climate change data, change in paddy rice growing period and land use were considered. The climate change data were generated using high-resolution A1B climate data provided by the Korea Meteorological Administration (KMA). The paddy rice growing period changes were estimated based on the generated temperature data. The results of previous studies were used to predict future change in land use changes in the reservoir watershed and irrigation areas.

2. Data and methods

The impact of climate change on the water storage requirements of an agricultural reservoir requires the generation of climate change data, estimation of growing period, simulation of land use change and analysis of reservoir water balance (Fig. 2). Projected climate change data that included rainfall and temperature were generated using high-resolution climate scenarios during the baseline period and 2011–2100. The paddy rice growing period and transplanting date were estimated using temperature data. Evapotranspiration, effective rainfall, and runoff were calculated using the generated climate data. The land use changes in the reservoir watershed and irrigation field area were based on results from Oh et al. (2012). The reservoir water balance was also analyzed with respect to land use changes in the reservoir watershed and irrigation area.

2.1. Site description

Eight irrigation districts were selected to compare the impacts of climate change in various regions with respect to the geographical characteristics of the agricultural reservoir, as shown in Fig. 3. Watershed areas, irrigated areas, percolation, conveyance losses, and effective water storage capacity for the reservoir, which were suggested by hydrology reports for each design, were examined, and the findings are shown in Table 1. Four reservoirs, including the Madun (Res. A), Wonchang (Res. B), Wonnam (Res. C) and Gopung (Res. D), are located in the central region, which is located between 36 and 38° N, and others, including the Ingyo (Res. E), Daepo (Res. F), Mabuk (Res. G) and Namsung (Res. H) reservoirs, are located in the southern region, between 34 and 36° N. The largest watershed area, irrigation area, and effective water storage capacity were found in

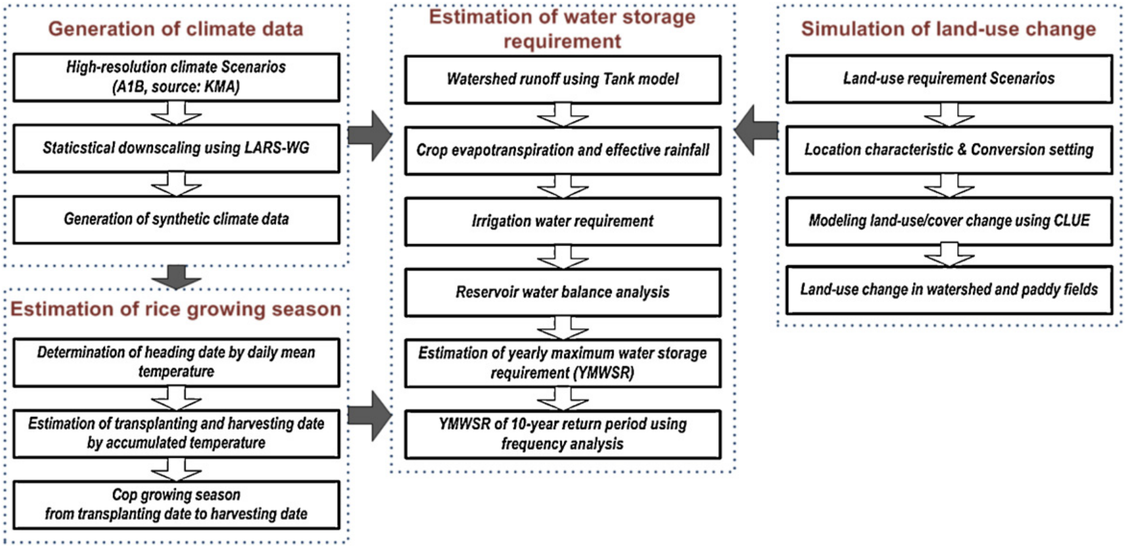


Fig. 2. A procedure diagram for impact of climate change on the water storage requirements of an agricultural reservoir.

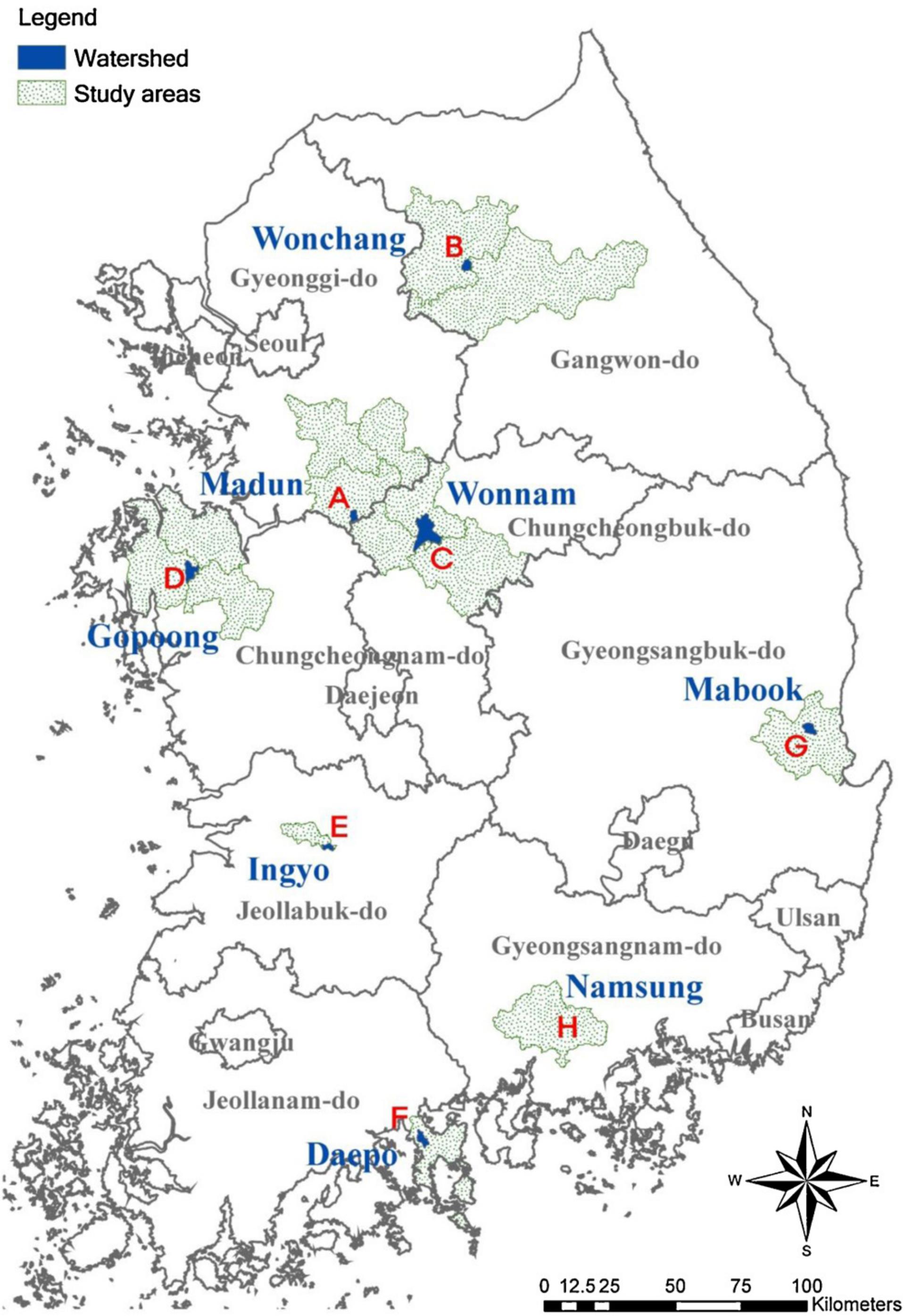


Fig. 3. Locations of the eight agricultural reservoirs in this study.

Table 1
Basic data of the eight agricultural reservoirs and irrigation areas used in this study.

Symbol	Reservoir	Meteorological station	Watershed area (ha)	Irrigated area (ha)	Deep percolation (mm/day)	Conveyance loss (%)	Effective water storage capacity (1000 m^3)
A	Madun	Suwon	1190.0	451.4	4.0	10	3486.0
B	Wonchang	Chuncheon	1273.0	676.9	6.5	20	3214.0
C	Wonnam	Chungju	7563.0	1402.0	5.5	15	8,690.2
D	Gopung	Seosan	2536.0	1185.0	5.1	10	7821.8
E	Ingyo	Jeonju	841.0	188.4	5.0	10	1,376.2
F	Daepo	Yeosu	1458.0	296.7	4.0	15	1380.1
G	Mabuk	Pohang	1618.0	583.6	5.0	10	6,160.0
H	Namsung	Jinju	373.0	221.7	4.1	15	1622.7

Source of data: Yoo et al. (2012); KRC (2012).

Res. C, and the largest percolation and conveyance losses were in Res. B.

2.2. Generation of climate data

The KMA projected climate change scenarios in the SRES A1B, A2 and B1 scenarios using the GCM, ECHO-G (ECHAM4 (European Centre Hamburg Model) and HOPE-G (Hamburg Ocean Primitive Equation Model-Global)) (the 30 years between 1971 and 2000, and the 100 years between 2001 and 2100) (KMA, 2008). Of the three scenarios, A1B was selected as the 'national standard climate change scenario' by the KMA.

The 'climate change scenario of the Korean peninsula' with a resolution of 27 km, was downscaled for the A1B scenario using the MM5 regional climate model. The use of high-resolution regional climate model (RCM) to examine the hydrological impacts of climate change has grown significantly in recent years due to the improved representation of the local climate (Van Roosmalen et al., 2010). The KMA produced a high-resolution (10 km) climate change scenario by applying PRISM (Parameter-elevation Regressions on Independent Slopes Model), allowing a statistical downscaling of the 'climate change scenario of the Korean peninsula'. In the high-resolution climate change scenario, the daily maximum, minimum and average temperatures and the monthly rainfall data for the years 2000–2100 is projected by the Climate Change Information Center of the KMA (2012). In this study, projected climate change data from the high-resolution climate change scenario were used to generate a time series of future climate data using the LARS-WG (Long Ashton Research Station Weather Generator) tool developed by Semenov and Brooks (1999), a stochastic weather generator, as the daily rainfall needed to meet IWRs. Bae et al. (2007) used LARS-WG at 54 meteorological stations in South Korea and found that LARS-WG reflects regional climate characteristics that are not reflected by other climate models. The parameters of the LARS-WG model were estimated using meteorological data obtained from each of the eight metrological stations from 1974 to 2010. To determine the statistically significant differences between the observed and simulated climate data, a *t*-test was performed within the LARS-WG model. Simulated climate data were generated for 300 years, and the probability distributions of the simulated data were close to the long-term observed distributions for the site in question (Semenov and Barrow, 2002). The estimated parameters were verified by a *t*-test and found to have a significance level of 1% for all stations. In this study, based on the simulation period of 1971–2000, climate change scenarios were generated for the next 90 years: 2011–2040 (2025s), 2041–2070 (2055s) and 2071–2100 (2085s).

2.3. Estimation of rice growing season

In general, temperature determines the rate of crop development and consequently affects the length of the total growing period (Doorenbos and Kassam, 1979). For rice, the transplanting, heading and harvesting dates and the growing period are estimated using the cumulative temperature. For example, a single cropping of meddle rice requires a cumulative temperature of 2150 °C from transplanting to full heading and a temperature of 880 °C from full heading to maturation in China (IRRI, 1997). In this study, the transplanting and harvesting dates are estimated by the accumulated temperature based on the heading date which is calculated from the number of consecutive days of the optimum ripening period that had a daily mean temperature of 21–23 °C for 40 days after flowering. The transplanting date is defined as the day at which the accumulated temperature from the transplanting date to the heading date is 1500–2200 °C (extremely early maturing rice: 1500 °C–late maturing rice: 2200 °C). The harvesting date is defined as the day when the accumulated temperature from heading date to harvesting date reaches 1100 °C. The process is indicated in Fig. 4 (Park and Lee, 2005).

2.4. Land use change

Land use changes in a reservoir watershed and irrigation area affect inflow to the reservoir and paddy irrigation water demand. An appropriate simulation model is required for predicting future land use changes in a climate change scenario. The CLUE (Conversion of Land Use Change and its Effects) model, a type of integrated land use simulation model, was developed to model the competition among land use types under different socio-economic conditions and biophysical driving factors (Veldkamp and Fresco, 1996; Verburg et al., 2002, 2006; Veldkamp and Verburg, 2004). More recent studies using the CLUE model include Schulp et al. (2008), which studied the influence of land use change on carbon sequestration and Oh et al. (2011, 2012), which simulated land use changes in small regions such as a watershed or province. In this study, the results of Oh et al. (2012) were used, as shown in Table 2. Oh et al. (2012) conducted a study to predict future land-cover changes and to analyze regional land-cover changes in irrigation areas and agricultural reservoir watersheds in a climate change scenario. To simulate future land-cover according to the climate change scenario A1B, CLUE was used to model the competition among land use types based on socioeconomic and biophysical driving factors. For the study areas, eight agricultural reservoirs were selected from eight different provinces across nation. The simulation results from 2010 to 2100 predicted the future land use changes under the scenario conditions. For Res. A in Gyeonggi-do, the total decrease in paddy area was similar to that found in

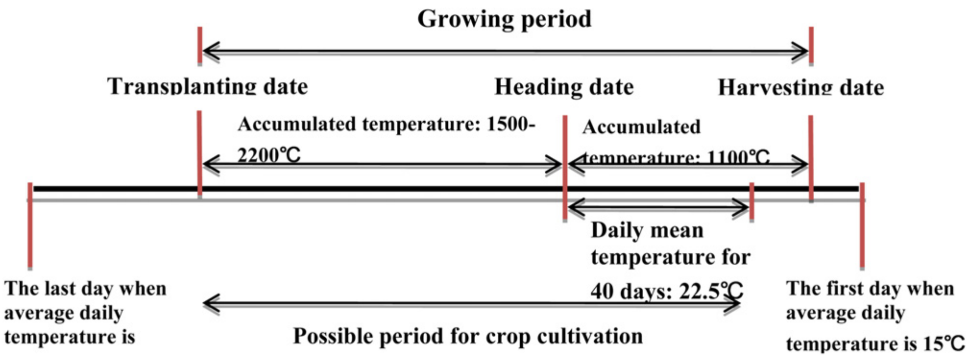


Fig. 4. Standards for estimating the growing season and period of paddy rice

Source: Modified from Park and Lee (2005).

the 'Base demand scenario' of *Comprehensive Water Resources Plan-Water Vision 2020* published by MCT (2006), while the decreased paddy areas in other sites were less than the amounts predicted in the 'High demand scenario' of *Water Vision 2020*. The paddy area in the most irrigated regions, located downstream from the agricultural dam reservoir, showed only a slight decrease, with changes below 5%. However, within most of the agricultural reservoir watersheds located upstream of a dam, the areas of paddy and upland were significantly decreased while the forest areas were continuously increased.

2.5. Reservoir operation model

2.5.1. Daily Irrigation Reservoir Operation Model (DIROM)

A water-balance analysis for each reservoir was performed using the Daily Irrigation Reservoir Operation Model (DIROM), which has been utilized to analyze the water balance of a reservoir (Kim and Park, 1988a, 1988b). DIROM is a simulating model for daily inflow and the release rate for irrigation reservoir composed of the two modules. The first module is a Tank model to estimate inflow into reservoirs (watershed runoff) while the second is IWR model to release rates for reservoir (Jang et al., 2012). The reservoir water balance represented in the DIROM is defined as:

$$ST_t = ST_{t-1} + IF_t + RF_t - (RL_t - RO_t - RE_t - LO_t), \qquad (1)$$

where t is the time (day), ST is the reservoir storage (m^3), IF is the inflow (m^3), RF is the rainfall (m^3), RL is the release water supply used for agriculture irrigation (m^3), RO is the overflow by the sluice gates (m^3), RE is the evaporation loss (m^3) and LO is other losses (m^3), including percolation and dam seepage.

2.5.2. Rainfall-runoff model (Tank model)

The tank model, which is a well-known and typical conceptual rainfall-runoff model (Sugawara, 1979), was selected to simulate daily inflow rates in each reservoir for a data-scarce watershed. This model is very simple, but the output behavior is not as simple and can represent many types of hydrographs in an area of mixed land use area, including paddy fields. The complex behavior is caused by the non-linear structure that results from setting the side outlets somewhat above the bottom of each tank. In the present study, the runoff in a reservoir watershed (reservoir inflow) was estimated using the modified tank model suggested by Kim and Park (1988a). Considering the characteristics of agricultural reservoirs in Korea, this model was simplified from a 4-stage to a 3-stage tank by eliminating the fourth tank. The first tank has two side outlets, and the other tanks have one side outlet. The outputs through the side outlets of the first (located at the top), second, and third (located at the bottom) tanks are considered to be surface runoff, intermediate runoff, and base flow, respectively (Kim and Park, 1988a). This method estimates the model's parameters using an empirical formula with the variables of watershed area and ratio of land use ratio including paddy, upland, forest and others by taking into account the characteristics of agricultural reservoirs.

2.5.3. Irrigation water requirement

The IWR (release rate) model reflects the IWR, including the water requirement for transplanting and the minimum release for maintaining canal flow (conveyance losses) (Kim and Park, 1988b). The daily IWR is defined as the depth of water needed to counteract the water loss that occurs through the crop evapotranspiration (ETc) of a disease-free crop growing in large fields and to achieve the full production potential in the given growth environment (Yoo et al., 2008).

The IWR for paddy rice is calculated using a water-balance concept as described by equation (2) (Jensen et al., 1990):

$$IWR = ETc + DP + LR + MR + LP - EFR, \qquad (2)$$

where ETc is the crop evapotranspiration (mm), DP is the deep percolation (mm), LP is the land preparation, including the transplanting water requirement, LR is the leaching requirement (mm), MR is the miscellaneous water requirement (mm), and EFR is the effective rainfall (mm) as defined below. The transplanting water requirement is assumed to be 140 mm, as suggested by MAF (1998) in Korea.

In general, the leaching and miscellaneous water requirements in ponding rice fields are negligible (Yoo et al., 2008). The leaching water requirement was supplied only when control of the soil salinity is required, and the amount of the miscellaneous water requirement is small enough to be ignored. Therefore, the equation (3) is used a simpler and more commonly used equation for computing IWR in a paddy field after transplanting.

$$IWR = ETc + DP - EFR, \qquad (3)$$

where ETc is determined by multiplying the reference crop evapotranspiration by the crop coefficients of paddy rice. The reference crop evapotranspiration is computed using the FAO Penman–Monteith method, and the value used for the crop coefficients of paddy rice are those given by Yoo et al. (2006). DP values can be found in Table 1.

EFR represents the amount of rainfall water that is available for crop growth with the exception of the loss from surface runoff. EFR during the irrigation season depends on such factors as rainfall amount, rainfall intensity, topography, soil infiltration rate, soil moisture, and water management. The effective rainfall for paddy fields is calculated using a freeboard model (IRRI, 1977) to simulate the depth of the ponding water. The freeboard model is shown as equation (4):

$$PD_t = PD_{t-1} + IR_t + RF_t - ETc_t - DP_t - SR_t, \qquad (4)$$

where t is the time (day), PD is the ponding water depth (mm), SR is the surface runoff in the paddy field outlet (mm), IR is the irrigated water (mm), and RF is rainfall (mm). Rainfall of less than 5 mm/day is considered insignificant (Dastane, 1978; Chung et al., 2006).

Therefore, EFR is expressed as:

$$\begin{aligned} EFR_t &= RF_t \qquad \text{for } SR_t = 0 \\ EFR_t &= RF_t - SR_t \qquad \text{for } SR_t > 0 \end{aligned} \qquad (5)$$

Some suggestions have been made for using the freeboard model: the outlet height in the paddy field should be 70 mm, and the irrigation is supplied for the controlled ponding water depth for each growth stage, as suggested by Doorenbos and Kassam (1979) and Jang et al. (2004).

3. Results and discussions

3.1. The growing season and period of paddy rice

The changes in the paddy rice growing season and period due to climate change were analyzed using the climate data from eight meteorological stations. The transplanting, heading and harvesting dates were estimated using the accumulated temperature during the growing period and the representative transplanting, heading, and harvesting dates were calculated using the average date based on five days from each of the central and southern regions. The results are indicated in Table 3. In the four reservoirs in the central region, the baseline heading date was estimated to be August 20. Approaching the 2085s, the heading date was delayed to August 31. In the southern regions, the baseline heading date was estimated to be August 31. Approaching the 2085s, the heading date was delayed to September 5. Based on the changes in the heading date, the transplanting and harvesting dates also changed over time. In the central

Table 2
Land-cover changes in agricultural reservoir watersheds and irrigated areas.

AreaReservoir		Landcover	Baseline	2025s	2055s	2085s
		(ha)	Area			
A	Watershed	P	86	73	32	24
		U	63	51	29	15
		F	960	969	1006	1023
		O	81	97	123	128
	Irrigated area		451.4	442.4	441.3	440.1
B	Watershed	P	–	–	–	–
		U	–	–	–	–
		F	1253	1247	1247	1247
		O	20	26	26	26
	Irrigated area		676.9	668	665.4	660.4
C	Watershed	P	720	685	666	649
		U	962	780	757	752
		F	5369	5323	5425	5526
		O	512	775	715	636
	Irrigated area		1402	1334	1297	1264
D	Watershed	P	153	138	115	90
		U	211	128	82	60
		F	2032	2120	2159	2176
		O	140	150	180	210
	Irrigated area		1185	1184	1154	1116

Reservoir	Baseline	2025s	2055s	2085s
	Area			
E	85	81	59	57
	23	3	3	2
	682	694	712	718
	51	63	67	64
	188.4	188.4	182.7	177.2
F	142	142	142	142
	116	93	80	80
	1079	1061	1038	1038
	121	162	198	198
	296.7	296.7	296.7	296.7
G	39	37	34	32
	23	19	19	14
	1516	1515	1523	1532
	40	47	42	40
	583.6	583.6	583.6	583.6
H	31	26	25	25
	2	2	1	1
	325	330	332	332
	15	15	15	15
	221.7	220.3	216.3	212.2

Source of data: Oh et al. (2012).
P: paddy, U: upland, F: forest, O: others including water, built-up and barren land.

region, the baseline transplanting date was May 21, the baseline harvesting date was October 6, and the baseline growing period was 139 days. Approaching the 2085s, the transplanting date was delayed to June 16, the harvesting date was delayed to October 21, and the growing period was decreased to 128 days. In the southern region, the baseline transplanting date was June 1, the baseline harvesting date was October 11, and the baseline growing period was 133 days. Approaching 2085s, the transplanting date was delayed to June 21, the harvesting date was delayed to October 25, and the growing period was decreased to 127 days.

3.2. *Runoff*

The changes in annual rainfall amount, which directly affect runoff, are shown in Fig. 5. During the 2025s, rainfall is projected to increase an average of 10.4% in the central region and 6.7% in the southern region compared to the baseline. During the 2055s and 2085s, rainfall is predicted to increase an average of 13.9% and 15.6% in the central region, and 15.6% and 22.0% in the southern region, respectively, compared to the baseline. The rate of rainfall increase was found to be larger in the central region during the 2025s, but was found to be larger in the southern region during the 2055s and 2085s.

Runoff from reservoir watersheds in the eight irrigation districts was calculated for the baseline, 2025s, 2055s and 2085s using the tank model. The runoff results are shown in Fig. 6. During the 2025s, runoff increased an average of 113.4 mm (13.0%) in the central region and 114.4 mm (8.4%) in the southern region compared to the baseline. During the 2055s and 2085s, rainfall increased an average of 160.8 mm (18.4%) and 217.0 mm (24.9%) in the central region, and 184.1 mm (21.2%) and 241.9 mm (29.2%) in the southern region, respectively, compared to the baseline. The district that showed the largest increase in runoff rate was Res. B, and that the district with the smallest increase was Res. A.

The results were consistent with the trend of increased rainfall in those eight districts. The average increase in the rates of rainfall

Table 3
The representative transplanting, heading and harvesting dates in the central and southern regions according to climate change.

Period	Region	Reservoir	Transplanting date		Heading date		Harvesting date		Growing period
Baseline	Central	A	05-14	05-21	08-14	08-20	10-03	10-06	142
		B	05-21		08-19		10-09		141
		C	05-26		08-20		10-10		137
		D	05-19		08-19		10-09		143
	Southern	E	05-27	06-01	08-23	08-31	10-12	10-11	138
		F	05-27		08-22		10-12		138
		G	06-02		08-24		10-14		134
		H	06-01		08-28		10-17		138
2025s	Central	A	05-24	06-01	08-19	08-25	10-09	10-11	138
		B	06-02		08-24		10-15		135
		C	06-04		08-25		10-15		133
		D	05-30		08-24		10-14		137
	Southern	E	05-31	06-06	08-25	08-31	10-14	10-16	136
		F	06-03		08-26		10-16		135
		G	06-06		08-26		10-15		131
		H	06-06		08-30		10-19		135
2055s	Central	A	06-05	06-11	08-25	08-31	10-15	10-16	132
		B	06-11		08-29		10-19		130
		C	06-14		08-30		10-20		128
		D	06-11		08-30		10-20		131
	Southern	E	06-12	06-16	08-31	09-05	10-20	10-21	130
		F	06-12		08-30		10-19		129
		G	06-14		08-30		10-19		127
		H	06-18		09-06		10-26		130
2085s	Central	A	06-11	06-16	08-28	08-31	10-18	10-21	129
		B	06-16		08-31		10-20		126
		C	06-19		09-01		10-22		125
		D	06-15		08-31		10-20		127
	Southern	E	06-19	06-21	09-04	09-05	10-24	10-25	127
		F	06-17		09-02		10-22		127
		G	06-20		09-03		10-24		126
		H	06-26		09-11		10-31		127

was estimated to be 8.5% (2025s), 14.8% (2055s) and 20.4% (2085s), and the corresponding increase in the rates of runoff was higher than the rainfall increase rates, with values of 10.7% (2025s), 19.8% (2055s) and 27.0% (2085s), respectively. These results indicate that runoff from these watersheds is being increased due to land use changes and increased rainfall.

3.3. *Crop evapotranspiration (ETc)*

ETc, which is a major component of the crop water requirement in a paddy during the growing season after transplanting, is shown in Table 4. The average baseline value of total ETc exhibited a range, with a minimum of 441.0 mm and a maximum of 493.0 mm. The total ETc was in the range of 419.0 mm–477.6 mm during the 2025s, 407.0 mm to 467.7 mm during the 2055s, and 446.4 mm to 536.9 mm during the 2085s. The average decrease in the rates of total ETc during the three different periods compared to the baseline was 5.0% (2025s), 7.4% (2055s) and 9.6% (2085s) in the central region and 3.2% (2025s), 6.1% (2055s) and 7.5% (2085s) in the southern region, respectively. The rate of decrease in the ETc was found to be greater in the central region than in the southern region.

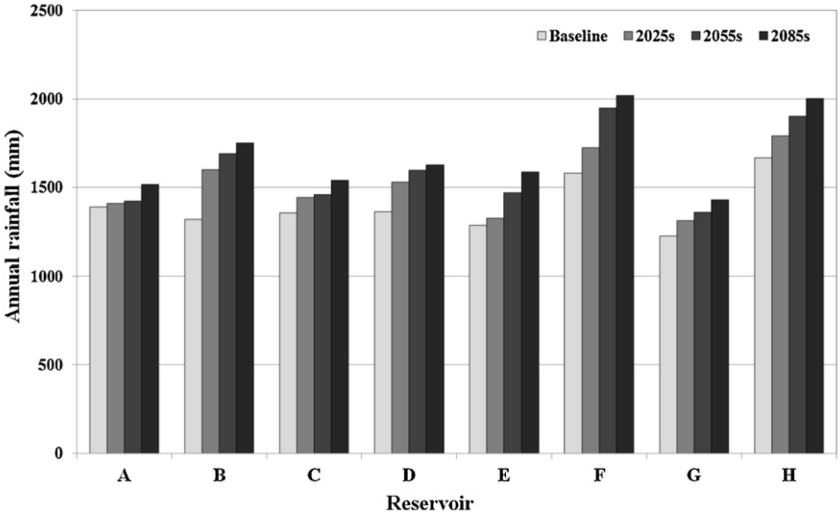


Fig. 5. Annual rainfall in the eight reservoirs during the period baseline, 2025s, 2055s and 2085s.

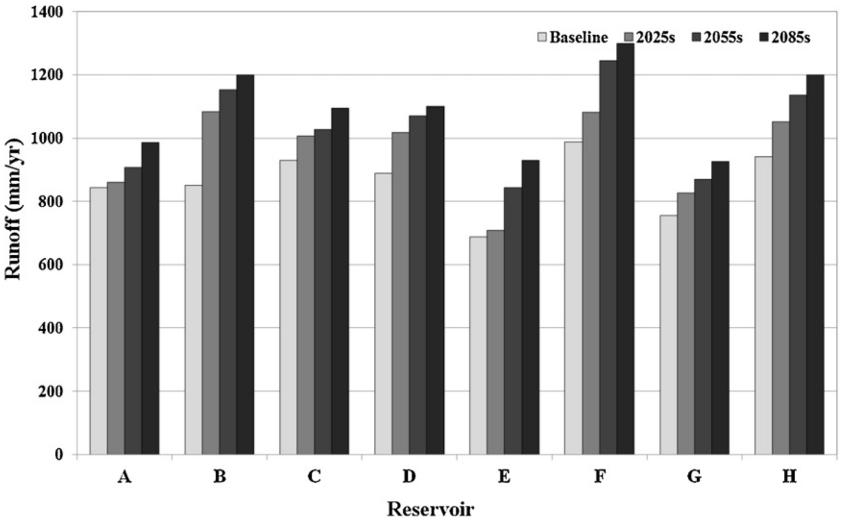


Fig. 6. Annual runoff in the eight reservoirs watersheds during the period baseline, 2025s, 2055s and 2085s.

Table 4
The total and daily crop evapotranspiration (ETc) during a growing season after transplanting in the eight reservoirs.

Reservoir	Period (unit)	Baseline			2025s			2055s			2085s		
		DAT[1](days)	Total (mm/DAT)	Avg. (mm/day)	DAT (days)	Total (mm/DAT)	Avg. (mm/day)	DAT (days)	Total (mm/DAT)	Avg. (mm/day)	DAT (days)	Total (mm/DAT)	Avg. (mm/day)
A	ETc	112	493.0	4.40	105	477.6	4.55	101	467.7	4.63	96	459.4	4.79
	Change[2]		–	–		−3.1%	3.3%		−5.1%	5.2%		−6.8%	8.7%
B	ETc		443.5	3.96		419.0	3.99		407.0	4.03		394.8	4.11
	Change		–	–		−5.5%	0.8%		−8.2%	1.8%		−11.0%	3.9%
C	ETc		473.8	4.23		447.3	4.26		441.5	4.37		424.4	4.42
	Change		–	–		−5.6%	0.7%		−6.8%	3.3%		−10.4%	4.5%
D	ETc		470.5	4.20		443.6	4.22		425.4	4.21		422.0	4.40
	Change		–	–		−5.7%	0.6%		−9.6%	0.3%		−10.3%	4.6%
E	ETc		441.0	3.94		422.6	4.03		410.6	4.07		407.0	4.24
	Change		–	–		−4.2%	2.2%		−6.9%	3.2%		-7.7%	7.7%
F	ETc		479.9	4.28		471.8	4.49		448.3	4.44		430.0	4.48
	Change		–	–		−1.7%	4.9%		−6.6%	3.6%		−10.4%	4.5%
G	ETc		461.4	4.12		435.8	4.15		432.8	4.29		436.1	4.54
	Change		–	–		−5.6%	0.7%		−6.2%	4.0%		−5.5%	10.3%
H	ETc		446.5	3.99		439.7	4.19		425.4	4.21		418.0	4.35
	Change		–	–		−1.5%	5.0%		−4.7%	5.7%		−6.4%	9.2%

DAT: days after transplanting. Change: rate difference in comparison to baseline.

Table 5
Comparison of average change rate in crop evapotranspiration (ETc), effective rainfall (EFR) and irrigation water requirement (IWR) with other studies (Yoo et al., 2012; Chung, 2009; Chung et al., 2010).

Variable	Region	Period	This study	Yoo et al. (2012)	Chung (2009)	Chung et al. (2010)	
			A1B sce.		B2 sce.		A2 sce.
ETc	Central	2025s	5.0%	1.3%	–	–	–
		2055s	7.4%	5.5%			
		2085s	9.6%	8.8%			
	Southern	2025s	3.2%	3.4%			
		2055s	6.1%	6.2%			
		2085s	7.5%	9.8%			
EFR	Central	2025s	0.0%	5.2%			
		2055s	−4.1%	4.7%			
		2085s	−8.1%	2.2%			
	Southern	2025s	−1.1%	4.2%			
		2055s	−2.3%	9.2%			
		2085s	−6.7%	11.2%			
IWR	Central	2025s	8.5%	−2.0%		–	–
		2055s	9.1%	1.0%		−1.3%	−7.4%
		2085s	13.3%	5.0%		0.7%	5.2%
	Southern	2025s	5.6%	0.1%	5.3%	–	–
		2055s	9.3%	−1.7%	8.1%	−5.1%	−8.6%
		2085s	12.4%	−0.2%	2.2%	−15.3%	−6.9%

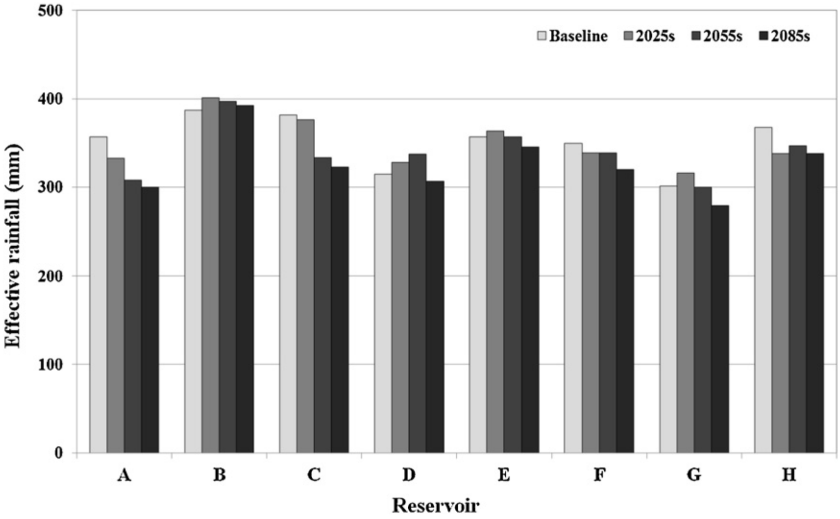


Fig. 7. The total effective rainfall (EFR) during a growing season after transplanting the eight reservoirs.

The findings of Yoo et al. (2012) were similar to the results of this study as seen in Table 5, except in the changes in crop-growing period. Yoo et al. (2012) estimated the average increase in the rates of ETc in the central region to be 1.3–8.8%, whereas the rates for the southern region were estimated to be 3.4–9.8%. This means that the ETc trends predicted by Yoo et al. (2012) were different from those predicted by this study during the crop-growing period. In this study, the increase in daily average ETc was 2.3% (2025s), 3.4% (2055s), and 6.7% (2085s) compared to the baseline. This indicates that, although the total ETc during the paddy growing period decreased, the daily ETc showed a tendency to increase. Though the daily ETc increased, due to the temperature increases that occur with climate change, the total ETc during the growing period was reduced because the growing period of paddy rice was reduced by 7–16 days.

3.4. Effective rainfall (EFR)

Fig. 7 shows the results of the EFR calculation during a growing season after transplanting. Annual rainfall showed a tendency to increase in all of the districts and periods, but EFR differed according to district and period. In Res. A, C, F, and H, EFR decreased during all the periods in comparison to the baseline, whereas it increased in Res. E and G during the 2025s. A tendency to decrease was calculated for Res. D only during the 2085s, and EFR increased during all of the periods in Res. B. The differences in the EFR trends between the reservoirs were relatively large, although they were located in close proximity. The reason why EFR differs by district and period might be due to differences in the number of rainy days and rainfall intensity, as well as the flooding effect of rainfall in a paddy field. Additionally, reductions in the crop-growing period that were attributed to decreases in EFR were the same as the decreasing trend of ETc. Yoo et al. (2012) estimated that the average rates of increase of the EFR would be 5.2–2.2% (central region), and 4.2–11.2% (southern region), as shown in Table 5. As for the ETc, the difference in EFR could have been caused by the shortened crop-growing period.

3.5. Irrigation water requirement (IWR)

Fig. 8 shows the IWR values of the eight districts using average ETc and EFR values for 30 years during the baseline, the 2025s, 2055s and 2085s. The IWR showed a trend toward decreasing in all of the periods compared with the baseline. The average rates of decrease in the IWR during the three periods were 8.5% (2025s), 9.1% (2055s) and 13.3% (2085s) in the central region, and 5.6%

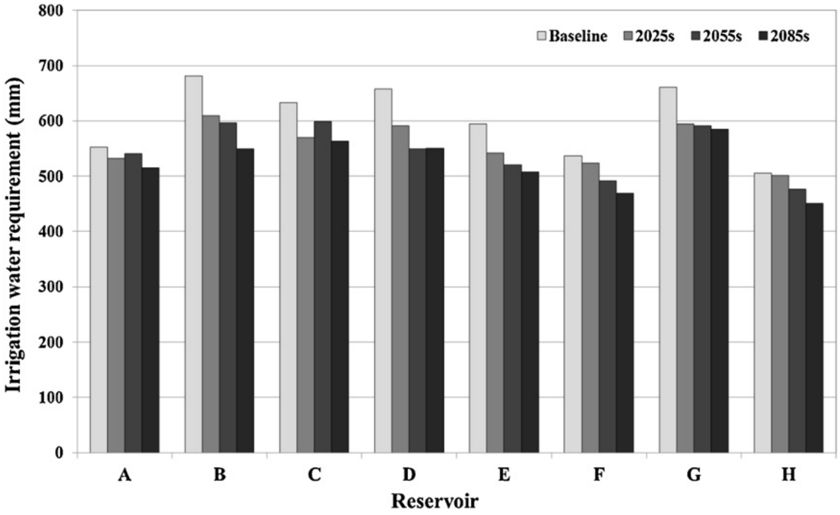
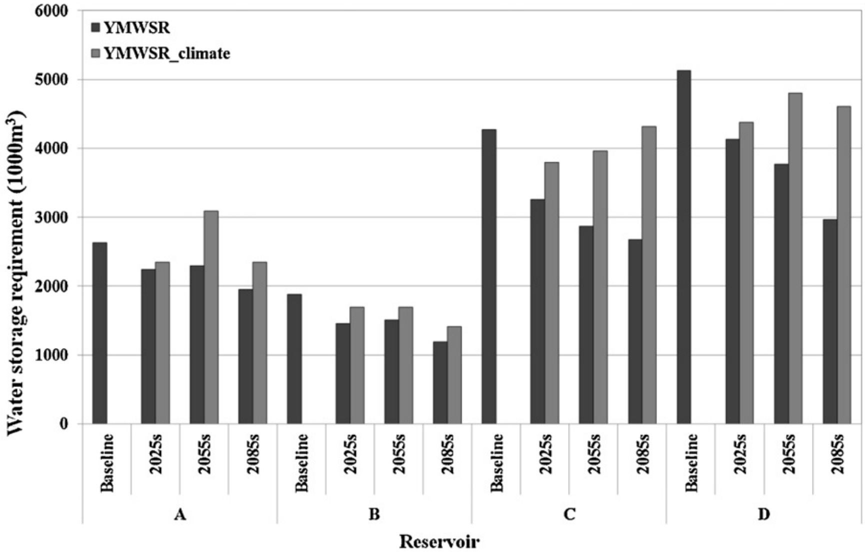
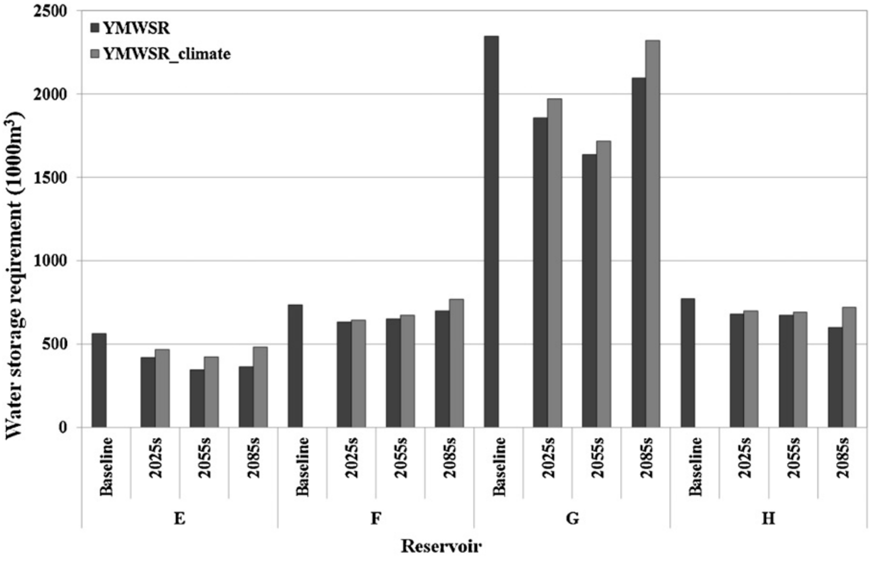


Fig. 8. The total irrigation water requirement (IWR) during a total growing season in the eight irrigation districts.



(a) Central region



(b) Southern region

Fig. 9. Comparison between YMWSR and YMWSR_climate in the central and southern regions (YMWSR: YMWSR considering three conditions including the climate variable, growing season and land-use change, YMWSR_climate: YMWSR considering only climate variable changes).

(2025s), 9.3% (2055s) and 12.4% (2085s) in the southern region. This finding was consistent with the changes in ETc and EFR. The decrease in the growing period by 7–16 days after transplanting meant a 6–14% reduction in the total baseline growing period. If the growing period is shortened, ETc and percolation are also decreased as much as the reduction in growing period. The above results suggest that the major causes of the IWR decrease are ETc and percolation, followed by a shortened growing period.

Table 5 shows comparison of change rate in IWR with other studies. Chung et al. (2010) estimated the average rates of change in the IWRs for the central and the southern regions to be −1.3 to 0.7% and −15.3 to −5.1% in A2 scenario, −7.4 to 5.2% and −8.6 to −6.9% in B2 scenario. The trends in the IWRs for the central region were different from the results of this study, while those for the southern region were similar to the results of this study. Chung (2009) estimated the average rates of change in the IWRs for the southern region to be 2.2–8.1%, which are different from the results from Chung et al. (2010) and this study. Yoo et al. (2012) estimated the average rates of change in the IWRs for the central and southern regions to be −2.0 to 5.0%, and −1.7 to 0.2%. This was caused by differences in the climate change data generation methods (GCM and downscaling), IWR estimation methods (ETo and EFR), and crop-growing seasons used in the studies.

3.6. Water storage requirement

The yearly maximum water storage requirement was calculated using a water-balance analysis of the reservoirs based on the runoff, which is the inflow from a reservoir watershed, and the IWR, which is the water release in a reservoir. In Korea, the agricultural reservoir capacity is decided based on the YMWSR of a drought for a ten-year return period (hereinafter referred to as ‘YMWSR’) (MAF, 1998). Accordingly, YMWSR was estimated using a frequency analysis and the results were compared. A Gumbel probability distribution function, which was estimated using a probability weighted moments method, was verified by a goodness-of-fit test including the Kolmogorov–Smirnov (K–S) with a significance level of 5%. YMWSR was calculated using the Gumbel PDF and Chow frequency factor method (Chow, 1951); the results of the YMWSR are shown in Fig. 9.

YMWSRs of all reservoirs during all periods showed a trend toward decrease. The average decrease rates of YMWSR were 9.6% (2025s), 21.5% (2055s) and 26.5% (2085s) in the central region, and 5.1% (2025s), 7.3% (2055s) and 15.2% (2085s) in the southern region. The YMWSR's decrease was caused by an increased inflow into the reservoirs due to high runoff and decreased release from reservoirs due to reduced IWRs and irrigated areas. The reservoirs with the higher irrigated-watershed area ratio (I-W_{ratio}) have more decreased YMWSRs.

For the three periods, on average, the largest decreases were found in Res. C and E. This decrease was due to the highest I-W_{ratio} of 5.4–1 and relatively large reductions in the IWR and irrigation area, although Res. C's rate of runoff increase was relatively small (12%) compared with that of other reservoirs. Additionally, Res. E's relatively high rate of release increase (20.4%) and relatively large reductions in the IWR and irrigation area contributed to the largest decrease rates.

Conversely, Res. F's rate of decrease in YMWSR was found to be the smallest, although the rate of runoff increase and the I-W_{ratio} were relatively large. Although Res. A's rate of runoff increase and rate of IWR decrease were the smallest, the rate of the YMWSR decrease was not the lowest. It is considered that the relative decrease in the reservoir effect caused by spillway overflow from heavy rainfall events was the cause of this decrease, despite the increase in the inflow into the reservoir due to increased annual rainfall.

The YMWSR (hereafter referred to as 'YMWSR_climate') was calculated for the eight reservoirs, taking into account only climate change variables, including temperature and rainfall, with the assumption that there were no changes in growing period or land use. The results of the YMWSR_climate were compared with the YMWSR calculated with all conditions considered. Fig. 9 shows the results of the YMWSR_climate and YMWSR calculation for the central and southern regions, respectively.

The value of the YMWSR in the central region was smaller by an average of 9.6% (2025s), 21.5% (2055s) and 26.5% (2085s) compared with the values of YMWSR_climate during the three periods. The value of the YMWSR in the southern region was smaller by an average of 5.1% (2025s), 7.3% (2055s) and 15.2% (2085s) compared with the values of the YMWSR_climate for the three periods. As time passed, the difference between the results of the two YMWSR comparisons grew larger due to a decrease in irrigation area with land use changes and the increasing difference in the crop-growing period.

The average decreases per irrigated area according to the two YMWSR results by district for the three periods were found to be 98.2 mm (Res. A), 31.9 mm (Res. B), 84.9 mm (Res. C) and 82.6 mm (Res. D) in the central region. The differences in the decreases calculated for the four reservoirs, in the southern region were 45.2 mm (Res. E), 11.9 mm (Res. F), 23.8 mm (Res. G) and 24.9 mm (Res. H). The decrease in the differences between the two YMWSR calculations was larger in the central region because the irrigation area and land use changes in the irrigation districts in the central region of the country were relatively greater than in the southern region. The results indicated that the reason for the greatest difference between the two YMWSR values was that the largest decreases in irrigation area in Res. C. There was almost no change in the irrigation area in Res. F, where the YMWSR change was estimated to be the smallest.

4. Conclusions

In this study, the changes in climate, growth duration and land use were designated as the main factors affecting the supply and demand of reservoir waters, and four reservoirs each in the central and southern districts were analyzed to determine their influences. The results are shown below.

The rising temperatures cut the length of the period required to reach the necessary cumulative temperature, resulting in the reduction of growth duration. Increased rainfall led to increased runoff, and the increase in the latter was greater than that of the former. The changes in rainfall pattern and land use within the watersheds are considered to be the main reasons for these phenomena. Average daily ETc and EFR values increased, due to the increased temperatures and rainfalls; however, their totals for the whole growth period were decreased due to a reduction in the growth period. The decrease in the rate of the ETc in the central district was greater than that in the southern district. The EFR exhibited a tendency toward relatively increased difference, even between closely located reservoirs.

The general tendency for the IWR to decrease was caused by the reduction in growth period, which made the decrease in water requirements (ETc and infiltration) greater than that of EFR. Thus, climate change exerts great effects on agricultural water resources through changes in the supply and demand of water in the growth periods together with direct changes in the ETc, EFR and runoff. The YMWSRs of all reservoirs showed trends toward decrease for all periods. The rate of decrease in the central district was greater than that in the southern district because of the central district's relatively greater rates of runoff increase, IWR and irrigation area. This study only dealt with the agricultural water supply with respect to the change in growth period, which would affect the cumulative amount of solar radiation and consequently the crop production.

There are factors affecting water requirements other than the key factors that were considered in this study: changes of cultivation practice such as drainage practice, crop farming systems (two crop- or double crop-farming), changes in the water-supply duration (due to changes in IWR in upland and greenhouse farming systems), and changes in crop varieties and coefficients. These and other factors should be included in further assessments of the effects of climate change on agricultural water requirements.

This study includes a number of limitations and uncertainties. For instance, the NIWRs and EFRs could produce inaccurate results because the IWR model used various assumed parameters, such as outlet heights and ponding water depths in the paddy field. DIROM is a model developed for data-scarce watersheds with agricultural reservoirs and is based on parameters using the empirical equations; therefore, its results could also include uncertainties (e.g., error, bias). This study used only the SRES A1B scenario instead of other SRES scenarios; therefore, future studies should include various climate change scenarios and their results should be compared.

Although the applicability of our results is limited, they can act as useful tools for the development of agricultural water resources and estimation of capacity and capability and contribute to the establishment of counter-measures to minimize drought risks and the development of related policies in the future.

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