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A study on the vulnerability of field water supply using public groundwater wells as irrigation in drought-vulnerable areas with a focus on the Dangjin-si, Yesan-gun, Cheongyang-gun, and Goesan-gun regions in South Korea

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Abstract

The severe effects of climate change, such as global warming and the El Niño phenomenon, have become more prevalent. In recent years, natural disasters such as drought, heavy rain, and typhoons have taken place, resulting in noticeable damage. Korea is affected by droughts that cause damage to rice fields and crops. Societal interest in droughts is growing, and measures are urgently needed to address their impacts. As the demand for high-quality agricultural products expands, farmers have become more interested in water management, and the demand for field irrigation is increasing. Therefore, we investigated water demand in the irrigation of drought-vulnerable crops. Specifically, we determined the water requirements for crops including cabbage, red pepper, apple, and bean in four regions by calculating the consumptive water use (evapotranspiration), effective rainfall, and irrigation capacity. The total consumptive water use (crop evapotranspiration) estimates for Dangjin-si (cabbage), Yesan-gun (apple), Cheongyang-gun (pepper) in Chungnam, and Goesan-gun (bean) in Chungbuk were 33.5, 206.4, 86.1, and 204.5 mm, respectively. The volumes of groundwater available in the four regions were determined to be the following: Dangjin-si, 4,968,000 m^3; Yesan-gun, 4,300,000 m^3; Cheongyang-gun, 1,114,000 m^3, and Goesan-gun, 3,794,000 m^3. The annual amounts available for the representative crops, compared to the amount of evapotranspiration, were 313.9% in Dangjin-si, 29.5% in Yesan-gun, 56.1% in Cheongyang-gun, and 20.1% in Goesan-gun.

Keywords: climate change, drought, evapotranspiration, irrigation water

Introduction

The effects and severity of climate change events, such as global warming and the El Niño phenomenon, have become more prevalent. Recently, natural disasters such as droughts, torrential rains, and typhoons have increased, and the damage caused by these disasters has been substantial (Shin et al., 2017). Among these natural disasters, water shortages caused by drought not only result in significant damage across society in agriculture and industrial sectors but also increase societal costs in terms of damage compensation and recovery (Ryu et al., 2019). The Republic of Korea is affected by drought. According to a recent article in the Hankook Ilbo, the average number of precipitation days in Korea during the recent rainy season was 15.8 days, lower than the annual average (17.2 days) (Shin, 2019). Precipitation during this period was 197.6 mm, which is only 54% of the annual average (366.4%) (Shin et al., 2019). As such, groundwater reserves in most parts of the country are declining due to the lack of precipitation. The damage to paddy field crops from drying up due to the decreasing groundwater reserves has led to societal interest in drought, and countermeasures are urgently needed (Lee et al., 2018). Moreover, due to rapid climate change, the intensity and frequency of droughts has increased by 86%, from 0.36 times·year^{-1} (1904 - 2000) to 0.67 times·year^{-1} (2000 - 2015) (Jeon et al., 2017). In particular, substantial drought damage occurred from May to September 2015, when the national precipitation was 548.6 mm, 53.8% lower than the average amount. In the same year, crop damage occurred due to a water shortage in most agricultural lands, except in the southern region. The total drought-damaged area was 75.13 km^2, including 29.77 km^2 of paddy fields and 45.36 km^2 of field crops (Choi et al., 2018). However, current drought countermeasures focus on supportive actions that can be taken after the outbreak of drought. According to the National Water Resources Management Information System (WAMIS; www.wamis.go.kr), in 2016, 3,230 km^2 of field crops were irrigated areas with upland water supply facilities, which is only 43.3% of the country's cultivated area and a smaller area than irrigated paddy land (81.3%) (Shin et al., 2019). Therefore, irrigation improvement projects through the development of agricultural water supply are core parts of the agricultural infrastructure. These projects increase agricultural production and have mainly targeted rice paddies to increase self-sufficiency in rice production. However, due to changes in agricultural product consumption caused by economic and income growth, demand for crops other than rice has recently increased. Also, the importance of field farming has been highlighted in the establishment of the Korea-China free trade agreement (FTA), and the promotion of field-based maintenance, including improvement of field irrigation, has been emphasized (Kim, 2014). The volume of research on the generalization of farmland for growing field crops in paddy fields is also gradually increasing. The increase in the volatility of water resources due to climate change has a significant impact on field crops. An effective water management plan should be established according to the weather and climate characteristics, soil environment, and crop type for each cultivation area (Shin, 2017). Korea has many sloping agricultural lands and lacks the infrastructure for irrigation. Irrigation should be available for crops as needed, but this is not taking place due to insufficient infrastructure and the lack of information on adequate irrigation by crop and growth period (Jung et al., 2011). As the demand for high-quality agricultural products increases, so has interest in water management among farmers, leading to increased demand for irrigation water supply. Accordingly, it is necessary to study the consumptive water use and irrigation requirements for crops vulnerable to droughts such as Chinese cabbage and pepper. Jung et al. (2011) created a water-saving irrigation manual by calculating the potential evapotranspiration and using experimental field data to obtain the crop coefficient for autumn Chinese cabbage. Eom et al. (2012) assessed the amount of water saved when cultivating peppers in the field. Similarly, Shin et al. (2017) evaluated the spatial irrigation requirements and distribution patterns based on the simulation results of soil moisture during the growth period of peppers. Hong et al. (2015) applied soil moisture data from the Weather Research Forecasting (WRF) model to autumn Chinese cabbage to calculate the soil moisture and required field area. Lee and Shin (2016) calculated the appropriate number of irrigation days and the amount of irrigation water required for radish, potato, cabbage, barley, and beans. Nam et al. (2014) estimated the consumptive water use and irrigation requirements for field crops affected by climate change in the future including bean, corn, potato, pepper, spring cabbage, and autumn cabbage. Choi et al. (2019) analyzed irrigation times by calculating the amount of additional irrigation water required (using the Field Crop Water Management Guideline and rainfall data provided by the Meteorological Administration) for major field crops and their main production areas in Korea. In the present study, to develop strategies for managing water shortage due to drought, this study selected four regions characterized by cabbage (Dangjin-si), apple (Yesan-gun), red pepper (Cheongyang-gun), and soybean cultivation (Goesan-gun) and determined their effective rainfall, evapotranspiration, and irrigation efficiency. This study calculated the amount of irrigation applied and assessed groundwater supply using field wells to determine whether groundwater supply was sufficient, and identified the additional irrigation requirements in each region.

Materials and Methods

Selection of experimental areas

We selected Dangjin-si, Yesan-gun, and Cheongyang-gun, Chungnam Province and Goesan, Chungbuk Province as the main production areas of cabbage, apple, red pepper, and beans, respectively, in China (Fig. 1) Dangjin-si is in the northernmost part of Chungnam Province, facing the sea, and has low annual precipitation. The predominant soil series is the Asan series, which is distributed in the low hills and hill lands with the granite gneiss and schist weathering residuum as the parent material. As a clay loam soil, the area has good soil drainage. More detailed information on this area is as follows: the area is 704.43 km^2; the city has a population of 172,816; the average annual temperature is 12.2℃; the average temperature in January is -1.2℃; the average temperature in August is 25.2℃, and the annual precipitation is 830.4 mm. The

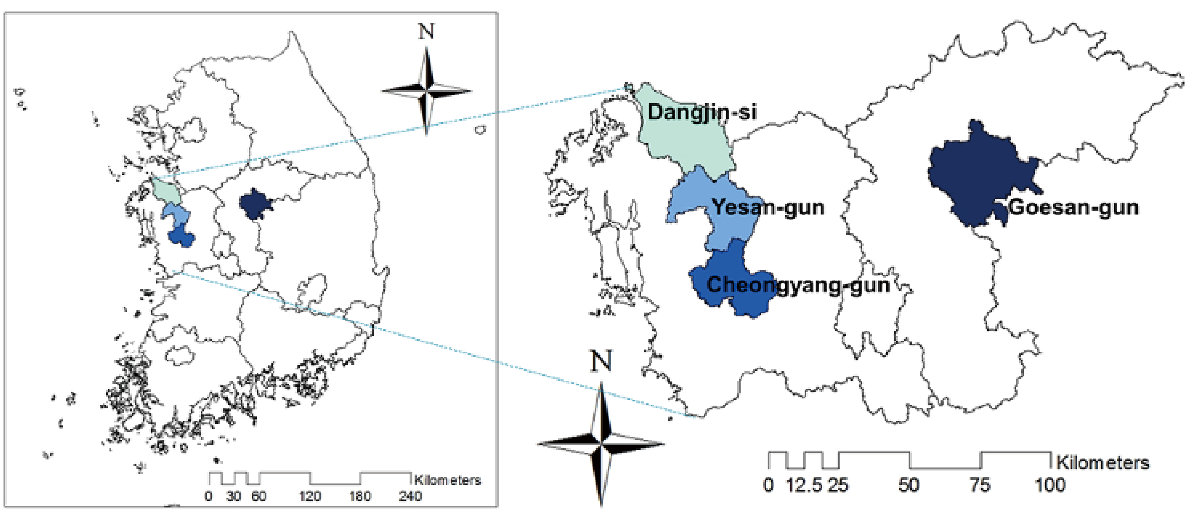

Fig. 1. Study area.

total cultivated acreage is 245.66 km^2, and the cultivated acreage for the upland field is 40.39 km^2 (Dangjin-si, 2018). Yesan-gun is in the northwestern part of Chungnam Province, and due to a temperate monsoon and continental climate, more than half of the precipitation is concentrated in the summer season. Significant fruit tree cultivation, including apples, occurs in the hilly areas of the mountain area. The dominant soil series is the Sachon series, an alluvial soil that is distributed on low hilly land as a weathered alluvial layer of granite and granite gneiss, and has poor drainage. More detailed information for this area is as follows: the area is 542.62 km^2; the city has a population of 82,288; the average annual temperature is 12.6℃; the average temperature in January is -3.6℃; the average temperature in August is 27.9℃, and the annual precipitation is 1199.5 mm. The total cultivated acreage is 176.81 km^2, and the cultivated acreage for upland fields is 60.15 km^2 (Yesan-gun, 2019). Cheongyang-gun is located in the central part of Chungnam Province and is greatly influenced by heavy rain due to the mountain range with an altitude above sea level of more than 500 m and the seasonal rain front. Its predominant soil series is the Asan Series. More detailed information is as follows: the area is 479.12 km^2; the city has a population of 33,426; the average annual temperature is 11.5℃; the average temperature in January is -2.2℃; the average temperature in August is 24.3℃, and the annual precipitation is 917.5 mm. The total cultivated acreage is 83.50 km^2, and the cultivated acreage for upland fields is 19.64 km^2 (Choengyang-gun, 2018). Goesan-gun is in the central part of Chungbuk Province. The southeastern part of Goesan-gun has a low altitude, and the northern part is typical mountainous terrain with high elevation. Goesan-gun has a distinctly continental climate with a temperature difference of close to 30° between the warmest and the coldest months. The dominant soil series is the Samgag series, lithosols distributed in sloping soil as a weathered residuum of granite and granite gneiss, and has the area has excellent drainage. More detailed information is as follows: the area is 842.16 km^2; the city has a population of 39,854; the average annual temperature is 11.1℃; the average temperature in January is -3.2℃; the average temperature in August is 24.3℃, and the annual precipitation is 1236.8 mm. The total cultivated acreage of 112.77 km^2 and the cultivated acreage for upland fields is 78.45 km^2 (Goesan-gun, 2018). Different irrigation methods are used for each crop, such as drip irrigation for apples in Yesan-gun and peppers in Cheongyang-gun, a fountain hose for cabbages in Dangjin-si, and furrow irrigation or sprinklers for beans in Goesan-gun.

Calculation method for irrigation requirements (upland irrigation water)

Field irrigation requirements should be based on accurate estimates of effective rainfall for actual crops, taking into account precipitation and changes in soil moisture due to precipitation. Upland fields have low effective rainfall due to low groundwater levels, and penetration loss occurs rapidly due to the soil characteristics. The active soil layer is limited to the root area, and therefore the range is narrow, with a low effective rainfall rate. The soil characteristics must be accurately determined to estimate the irrigation requirements for an area. The main factors that determine the irrigation requirements for the upland fields are field capacity and the amount of growth inhibitory moisture, which determines the effective soil moisture and soil moisture range. Such moisture (water) consumption factors are determined through a soil survey. Furthermore, intermittent irrigation water requirements must be determined. These values are usually calculated by the total readily available moisture (TRAM) as determined by a soil survey.

Estimation of consumptive water use (crop evapotranspiration)

The consumptive water use of crops involves various factors such as evapotranspiration, infiltration rate, the amount of capillary rise, and the effective rainfall. However, it is not possible to measure all the factors when planning field irrigation, so here only evapotranspiration is calculated for convenience and used in the irrigation plan. The evapotranspiration is calculated by multiplying the potential evapotranspiration by the crop coefficient. Potential evapotranspiration varies depending on weather conditions, so it differs from the actual evapotranspiration based on the type of crop. Accordingly, potential evapotranspiration value must be corrected through the crop coefficient according to Equation (1) (Lee, 2003).

$$\text{Crop evapotranspiration} = \text{Potential evapotranspiration} \times \text{Crop coefficient} \quad (1)$$

Previous studies have mainly used the Blaney-Criddle (B-C) and FAO-Penman methods to estimate the evapotranspiration for field crops. However, in recent years, the Penman-Monteith method using complex weather data has been recommended by the Food and Agricultural Organization of the United Nations (FAO), the International Commission on Irrigation and Drainage (ICID), and the World Meteorological Organization (WMO) (Moon et al., 2017). The Penman-Monteith method is widely used in hydrological and meteorological processes (Park et al., 2017). It is known to provide a consistent value for crop demand on a global level and has excellent applicability by supplementing the shortcomings of the existing Penman method. The Penman-Monteith equation is also applied to the Hydrological Operation Model for Water Resources System (HOMWRS) developed by the Korea Rural Community Corporation. Fig. 2 presents the procedure for

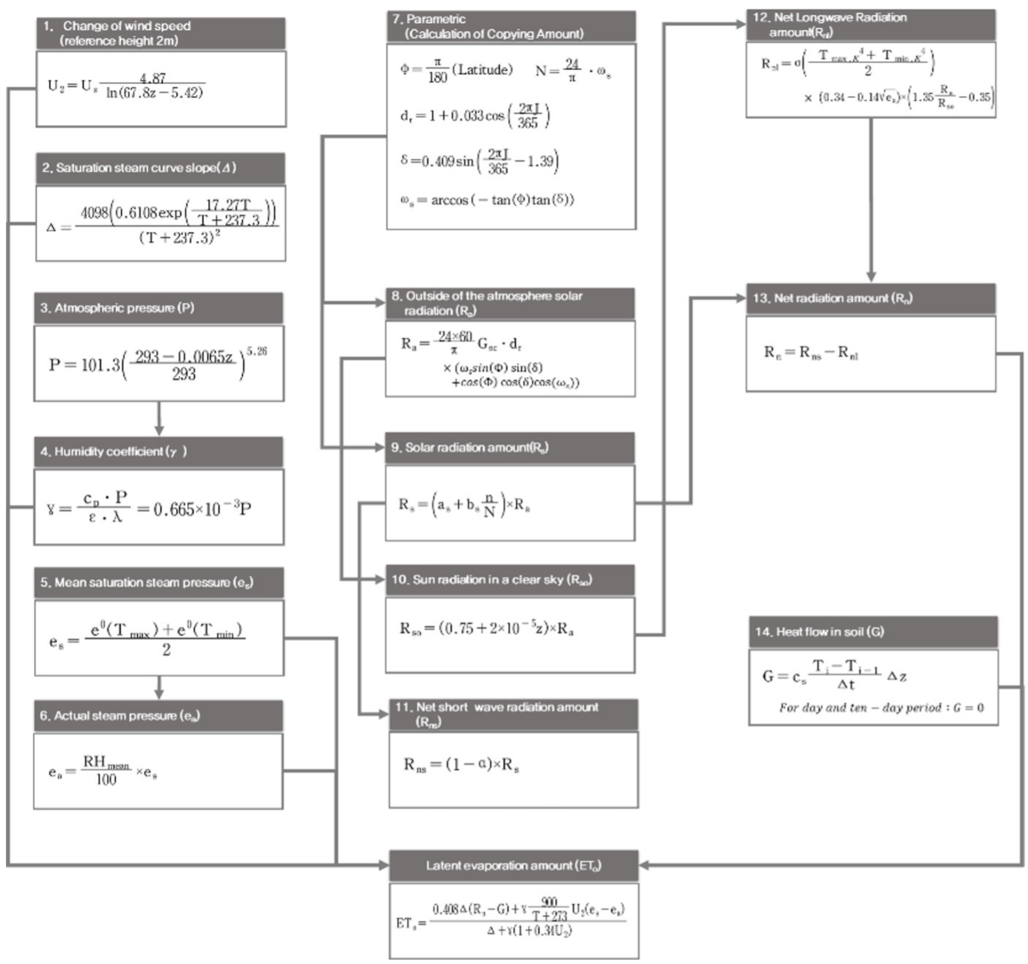

Fig. 2. Estimating the potential evapotranspiration (FAO-56).

calculating the potential evapotranspiration suggested by FAO. Table 1 lists the crop coefficient for each crop to estimate the evapotranspiration required for this study.

Table 1. Crop coefficient by crop (Korea Rural Community Corporation, 2020).

Division		Pepper	Fruit tree	Cabbage	Bean
January					
	The first ten days of the month	-	-	-	-
	The middle ten days of the month	-	-	-	-
	The last ten days of the month	-	-	-	-
February					
	The first ten days of the month	-	-	-	-
	The middle ten days of the month	-	-	-	-
	The last ten days of the month	-	-	-	-
March					
	The first ten days of the month	-	-	-	-
	The middle ten days of the month	-	-	-	-
	The last ten days of the month	-	-	-	-
April					
	The first ten days of the month	-	0.50	-	-
	The middle ten days of the month	-	0.50	-	-
	The last ten days of the month	-	0.50	-	-
May					
	The first ten days of the month	-	0.72	-	-
	The middle ten days of the month	-	0.72	-	-
	The last ten days of the month	0.35	0.85	-	0.35
June					
	The first ten days of the month	0.35	0.95	-	0.35
	The middle ten days of the month	0.35	0.95	-	0.58
	The last ten days of the month	0.55	1.00	-	0.80
July					
	The first ten days of the month	0.80	1.05	-	1.00
	The middle ten days of the month	0.95	1.05	-	1.00
	The last ten days of the month	0.95	1.05	-	1.00
August					
	The first ten days of the month	0.95	1.05	-	1.00
	The middle ten days of the month	0.95	1.05	0.35	1.00
	The last ten days of the month	0.95	1.05	0.35	1.00
September					
	The first ten days of the month	0.95	1.02	0.50	0.80
	The middle ten days of the month	0.87	1.02	0.65	0.60
	The last ten days of the month	0.80	1.02	0.80	0.45
October					
	The first ten days of the month	-	0.80	0.95	-
	The middle ten days of the month	-	0.80	0.95	-
	The last ten days of the month	-	0.80	0.95	-
November					
	The first ten days of the month	-	-	0.95	-
	The middle ten days of the month	-	-	0.95	-
	The last ten days of the month	-	-	-	-
December					
	The first ten days of the month	-	-	-	-
	The middle ten days of the month	-	-	-	-
	The last ten days of the month	-	-	-	-

Estimation of effective rainfall

Effective rainfall is the actual rainfall used for crop growth and is one of the most important factors in determining the required amount of field irrigation. The effective rainfall varies greatly depending on rainfall and field soil characteristics, but rainfall is the most influential variable. However, in the case of greenhouse cultivation, effective rainfall is not considered as precipitation is blocked by the greenhouse structure (Lee, 2004). The method for calculating effective rainfall set out in the Design Criteria for Planning Agricultural Infrastructure Improvement Projects, Irrigation Edition (MAFRA, 1998) does not include rainfall of less than 5 mm in calculations of effective rainfall. If the amount of available moisture is greater than 80% of the daily rainfall compared to the upper limit of effective rainfall, excluding the amount of available moisture just before rainfall from the TRAM of the field soil, with 80% of rainfall (R), the effective rainfall is the amount of available moisture. If it is smaller than 80% of the daily rainfall, the required amount for crops is the amount of moisture consumed in a state where the crop normally grows and is of good quality and yields. The amount of moisture affecting the crop involves various factors, including evapotranspiration, the infiltration rate, the amount of capillary rise, and the amount of effective rainfall. However, not all of the factors can be measured when planning field irrigation, so here only the evapotranspiration is calculated and utilized for convenience. The amount of effective rainfall is calculated using the following equation:

$$(0.8 \times R) \tag{2}$$

where R is the amount of rainfall and at $R < 5$ mm, $R = 0$.

The upper limit of effective rainfall (Ro) is calculated by subtracting the amount of moisture retention (the amount of available moisture) of the field just before rainfall from the TRAM. The effective rainfall applies to 80% of rainfall.

$$Ro = (\text{TRAM- Effective soil water content of the field just before rainfall}) \tag{3}$$

$$Ro \geq 0.80 \times R \Rightarrow \text{Effective rainfall} = 0.80 \times R \tag{4}$$

$$Ro < 0.80 \times R \Rightarrow \text{Effective rainfall} = Ro \tag{5}$$

Soil effective moisture capacity

Effective soil moisture, i.e., the proportion of soil moisture that is available to crops, varies according to soil characteristics. Generally, the upper limit of effective moisture is the maximum amount of water that the soil can maintain when downward water movement decreases after heavy rainfall, which is equivalent to TRAM. The lower limit of effective moisture is determined by taking into account the wilting point and the "Growth-inhibitory moisture point". Inhibitory moisture points, at which plant growth is slightly impeded, should also be considered when establishing a long-term daily irrigation plan. In our rural water demand survey, the wilting point was set as the lower limit of effective moisture, while the TRAM was set as 40 mm (KDI, 2012) for crops such as soybean and cabbage.

Soil moisture consumption

It is important to irrigate a field just before the soil moisture reaches the wilting point to restore the soil moisture in the root area back to the field capacity. At this time, the amount of irrigation water to be supplied can be determined as follows:

$$TAW = (FC - WP) \times Z_r \tag{6}$$

where TAW is total available water (mm) in the root area, FC is field capacity (%), WP is wilting point (%), and Zr is the depth of the crop roots (mm).

In theory, crops can uniformly use the amount of moisture up to the wilting point, but the amount of moisture reduction in the effective soil layer is often not constant. Moisture also decreases as it descends from the surface layer to the lower layer.

Water budget analysis by soil moisture routing

Daily water budget analysis by soil moisture routing in field soil to calculate effective rainfall can be expressed by the following equation:

$$D(t) = D(t-1) + R_e(t) + Req(t) - U(t) \tag{7}$$

where D(t) is field soil moisture in t days (mm), D(t-1) is field soil moisture in t-1 days (mm), Re(t) is effective rainfall in t days (mm), Req(t) is the net amount of irrigation water on t day (mm), and U(t) is the consumption amount in t days (mm).

The effective rainfall is determined from the potential effective rainfall mentioned above and is the value obtained by subtracting the runoff from the rainfall. If the potential effective rainfall is greater than the depth that the root area can contain, the effective rainfall is equal to the amount the root area can contain. When the potential effective rainfall is less than the depth of the root area, the effective rainfall is equal to the potential effective rainfall. The effective rainfall used by crops on the surface can be calculated by soil moisture routing according to the above calculation.

Estimation of irrigation requirement for uplands

The amount of required irrigation is calculated by taking into account the consumptive water use for the crop and the effective rainfall for each period, and the effective rainfall is determined by the water balance in the soil from the rainfall, irrigation, and consumption. The relationship between moisture in the soil, rainfall (potential effective rainfall), and the required amount of irrigation is as follows.

$$\text{If } D_{min} \leq D(t-1) + Re(t) - U(t),\ Req(t) = 0$$
$$\textit{If } D_{min} \square D(t-1) + Re(t) - U(t),\ Req(t) = D_{max} - D(t-1) - Re(t) + U(t) \tag{8}$$

Here, the change in soil moisture in the field, which is the effective rainfall of Re(t) = t days, can be obtained from the relationship between the rainfall, the required amount of rainfall, and the amount of soil moisture on the day. Soil moisture is determined based on the maximum amount of soil moisture (D_{max}) and the growth inhibitory moisture point (D_{min}), and irrigation is carried out when the soil moisture falls below the growth inhibitory moisture point. To determine irrigation requirements and water capacity, the method presented in the set of the planned water capacity in Design Criteria for Planning Agricultural Infrastructure Improvement Projects, Irrigation Edition (MAFRA, 1998) was used; Table 2 presents the calculation formulas. Irrigation efficiency also varies depending on the irrigation method and weather conditions; Table 2 presents more information about application efficiency and irrigation efficiency, which are important factors when calculating irrigation requirements and water capacity.

This study identified the conditions for estimating the consumptive water use (evapotranspiration), effective rainfall, and irrigation requirements in the test areas, Dangjin-si, Yesan-gun, Cheongyang-gun, and Goesan-gun. The meteorological data for effective rainfall from 1973 to 2016 were used. The application efficiency was set at 90%, the irrigation efficiency at 85%, and the crop coefficient is shown in Table 1. The cultivation area for each region was constructed using the statistical yearbook of the selected regions. According to the 2016 statistical yearbook, Dangjin-si has 262.8 ha (2.628 km^2) of cabbage cultivation area; Yesan-gun has 1,195.8 ha (11.958 km^2) of apple cultivation area; Goesan-gun has 1,257.2 ha (12.572 km^2)

of bean cultivation area, and Cheongyang-gun has 104.8 ha (1.048 km^2) of pepper cultivation area. TRAM was assumed to be 40 mm, and the details are presented in Table 4.

Table 2. Irrigation water and water duty formula.

Division	Details
Irrigation water (once)	
Net duty of irrigation water	Maximum planned day irrigation water requirement × irrigation interval
Field capacity	Net duty of irrigation water/application efficiency
Gross duty of irrigation water	Net duty of irrigation water/irrigation efficiency
Duty of water (irrigation area)	
Net duty of water	Day irrigation water requirement × irrigation area
Gross duty of water	Net duty of water/irrigation efficiency

Table 3. Application efficiency and irrigation efficiency by irrigation type.

Division	Application efficiency (%)	Return loss rate (%)	Irrigation efficiency (%)
Sprinkler irrigation	80 - 90	5 - 10	80 - 85
Trickle irrigation	90	5 - 10	80 - 85
Surface irrigation	70	5 - 10	60 - 65

Table 4. Conditions for calculation of irrigation water.

Division	Dangjin-si	Yesan-gun	Cheongyang-gun	Goesan-gun
Meteorological data	1973 - 2016	1973 - 2016	1973 - 2016	1973 - 2016
Application efficiency	90%	90%	90%	90%
Irrigation efficiency	85%	85%	85%	85%
Crop coefficient	Table 2			
Cultivated area	2.628 km^2	11.958 km^2	1.048 km^2	12.572 km^2
TRAM (Supposition)	40 mm	40 mm	40 mm	40 mm
Irrigation interval	Total readily available moisture (TRAM)/maximum daily amount of water used			
Historical base year	2016	2016	2016	2016

Available groundwater for irrigation in the upland field

The capacity of groundwater wells for irrigation is flexible when evaluating vulnerability to field drought. This capacity is critical to determine whether or not to supply agricultural water in a field drought situation. This study used the groundwater data from 2016 provided by the National Groundwater Information Center (GIMS; www.gims.go.kr). Table 5 lists the groundwater volume for the selected regions for the upland field, the field area and the cultivation area by crop, and the amount of available groundwater per unit area. The cultivation area of cabbage in Dangjin-si was 6.5% of the total field area, the cultivation area of apples in Yesan-gun was 19.9%, the cultivation area of peppers in Cheongyang-gun was 5.3%, and the cultivation area of beans in Goesan-gun was 16.0%. The number of groundwater wells for agricultural purposes from highest to lowest was Dangjin-si, Goesan-gun, Yesan-gun, and Cheongyang-gun. The amount of underground water for the upland field from highest to lowest was Dangjin-si, Yesan-gun, Goesan-gun, and Cheongyang-gun. The field area from largest to smallest was Goesan-gun, Yesan-gun, Dangjin-si, and Cheongyang-gun. The amount of available water collected per unit area was ranked from Dangjin-si, Yesan-gun, Cheongyang-gun, and Goesan-gun. In Goesan-gun, the amount of available underground water is low compared to the field area. Dangjin-si has a large amount of groundwater and available underground water compared to the field area, and the amount of available water collected per unit area was calculated to be 123,020 $m^3 \cdot km^{-2} \cdot year^{-1}$.

Table 5. Wells and available groundwater volume.

Area	Number of wells	Available groundwater volume ($m^3 \cdot year^{-1}$)	Field area (km^2)	Crop	Crop cultivation area (km^2)	Amount of attainable water per unit area ($m^3 \cdot km^{-2} \cdot year^{-1}$)
Dangjin-si	2,622	4,968,766	40.39	Cabbage	2.628	123,020
Yesan-gun	1,468	4,300,473	60.15	Apple	11.958	71,500
Cheongyang-gun	562	1,114,070	19.64	Pepper	1.048	56,720
Goesan-gun	2,315	3,794,109	78.46	Bean	12.572	48,360

Results and Discussion

Calculation results of consumptive water use (crop evapotranspiration)

The consumptive water use (crop evapotranspiration) in this study was calculated using HOMWRS, a simulation system for repair facilities provided by the Korea Rural Community Corporation. Peak evapotranspiration took place in August in Dangjin-si (cabbage) in Chungnam Province, and the total consumptive water use (crop evapotranspiration) was calculated to be 33.5 mm. In the case of Yesan-gun (apple), evapotranspiration mainly took place from June to September, and rapidly increased in June and August. In Cheongyang-gun (pepper), evapotranspiration took place from July to August, with the peak levels in August. In the Chungbuk Province, Goesan-gun (bean), the evapotranspiration was distributed from May to September, but it was highest in mid-July with 112.8 mm (Table 6).

Result of calculations for effective rainfall

The effective rainfall was measured using the rainfall provided by the meteorological observatory in each region: Seosan observatory for Yesan-gun and Dangjin-si, Cheonan observatory for Cheongyang-gun, and Cheongju observatory for Goesan-gun. The TRAM for calculating the effective rainfall was assumed to be 40 mm, and the effective moisture just before rainfall was assumed to be 0 mm. The effective rainfall in Dangjin-si was 23.1 mm, and when considering the evapotranspiration of 33.5 mm, the supply of water from rainfall was insufficient. The effective rainfall in Yesan-gun in June and August was 23.5 mm and 23.1 mm, respectively. However, in June and August, evapotranspiration was 97.7 mm and 93.9 mm, and the water shortage was calculated to be 74.18 mm and 70.78 mm. In July and September, the effective rainfall was 156.5 mm and 39.6 mm, but the evapotranspiration was 12.0 mm and 2.8 mm, with water reserves of 144.48 mm and 36.80 mm. From these results, it was determined that a sufficient water supply was available for the growth of crops in Yesan-gun. The evapotranspiration in Cheongyang-gun in August was 79.9 mm, but the effective rainfall was only 33.5 mm, and the water supply was therefore insufficient by 46.38 mm. The evapotranspiration in June and August in Goesan-gun, Chungbuk Province, was 31.0 mm and 112.8 mm, respectively. However, the effective rainfall was 25.7 mm and 46.2 mm in June and August, indicating that rainfall could not provide a steady water supply. However, in July and September, sufficient water was supplied with 47.5 mm and 13.2 mm of evapotranspiration and 164.4 mm and 57.4 mm of effective rainfall, respectively (Table 6).

Table 6. Result of crop evapotranspiration, effective rainfall, and irrigation water.

Region (Crop)	Classification	Month												Total
		1	2	3	4	5	6	7	8	9	10	11	12	
Dangjin (Cabbage)	CE	-	-	-	-	-	-	-	33.5	-	-	-	-	33.5
	P	21.9	61.7	24.3	87.0	153.7	36.8	295.6	34.0	53.1	73.8	17.5	62.7	922.1
	ER	13.2	43.2	15.8	61.7	121.4	23.5	156.5	23.1	39.6	54.1	4.3	42.2	598.6
	NDW	-	-	-	-	-	-	-	88.3	-	-	-	-	88.3
	GDW	-	-	-	-	-	-	-	103.9	-	-	-	-	103.9
Yesan (Fruit tree)	CE	-	-	-	-	-	97.7	12.0	93.9	2.8	-	-	-	206.4
	P	21.9	61.7	24.3	87.0	153.7	36.8	295.6	34.0	53.1	73.8	17.5	62.7	922.1
	ER	13.2	43.2	15.8	61.7	121.4	23.5	156.5	23.1	39.6	54.1	4.3	42.2	598.6
	NDW	-	-	-	-	-	1,165.9	143.5	1,122.9	33.5	-	-	-	2,465.8
	GDW	-	-	-	-	-	1,371.7	168.8	1,321.0	39.4	-	-	-	2,900.9
Cheongyang (Pepper)	CE	-	-	-	-	-	6.2	-	79.9	-	-	-	-	86.1
	P	8.0	43.6	16.5	100.3	107.2	36.2	346.3	55.0	55.0	95.9	33.5	44.3	941.8
	ER	-	33.2	9.2	69.9	85.1	28.0	202.5	33.5	39.8	68.0	24.0	25.8	619.0
	NDW	-	-	-	-	-	6.4	-	83.7	-	-	-	-	90.1
	GDW	-	-	-	-	-	7.5	-	98.5	-	-	-	-	106.0
Goesan (Bean)	CE	-	-	-	-	-	31.0	47.5	112.8	13.2	-	-	-	204.5
	P	5.7	45.5	13.2	132.1	84.4	39.9	320.0	69.0	78.1	83.6	26.4	40.1	938.0
	ER	-	31.4	5.1	100.6	65.2	25.7	164.4	46.2	57.4	58.7	16.7	28.6	600.0
	NDW	-	-	-	-	-	391.0	595.9	1,419.4	164.7	-	-	-	2,571.0
	GDW	-	-	-	-	-	460.0	701.1	1,669.9	193.8	-	-	-	3,024.8

CE, crop evapotranspiration (mm); P, precipitation (mm); ER, effective rainfall (mm); NDW, net duty of water (1,000 m^3); GDW, gross duty of water (1,000 m^3).

Result of irrigation requirement calculations

The Design Criteria for Planning Agricultural Infrastructure Improvement Projects Irrigation Edition (MAFRA, 1998) specify that the amount of irrigation required is determined from the net amount of irrigation water by calculating the TRAM. Therefore, the net amount of irrigation water was calculated as 40 mm TRAM, as shown in Table 7. Table 7 also presents the field irrigation capacity based on the net duty of water divided by the application efficiency. The gross duty of water is based on the net amount of irrigation water divided by the irrigation efficiency.

The net duty of water required for the entire region is calculated by multiplying the daily consumptive water use by the irrigation area, and the gross duty of water is calculated by dividing the net duty of water by the irrigation efficiency. The formulas for calculating the net duty of water and gross duty of water are as follows.

$$\text{Design water amount} \times \text{irrigation area} \quad (9)$$

$$\text{Net duty of water amount/irrigation efficiency} \quad (10)$$

Table 7. Calculation of irrigation water.

Division	Formula	Calculation result
Irrigation water amount		
Net irrigation water amount	TRAM	40 mm
Field irrigation water amount	Net irrigation water amount/application efficiency	40 mm/90% = 44.4 mm
Gross duty of irrigation water amount	Net irrigation water amount/irrigation efficiency	40 mm/85% = 47.1 mm

TRAM, total readily available moisture.

Table 6 lists the net duty of water and gross duty of water for Dangjin-si, Yesan-gun, Cheongyang-gun and Goesan-gun, and the calculation results for each region. The cropping period of cabbage in Dangjin-si is from mid-August to mid-November. From September to November, the effective rainfall generated during cultivation is greater than the irrigation water demand. However, because there was no rainfall in August when the irrigation is needed, the maximum net duty of water was calculated at 6000 m^3, and the total net duty of water was calculated at 88,300 m^3. The maximum gross duty of water, considering an irrigation efficiency of 85%, was calculated to be 7,100 m^3, and the total gross duty of water was calculated to be 103,900 m^3. The cropping period for apple in Yesan-gun is from early April to mid-November. From April to June and from October to November, there was more rainfall than the irrigation water demand, so irrigation water was not needed. In July and September, there is rainfall during the cultivation period compared to the irrigation water demand, so the demand for irrigation water is small. In June and August, when irrigation was necessary, there was little rainfall, so the maximum net duty of water per month was estimated to be 65,800 m^3 in June, 76,500 m^3 in July, 75,300 m^3 in August, and 33,500 m^3 in September. The total net duty of water per month was estimated to be 1,165,900 m^3 in June, 143,500 m^3 in July, 1,122,900 m^3 in August, and 33,500 m^3 in September. The gross duty of water, considering an irrigation efficiency of 85%, was calculated to be 77,400 m^3 in June, 90,000 m^3 in July, 88,600 m^3 in August, and 39,400 m^3 in September, and the total gross duty of water was 1,371,700 m^3 in June. It was estimated to be 168,800 m^3 in July, 1,321,000 m^3 in August, and 39,400 m^3 in September. The cropping period for peppers in Cheongyang-gun is from the end of May to the end of September. High rainfall levels occurred in May, July, and September, and therefore irrigation was not required. Based on the irrigation water demand in June and August, the maximum net duty of water was calculated as 3,100 m^3 in June and 6,000 m^3 in August, and the total net duty of water was 6,400 m^3 in June and 83,700 m^3 in August. The maximum gross duty of water, based on an irrigation efficiency of 85%, was calculated as 3,700 m^3 in June and 7,000 m^3 in August, and the total maximum gross duty of water was 7500 m^3 in June and 98,500 m^3 in August. The cropping period for beans in Goesan-gun is from early May to the end of September. Due to high rainfall levels in May, irrigation was not required. The demand for irrigation from June to September, as the maximum net duty of water, was calculated as 62,900 m^3 (June), 89,300 m^3 (July), 88,000 m^3 (August), and 36,500 m^3 (September). The total net duty of water was estimated to be 391,000 m^3 in June, 595,900 m^3 in July, 1,419,400 m^3 in August, and 164,700 m^3 in September. The maximum gross duty of water, based on an irrigation efficiency of 85% was determined to be 74,000 m^3 in June, 105,000 m^3 in July, 103,500 m^3 in August, and 42,900 m^3 in September. The total gross duty of water was calculated to be 460,000 m^3 in June, 701,100 m^3 in July, 1,669,900 m^3 in August, and 193,800 m^3 in September.

Comparative analysis of irrigation water requirement and groundwater well supply capacity

The amount of attainable water supply was estimated by calculating the available water from groundwater wells per unit cultivated area as a portion of the total field area. This value represented the amount of groundwater used in each region in 2016. In the case of cabbage in Dangjin-si, the available amount for the crop cultivation area was 323,296 $m^3 \cdot year^{-1}$, and the water supply capacity was sufficient as it represented 313.9% of the required amount. The available amount per cultivation area of apple in Yesan-gun was 854,947 $m^3 \cdot year^{-1}$, 29.5% of the required amount. The available amount per cultivation area of pepper in Cheongyang-gun was 59,447 $m^3 \cdot year^{-1}$, 56.1% of the required amount. The available amount per cultivation area of beans in Goesan-gun was 608,025 $m^3 \cdot year^{-1}$, 20.1% of the required quantity. In the case of Yesan-gun (apple) and Goesan-gun (bean), it appears that the agricultural production facilities for securing water should be expanded (Table 8).

Table 8. Supply volume of groundwater wells per cultivation area.

Area	Groundwater usage (m^3/ year)	Crop	Crop cultivation area (km^2)	Amount of attainable water per unit area ($m^3 \cdot ha^{-1} \cdot year^{-1}$)	Volume of water available for crop cultivation ($m^3 \cdot year^{-1}$)	Possible water supply (%)	Required water volume ($m^3 \cdot year^{-1}$)
Dangjin-si	4,968,766	Cabbage	2.628	123,020	323,296	313.9	103,000
Yesan-gun	4,300,473	Apple	11.958	71,500	854,947	29.5	2,900,900
Cheongyang-gun	1,114,070	Pepper	1.048	56,720	59,447	56.1	106,000
Goesan-gun	3,794,109	Bean	12.572	48,360	608,025	20.1	3,024,800

Conclusions

The results obtained from this evaluation of the consumptive water use (evapotranspiration), effective rainfall, and irrigation requirements in the selected regions (Dangjin-si [cabbage], Yesan-gun [apple], Cheongyang-gun [pepper] and Goesan-gun [beans]) can be summarized as follows.

1. HOMWRS, a simulation system for hydraulic facilities provided by the Korea Rural Community Corporation, was used to calculate the consumptive water use (crop evapotranspiration). The total consumptive water use (crop evapotranspiration) of Dangjin-si (cabbage) in Chungnam Province was estimated to be 33.5 mm, and the total consumptive water use (crop evapotranspiration) in Yesan-gun (apple) was calculated to be 206.4 mm. The total consumptive water use in Cheongyang-gun (pepper) was estimated to be 86.1 mm, while Goesan-gun (bean) in Chungbuk Province was 204.5 mm.

2. The irrigation requirements and the amount of underground water available for field wells was determined to be 313.9 % of the required amount in Dangjin-si (cabbage), indicating a secure water supply. However, in Cheongyang-gun (pepper) it was 29.5% of the required amount, in Yesan-gun (apple) it was 56.1% of the required amount, and in Goesan-gun (bean) it was 20.1% of the required amount. Accordingly, if rainfall is continuously insufficient in these areas, water security should be enhanced by expanding water storage facilities such as storage tanks.

3. The findings of the present study can be used to identify water supply shortages based on data from wells and calculations of the irrigation availability and requirements of each region. In this manner, the amount of additional irrigation water needed can be determined. This study findings may facilitate the expansion of field irrigation facilities, and could also inform plans for additional irrigation to prevent damage to field crops due to droughts.

Conflict of Interests

No potential conflict of interest relevant to this article was reported.

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