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A Study on Constructive Methods of Smart Irrigation System using Drought Resilience Analysis

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Abstract

Increases in drought and flood frequency are global challenges caused by global climate change. Drought severely affects agricultural production. For efficient drought management in drought-prone regions, accurate evaluation of drought-related factors is crucial. We analyzed the drought resilience of napa cabbage cultivation by assessing the capacity per unit cultivation area against the effects of drought on crop production in Chungbuk and Chungnam, two midwestern South Korean provinces. Drought diagnosis and intensity assessment were performed by using the Standardized Precipitation Evapotranspiration Index (SPEI). Our analysis revealed that Chungnam had 10% higher napa cabbage production per unit cultivation area (kg/10a) compared with Chungbuk under the same drought conditions. Based on this result, we propose measures of implementing an information and communication technologies (ICT)-based smart irrigation system in Chungbuk, which is more vulnerable to drought.

Keywords: *Smart Irrigation System, ICT, Drought Resilience, napa cabbage*

1. Introduction

Amid increasing irrigation demands in agricultural areas driven by diversified agricultural techniques and increasing industrialization of rural areas, farm households are facing challenges of increased drought and flood frequency due to climate change. Among natural catastrophes, drought can cause especially severe damages to a greater extent than that estimated because of its uncertain duration and extent, unlike more predictable floods or storms. Agricultural drought is manifested in close association with agricultural production. Therefore, if insights can be gained into the related factors, countermeasures can be systematically and efficiently applied to drought-prone regions.

Shim (2009) reported that agricultural production has always been affected by drought and that an insufficient water supply for irrigation leads to decreases in agricultural production and also created challenges in irrigation water distribution. To address such problems, it is necessary to perform an in-depth analysis of the mechanism of drought and to establish countermeasures to ensure efficient irrigation water management and supply stability.

Natural catastrophe analyses have been conducted extensively by many researchers using the concept of resilience as a key analysis element. Resilience, when analyzing natural catastrophes such as earthquakes and floods, is broadly defined as the rapidity of post-disaster recovery of a system. Despite different focal points in various academic disciplines, two fundamental attributes belong to the definition of resilience: recovery and continuity. Recovery is the capacity of returning to the pre-event state, and continuity is the capacity to withstand the impact and maintain stability.

Because damages to agricultural areas through droughts and floods triggered by climate change are continuously increasing, numerous of studies have been conducted to

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develop methods for efficient irrigation management based on information and communication technologies (ICT).

Additionally, advances made in the information technology (IT) domain have brought about various forms of convergence technologies combining IT and other technologies to enhance the efficacy of a system and to diversify information services by adopting IT technologies. Smart social overhead capital is emerging as a promising solution to resource recycling and green business. Smart social overhead capital provides managers and users with useful information processed through real-time analysis and estimation by digitizing and integrating the raw monitoring data acquired from the infrastructure. The concept of smart water management has also been introduced in the field of water resources.

This study was conducted to analyze the drought resilience of the agricultural areas in Chungbuk and Chungnam provinces by applying the concept of resilience to drought-related conditions. As a result, it was determined that the drought resilience in Chungnam was higher than that in Chungbuk. On the basis of this analysis result, we selected regions in Chungbuk for application of the ICT-based smart irrigation system. This smart irrigation system is a sensor-based system that manages the water demand for crop cultivation. For example, if a water storage tank is installed for a unit farmstead, this system maintains the water level of the tank by monitoring rainwater accumulation and river water inlet to optimally supply irrigation water to the cropland operated by a farmstead within its irrigation network. This study presents the design and implementation of the ICT-based smart irrigation system.

2. Drought Resilience Analysis

2.1. Concept of Resilience

Holling (1973) defined resilience as the capacity of a system to persist and maintain the current state by absorbing the changes triggered by external forces. This term has been introduced and utilized in many different fields adopting similar definitions, including the domain of disaster risk management for national security.

In engineering, resilience is defined as the ability of a structure such as building or bridge to return to its original state after being shaken. In disaster analysis, it refers to the rapidity of a system to recover from the impacts of events such as earthquakes and floods. In psychology, it is defined as the ability of an individual to efficiently respond to trauma. When the concept of resilience is applied to social entities such as an organization or a society, it refers to the capacity to maintain stability or persist in the face of resource shortages or physical threats. Because resilience puts emphasis on the ability of an entity to respond to dangerous situations and provides insights into the causes of the vulnerability of an entity, it has also been termed as the “opposite side of vulnerability.” Resilience is also defined by using its two factors: recovery and continuity. Recovery is the capacity for returning to the pre-event state after sustaining impact-induced changes, and continuity is the capacity for withstanding the impact and maintaining stability.

In defining drought resilience in this study, we adopted the basic concept of resilience, which is the ability to withstand changes triggered by external forces, In this sense, external force is defined as the level of drought to which a region is exposed, and the ability to withstand changes is determined by the agricultural production in kilograms per unit area (10 a).

2.2 Test Regions and Experimental Crop

Chungbuk and Chungnam provinces are regions of low-precipitation located in the midwestern part of South Korea. Droughts triggered by climate change have exacerbated the dry conditions. For example, although a dramatic increase in rainfall occurred in 2008, it was still only 6%, or 22mm, more than the entire 2007 precipitation level of 364mm. In Chungnam, Daejeon, coastal areas sustained more severe drought damage than that reported inland.

Napa cabbage is a short-season crop; autumn napa cabbage is usually sown in August and is harvested in November. Because it consists primarily of water and grows rapidly, sufficient water supply during the growing period is crucial for its cultivation. Irrigation of napa cabbage fields is particularly important during its peak growing time and at planting time; six-fold yield increases have been reported in crops with irrigation during planting over those without irrigation. As such, drought in this period can cause enormous damage to napa cabbage production. We analyzed the drought resilience of Chungbuk and Chungnam by measuring the napa cabbage production per unit area of cultivation in the administrative divisions of towns and counties, known respectively as *si* and *gun*, under the same drought conditions.

The napa cabbage cultivation areas in Chungbuk and Chungnam are similar, at 2,565 ha and 2,895 ha, respectively. Figure. 1 depicts the evolution of the napa cabbage cultivation areas in both provinces between 2007 and 2012.

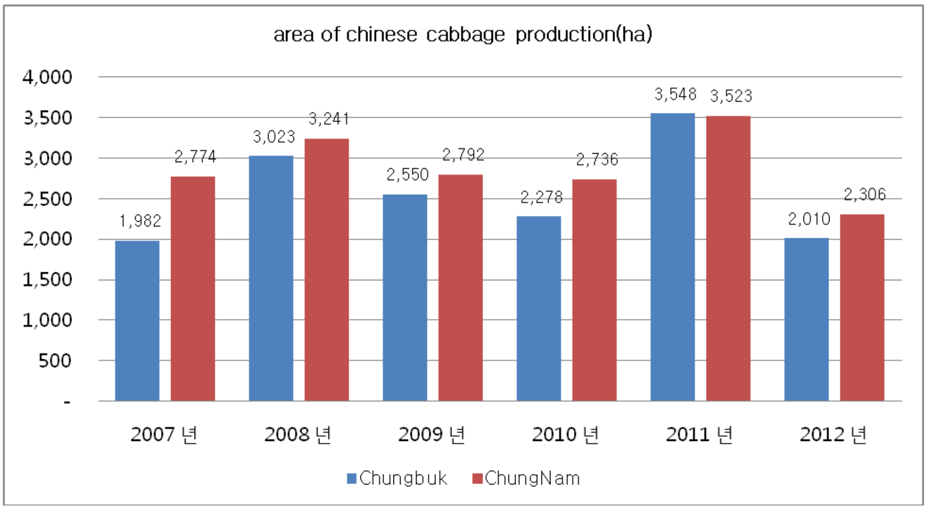

Figure 1. Napa Cabbage Cultivation Area in Chungbuk and Chungnam (unit: ha)

2.3 Results of the Drought Resilience Analysis

The napa cabbage production per unit area was calculated by extracting six years of data between 2007 and 2012 by using the statistical yearbooks of Chungbuk and Chungnam si/gun divisions. Chungnam reported a larger amount of production between 2007 and 2009, showing steady increases. However, abrupt decrease was reported in 2010, followed by recovery and an increasing tendency afterward.

Chungbuk showed generally lower production per unit area, with an increasing tendency to a lesser extent between 2007 and 2009 followed by a decrease in 2010 and recovery in 2011. However, an additional decrease was reported in 2012. Therefore, although napa cabbage production in both provinces showed similar patterns of increase and decrease during the six-year study period, considerable differences were reported in 2009 and 2012.

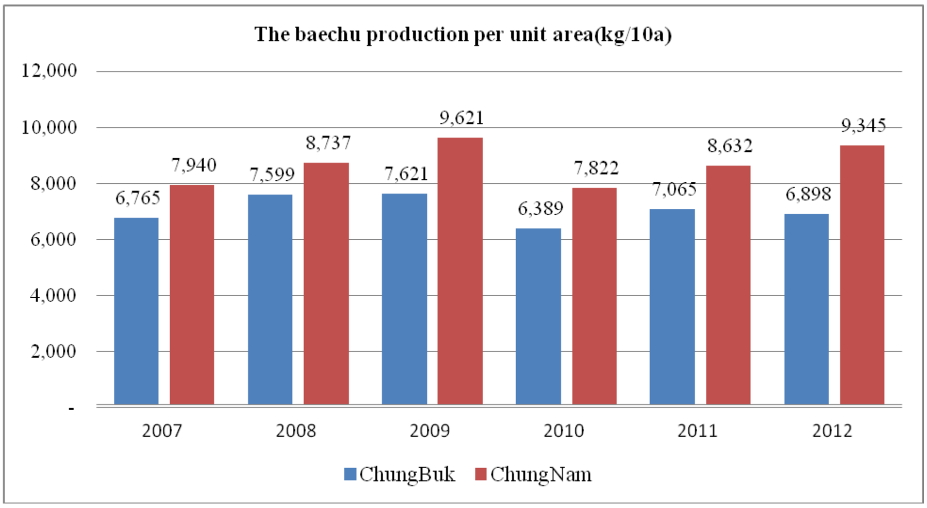

Figure 2. Napa Cabbage Production in Chungbuk and Chungnam (Data: statistical yearbooks)

Drought was assessed by using the Standardized Precipitation Evapotranspiration Index (SPEI), which was calculated according to data meteorological data of si/gun divisions. These data were collected from 40 weather stations from each province, including Cheongju, Chupung-nyeong, Chungju, Jecheon, and Boeun in Chungbuk and Daejeon, Seosan, Cheonan, Boryeong, Buyeo, and geumsan in Chungnam. The monthly SPEI for each region was calculated by using the meteorological data between August and November, which is the cultivation period of napa cabbage. A region was determined to have been affected by drought if it showed SPEI values lower than −1.5 on two or more occasions during the cultivation period. Table 1 shows the 21 drought-affected regions in both provinces in descending order of production.

The average napa cabbage production was calculated for each of these 21 regions under the same drought conditions. Cheongyang, Yesan, Seosan, Asan, and Gongju in Chungnam had the highest yields. The overall average production of the 12 drought-affected regions in Chungnam, 5,843 kg/10a, was 10% higher than that of the 9 drought-affected regions in Chungbuk, at 5,455 kg/10a.

On the basis of these results, we established a method for implementing the smart irrigation system in Chungbuk to provide the affected regions in this province with efficient drought control and agricultural irrigation water supply management.

Table 1. Napa Cabbage Production in the Drought-affected regions by *si/gun* division

Rank	Province	Si/Gun	Average napa cabbage production (kg/10a)
1	Chungnam	Cheongyang	9,899
2	Chungnam	Yesan	7,846
3	Chungnam	Seosan	7,638
4	Chungnam	Asan	7,480
5	Chungnam	Gongju	6,819
6	Chungbuk	Cheongju	6,767
7	Chungnam	Nonsan	6,651
8	Chungnam	Hongseong	6,200
9	Chungbuk	Jincheon	6,153
10	Chungbuk	Boeun	6,146
11	Chungbuk	Okcheon	5,621

12	Chungbuk	Chungju	5,400
13	Chungbuk	Gwaesan	5,315
14	Chungbuk	Cheongwon	4,837
15	Chungbuk	Danyang	4,741
16	Chungnam	Eumseong	4,543
17	Chungnam	Boryeong	4,433
18	Chungbuk	Yeongdong	4,118
19	Chungnam	Geunsan	4,056
20	Chungnam	Seocheon	3,563
21	Chungnam	Dangjin	989

3. Smart Irrigation System

3.1. Definition and Function of the Smart Irrigation System

Smart irrigation is a system for supplying and managing agricultural water in a manner that ensures maintenance of the optimal soil moisture content through sensor-based evaluation of the water demand for crop cultivation.

In this system, a water storage tank is installed in each farmstead, which is the smallest unit of agricultural operation, to secure and store agricultural water captured from precipitation or that introduced from rivers, thus implementing an intelligent water management system tailored to each farmstead. We defined a farmstead unit to include all agricultural facilities operated and managed by a farmstead such as houses, storehouses, crop cultivation facilities, and cropland.

3.2. Testbed for Application of the Smart Irrigation System

For application of the smart irrigation system, we selected an optimal testbed in which groundwater is the single water source and crop production often suffers from drought and flood damages due to the flooding of a stream nearby. By selected this drought- and flood-prone location as the testbed, we attempted to test the efficacy of the smart irrigation system in minimizing drought and flood damages in the particular farmstead and ensuring an efficient water management.

Figure. 4 shows the testbed selected and the setup for the application of this smart irrigation system.

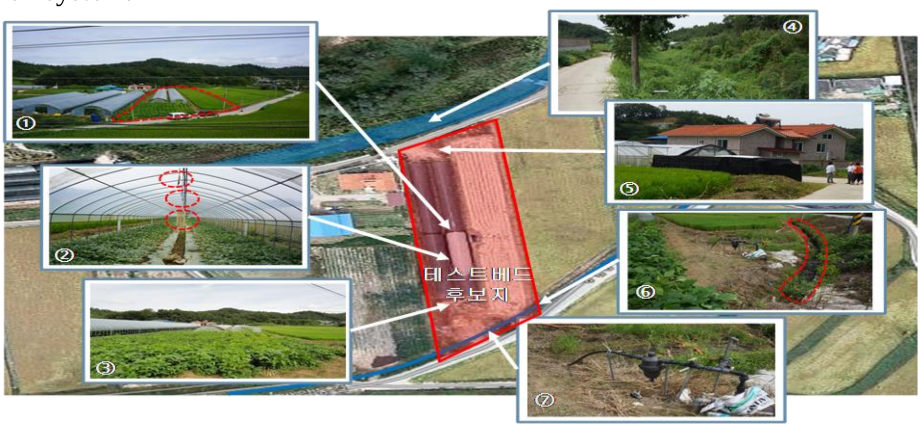

Figure 4. Testbed Selection and Setup

① Photograph of the testbed. ② Greenhouse interior. ③ Testbed cultivation field. ④ River adjacent to the testbed. ⑤ Water storage tank location.⑥ Existing drainage canal. ⑦ Existing groundwater pump.

3.3. System Network Sensors for Individual Irrigation-Related Factors

In the smart irrigation system, sensors are installed for measuring the individual irrigation factors to determine the optimal irrigation time and to estimate the optimal moisture content necessary for crop growth. In this way, optimal water rationing can be performed throughout the cultivation period by preventing over- or under-irrigation at any given time. The sensors play a determinant role in ensuring the efficient irrigation water management of each farmstead unit and in enhancing crop production by reflecting the topographical characteristics of the particular region.

The sensors reflect the irrigation-related factors among all environmental conditions involved in crop cultivation, including those of water management. Temperature enables the control of irrigation in a greenhouse. The temperature of the interior facilities is controlled by a directly spray of water. The humidity in the greenhouse air is also adjusted by spraying water inside the greenhouse. Higher humidity relates to more intensive transpiration in plants, which has a positive effect on photosynthesis. Soil moisture content is the most important environmental factor in crop growth, and each crop has a unique soil moisture demand. By maintaining the optimal soil moisture content for each crop, it is possible to prevent agricultural water from being wasted due to over-irrigation, thus enhancing crop production.

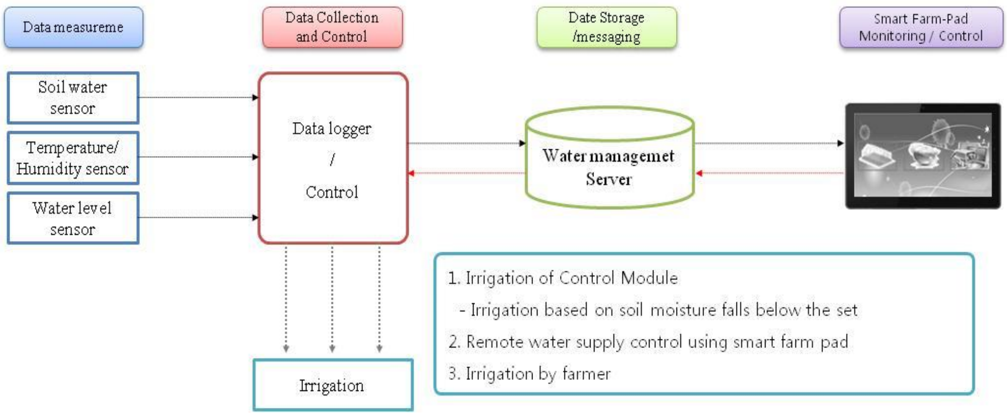

Figure 5. Flowchart of the Smart Irrigation System

Sensors for irrigation management factors gather data in 1 s increments and store them in the data logger. Data stored in the data logger are transferred to an online water management server for analysis.

We used the Stevens Hydra Probe soil moisture sensor (Stevens Water Monitoring Systems, Portland, Oregon, USA), which is easily installed and provides user-customized communication protocol enabling linkage to other devices.

On the basis of the measurement data retrieved from the water management server, meteorological data and crop information were derived by using *Smart Farm-PAD*. This application allows the user to make adequate irrigation-related decisions by monitoring the factors necessary for crop cultivation.

3.4. Design of the Smart Irrigation System

The data from the sensors are monitored by the unit hour as configured according to the needs of the user. Through data monitoring, the irrigation demands of the particular field can be analyzed, and the supply and storage amounts can be checked for maximum efficiency by supplying the optimal level of agricultural water.

The smart irrigation system uses groundwater and rainwater from the storage tank as water sources. Figure. 6 depicts the operational schematic for this system, which includes normal and emergency conditions. Under normal conditions, the soil moisture sensor measures the soil moisture content, and the optimal soil moisture content for each crop type is configured. Groundwater is supplied after checking the measured level against the configured level. The gauge mounted on the groundwater pipe automatically activates the groundwater pump. If the water flow rate is insufficient to be measured, the system switches to emergency conditions, and water is supplied from the rainwater storage tank. If the gauges for both groundwater and rainwater storage tank do not deliver measurement data, an alarm is transmitted to the user according to the operation procedure.

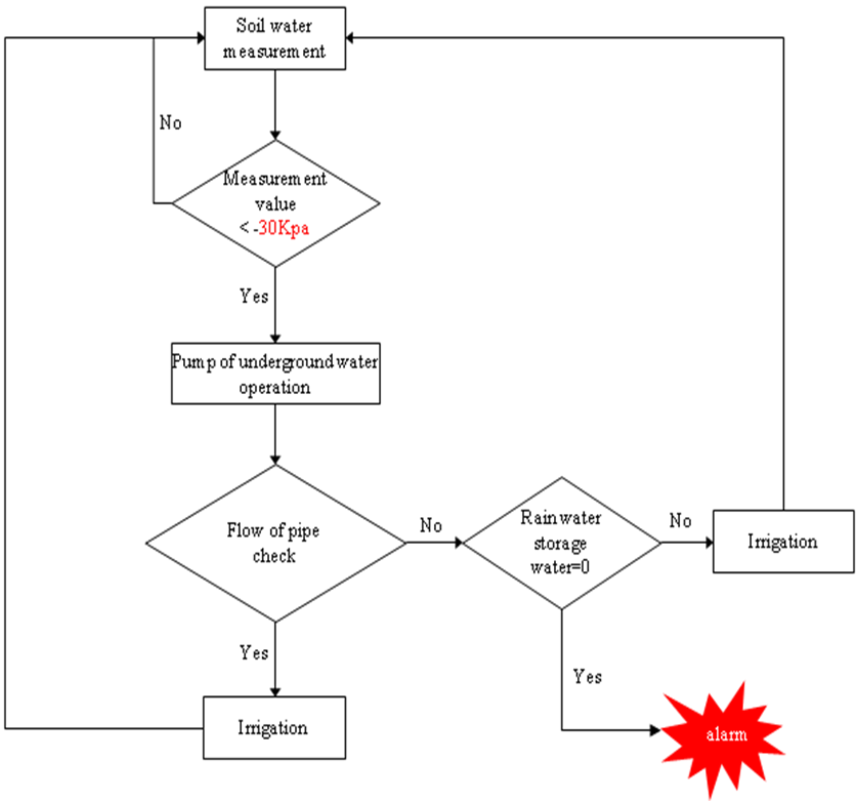

Figure 6. System Water Supply Operational Schematic

Figure. 7 shows the block plan for the installment of the smart irrigation system for the testbed. The block plan divides the greenhouse in three compartments. Compartment I is irrigated by the farm operator, Compartment II is irrigated according to the configured period and irrigation level, and Compartment III is irrigated by the smart irrigation system for maintaining optimal environments for crop cultivation according to the data delivered by the sensors. The operation of this system operation can be monitored by using electronic devices such as a smart phone or a personal computer. The system was designed to enable automatic on/off control by remote or data-based control to ensure that the real-time optimal soil moisture content of the crop is maintained according to the data measured by the soil moisture content sensor. Under normal conditions, both groundwater and tank water are used to reduce the utilization of groundwater, which is the single water source for the conventional irrigation channel. In emergency conditions due to drought, tank water is used to minimize the damage to the crops.

Alternatively, flood damage can be minimized by lowering the water level of the storage tank when typhoon events are expected, thus increasing the capacity for receiving river water.

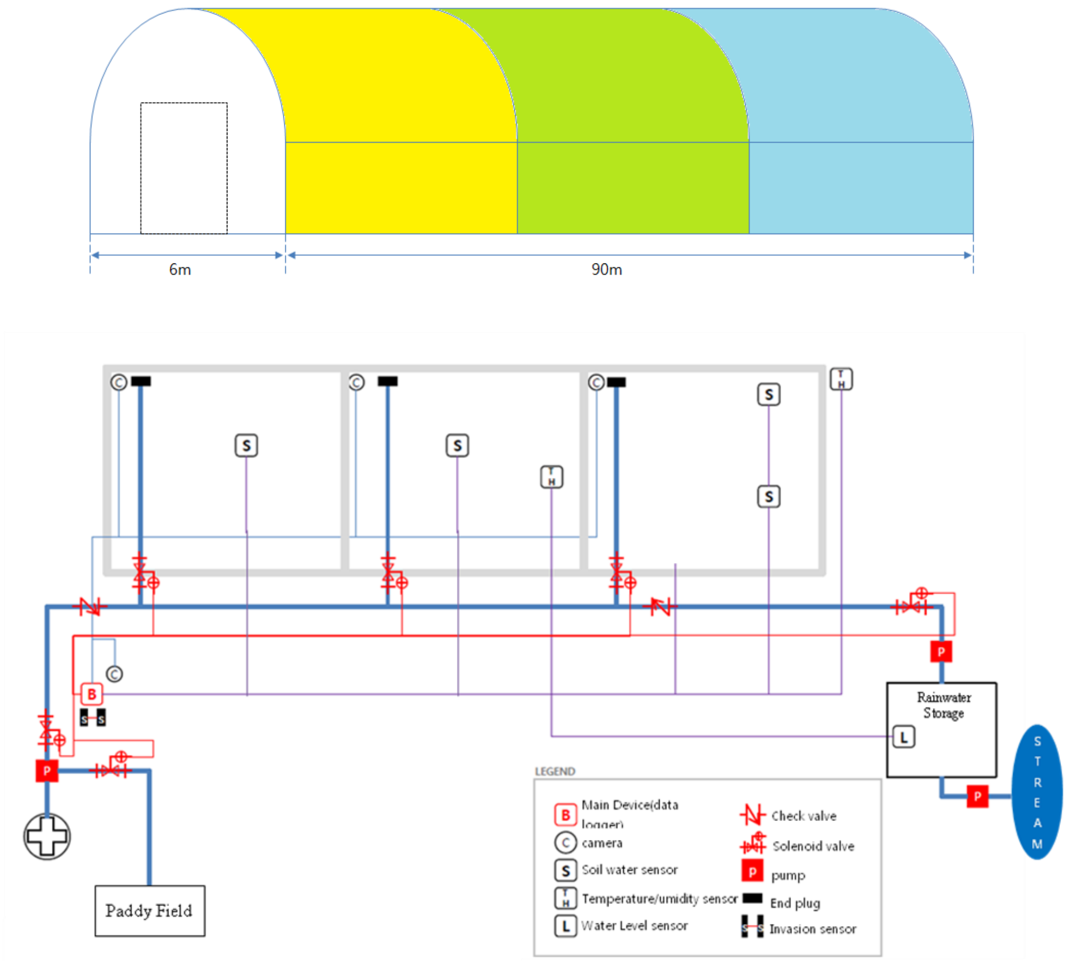

Figure 7. Block Plan for Installment of the Smart Irrigation System in the Testbed

4. Conclusion

In this study, we analyzed the drought resilience of napa cabbage cultivation regions by si/gun division in Chungbuk and Chungnam, two South Korean provinces of low-precipitation. The SPEI was used for drought diagnosis. A region was diagnosed to have been affected by drought when it showed SPEI values lower than −1.5 on two or more occasions during the cultivation period of August–November. Of 80 regions investigated, 21 were identified as drought-affected regions in which the corresponding napa cabbage productions per unit area over six years were compared. The five regions with highest production, Cheongyang, Yesan, Asan, Gongju, and Cheongju in Chungnam, generally showed 10% higher production than regions in Chungbuk under the same drought conditions.

On the basis of the analysis data, we selected a testbed region suitable for application of the smart irrigation system

Conventional ICT-based irrigation management has been studied by many researchers for management of agricultural reservoirs and weirs in large rivers; however, a farmstead-unit irrigation system has not been implemented thus far. Application of the smart irrigation system by farmstead unit is expected to enhance overall crop production by minimizing the drought-induced damage to crops of individual farmsteads.

In this study, we presented an efficient farmstead-unit agricultural water supply system implemented by a smart irrigation system on the basis of data measured by the water management sensors and meteorological data, and we applying the system to the selected testbed.

The smart irrigation system in this study was designed to ensure manual and automatic maintenance of the optimal soil moisture content by setting the optimal soil moisture level for each crop type. Moreover, this system can minimize the drought damage to crops by utilizing the installed rainwater storage tank.

This study presented a method for applying the smart irrigation system to farmstead units on the basis of drought resilience analysis. However, a follow-up study is necessary for enhancing the drought resilience of Chungbuk regions through application and monitoring of the smart irrigation system, which will greatly contribute to preventing damage induced by over-irrigation or drought, thus improving crop production in these regions.

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