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Development of an irrigation vulnerability assessment model in agricultural reservoirs utilizing probability theory and reliability analysis

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A B S T R A C T

The primary goal of water resource management is to maintain a secure and reliable supply of water that can meet the demands of responsible water resource planning. The development of a sustainable agricultural water management system is necessary to evaluate the capability of the water supply to adapt to changes in environmental conditions in relation to the passage of time. Because each reservoir has specific properties related to its watershed, irrigation district, and changes in inflow, they are essential to improve the current assessment methods. The purpose of this study is to propose an irrigation vulnerability assessment method that considers a probability distribution that uses time-dependent change analyses of the irrigation water requirements by paddy fields and the water supply capacity of agricultural reservoirs. Irrigation vulnerability indices are estimated to evaluate the performance of the water supply on the agricultural reservoir system using a probability theory and reliability analysis as an objective method to evaluate the stability of the water supply. The work presented in this paper addresses the potential impact of environmental changes on water supply and demand, as well as the associated reservoir operation performance, with an emphasis being placed on the probability of the current vulnerability. The environmental impact is particularly marked for irrigated paddy fields that utilize a reservoir agricultural vulnerability evaluation model to classify the relative and quantitative severity of irrigation vulnerabilities. Thus, it is a recommended practice in the development of water supply management strategies to manage the risk of an uncertain future.

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1. Introduction

Efficient water resource management, stable agricultural production, and proper distribution are all essential for a sustainable agriculture and the environmental protection of rural areas. The primary objective of water management is to establish a reasonable plan that considers the temporal and spatial equilibrium of water supply and demand. Korea has a monsoon climate with a warm temperate zone in which 70% of the annual rainfall occurs between June and September. The vulnerability of Korea's rural regions to water deficits and drought has increased in irrigated districts due to seasonal variations in precipitation and runoff (Nam et al., 2012b). Reservoirs that supply irrigation water to paddy fields play an important role in water resource management, as they have the capability to store excess water to dispense during periods of water deficits. A water shortage can occur at any period during crop growth, which may stress crops and decrease yield. It is important to be able to estimate the condition of a reservoir supply for the ongoing operation of agricultural reservoirs. Therefore, it is necessary to evaluate the overall growth stages of the water supply. In reservoir irrigation districts, the severity of agricultural water vulnerability must also be analyzed with respect to the relationship between the available reservoir storage conditions and the water requirements of paddy fields.

The water resource system is very complex due to meteorological and hydrological elements; therefore, different mathematical methodologies have been implemented in an attempt to mitigate these uncertainties. The level of uncertainty increases further still when surface water is diverted for irrigation due to the climate variability of meteorological and hydrological phenomena, including the frequency, intensity, and location of extreme events (Fussel and Klein, 2006; Paydar and Qureshi, 2012; Gu et al., 2013). Problems

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Table 1
Characteristics for agricultural reservoirs in this study.

Symbol	Reservoir	Effective storage capacity ($\times 10^3$ m^3)	Watershed area (ha)	Irrigated area (ha)	Design frequency of drought (years)	Construction year	Administrative district
Res. A	Asan	369.0	270.0	114.5	10	1959	Gyeongsangnam-do
Res. B	Dodeok	316.0	256.0	94.1	10	1959	Jeollanam-do
Res. C	Hyocheon	615.0	230.0	106.7	10	1964	Gyeongsangbuk-do
Res. D	Gwangi	783.3	365.0	239.4	10	1932	Jeollanam-do
Res. E	Shinpyeong	635.1	310.0	152.5	3	1970	Jeollanam-do
Res. F	Songak	463.0	254.0	161.0	3	1958	Chungcheongnam-do
Res. G	Topgok	451.8	378.0	133.7	3	1932	Gyeongsangnam-do
Res. H	Yoogok	687.0	320.0	130.9	10	1952	Jeollabuk-do

related to the operation of irrigation reservoirs are characterized by unpredictable hydrological variables, such as reservoir inflows and rainfall (Suresh and Mujumdar, 2004). The vulnerabilities of water resource systems exhibit great variation over time due to the high spatial and temporal variability of hydrological and meteorological variables (Jain and Bhunya, 2008). Because of the ever-increasing demand for irrigation water and the unreliability of stream flows, performance evaluations of reservoir operations are important and particularly difficult (Moradi-Jalal et al., 2007). It is essential that decision makers be aware of the significance of irrigation vulnerability measures and that they take these measures into account throughout the decision-making process.

Understanding the changes in environmental conditions on reservoirs with time is an important component of water resource management and the maintenance of a stable water supply. The change in rainfall patterns, and the hydrological impact thereof, can increase the probability of water shortages in agricultural reservoirs, affecting the future availability of agricultural water in different regions (Vano et al., 2010; Nam, 2013). Due to population growth, environmental changes, ecological changes in basins and irrigated areas, and socioeconomic development over the past several decades, the irrigation demand and water supply capacity has increased. All of these factors make the development of a sustainable agricultural water resource management system necessary to evaluate the adaptation capability of the water supply under changes in environmental conditions.

The objectives of this study were (1) to develop an irrigation vulnerability assessment methodology with respect to the potential water supply capacity and irrigation water requirement on a local scale, (2) to assess the risk of water supply failure using criteria from the probability distribution of water supply and demand, and (3) to predict the impact of the agricultural water supply and demand on reservoir operation to govern local water management decisions.

2. Materials and methods

2.1. Description of the study area

Approximately 18,000 agricultural reservoirs in Korea have been built in rice cultivation areas since 1900, for the purpose of securing reliable local water supplies while conserving the environment. Agricultural reservoirs are the main water sources, although others, including pumping stations and head works, supply water for approximately 449 thousand ha (approximately 58%) of the 772 thousand ha of the total irrigated paddy field area through irrigation facilities. According to the statistical yearbook of land and water development for agriculture in 2012, approximately 19% of the total agricultural reservoirs are managed by the Korean Rural Community and Agriculture Corporation (KRC) and approximately 81% are managed by local governments. Approximately 94% of the total agricultural reservoirs have a small irrigation area of less than 100 ha, and approximately 81% of the agricultural reservoirs that are managed by the KRC have a watershed area of less than 500 ha. Additionally, the reservoirs that are managed by the local governments are responsible 11% of the total storage capacity. Sixty-two percent of the KRC reservoirs and 64% of the local government reservoirs have been in operation for more than 50 years; therefore, it is necessary to evaluate water supply malfunctions or inefficiencies. The design frequency of drought, the number of years a reservoir needs to be able to withstand a drought phenomenon, for agricultural water resources in Korea is the 10-year drought (KRC, 2012). Approximately 22% of the agricultural reservoirs that are managed by the KRC, and approximately 86% of the agricultural reservoirs that are managed by local governments do not satisfy the capacity requirements for a 10-year drought. In this study, the target reservoirs are limited to agricultural reservoirs with average or normal characteristics managed by the KRC.

Agricultural reservoirs are the principal water source for paddy field irrigation and are primarily filled by precipitation from October to the end of March, when irrigation is unnecessary. A nationwide sample of eight agricultural reservoirs, from a similar watershed area of less than 500 ha, and a design frequency of drought of less than 10 years were selected for comparisons of the irrigation vulnerability probability in various regions with respect to the construction year and specific characteristics of the reservoirs, which were suggested by hydrology reports for each design as shown in Table 1. Three reservoirs, including the Hyocheon (Res. C), Songak (Res. F), and Yoogok (Res. H) reservoirs, are located in the central region between 36 and 38° N. The others, including the Asan (Res. A), Dodeok (Res. B), Gwangi (Res. D), Shinpyeong (Res. E), and Topgok (Res. G) reservoirs, are located in the southern region between 34 and 36° N. The largest watershed area was found in Res. G, and the largest irrigated area and effective storage capacity were in Res. D.

2.2. Agricultural water supply and demand assessment model

One irrigation reservoir generally has two components: a watershed and an irrigation district (Kim et al., 2003). The common agricultural water supply capacity of the reservoir is determined by the available supply, and it takes into consideration the water inflow to the basin, the water supply from irrigation facilities, and the water demand of the irrigated districts. In this study, agricultural water supply and demand systems of the reservoir are composed of a watershed, reservoir, and irrigation districts. The irrigation vulnerability assessment components selected were the water supply element, defined as the potential water supply capacity, and the water demand element, defined as the irrigation water requirement. The demand for irrigation and agricultural water is influenced by changing meteorological and hydrological elements such as precipitation, temperature, potential and actual evapotranspiration, and runoff in the watershed (Shen et al., 2013; Wu and Chen, 2013). The agricultural water supply and demand model consists of three major sub-models: the rainfall-runoff model for the watershed, the paddy water balance model for irrigation

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