VULNERABILITY ASSESSMENT OF AGRICULTURAL RESERVOIR WATER SUPPLY CAPACITY

Jehong Bang¹, Jin-Yong Cho²

ABSTRACT

Paddy rice is a staple food crop in South Korea, and 60% of paddy fields are supplied by irrigation water from about 17,000 reservoirs. Therefore, the assessment of agricultural reservoir water supply capacity is crucial to determine drought resistance capability for securing the stable food supply. However, operation rule has been set up with a conventional method and vague standards which only consider real-time water storage rate. To provide a reasonable basis for reservoir operation rule, in this study, we assessed the vulnerability of agricultural reservoir daily which considers two variables: potential water supply (PWS) and irrigation water requirement (IWR) within the irrigation period. As a pair of PWS and IWR can be produced for a year, more than 30 sets were calculated with long term weather data. The vulnerability of a reservoir means a probability that water requirement is higher than water supply; mathematically, P(IWR>PWS). We assessed the vulnerability of four study reservoirs daily, and the most hazardous periods was turned out to be the beginning of the transplanting season.

Keywords: Drought response, vulnerability probability, agricultural reservoir, potential water supply capacity, irrigation water requirement

1. INTRODUCTION

The stable water supply is achieved by efficient water resources management. Generally, rainfall trend shows variation based on region. Therefore, it is important to assess reservoir drought response capacity; vulnerability and make different water management strategy for each reservoir to cope with increasing climate change threatens. Agricultural reservoirs are the essential source for paddy field irrigation but can be largely influenced by climate. In this study, we assessed agricultural reservoir vulnerability with convolution process of two major variables in water management; potential water supply and irrigation water requirement.

2. MATERIALS AND METHODS

2.1 Study Area

Two agricultural reservoirs were selected for comparisons of the irrigation vulnerability probability. Go-Sam and Go-Jan reservoirs, located in the central region between 36° and 38°N, have a different range of hydrological properties; Go-Sam is bigger than Go-Jan. Table 1 indicates the sample reservoir properties description.
Table 1. Characteristics of agricultural reservoirs in this study

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Effective storage capacity (x10^3 m^3)</th>
<th>Watershed area (ha)</th>
<th>Irrigated area (ha)</th>
<th>Administrative district</th>
<th>Land use rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Go-Sam</td>
<td>15,217</td>
<td>7,100</td>
<td>2,970</td>
<td>Anseong-si, Gyeonggi-do</td>
<td>57.1 20.2 7.4</td>
</tr>
<tr>
<td>Go-Jan</td>
<td>409</td>
<td>450</td>
<td>83.4</td>
<td>Hwaseong-si, Gyeonggi-do</td>
<td>18.3 23.8 37.0</td>
</tr>
</tbody>
</table>

3.2 Agricultural water supply and demand assessment model and irrigation vulnerability assessment

One agricultural reservoir has two different components: a watershed and an irrigation district (Kim et al., 2003). The available supply determines the common agricultural water supply capacity of the reservoir, 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 (Nam et al., 2014). In this study, water supply and demand systems of the reservoir are composed of the watershed, reservoir, and irrigation area. The components of irrigation vulnerability assessment are water supply, defined as a potential water supply capacity, and the water demand element, defined as irrigation water requirement. The agricultural reservoir operation model can be run based on daily reservoir storage. It includes a hydrological model that simulates the inflow from the watershed and the release to the irrigation area during the irrigation period. The daily water storage in a reservoir is estimated by the following equation.

\[ RS(t) = RS(t-1) + RI(t) + PR(t) - (RO(t) + RF(t) + RE(t) + Loss(t)) \cdots (1) \]

Where RS is reservoir storage, RI is the reservoir inflow using TANK model (a typical concept rainfall-runoff model; Sugawara, 1979), PR is the precipitation to the reservoir surface, RO is the reservoir outflow, RF is the overflow amount of reservoir, RE is the evaporation loss, and Loss is the other loss. Generally, RO is not considered because it is very small compared with other components. RE is calculated by applying a pan coefficient ranging from 0.6 to 0.8 to estimate pond water surface evaporation, as suggested by Veihmeyer (1964). RI is estimated from the modified TANK model; wherein simulated runoff data are used as the daily inflow measurements for the reservoir operation model. RO depends on the daily water requirements and includes the water delivery requirement for maintaining conveyance losses, which is 20% of the amount released.

Irrigation water demand is calculated with the paddy water balance model developed to estimate the daily water demanded by paddy fields. Daily water requirements were defined as the ponding depth of the required water that occurs through the crop evapotranspiration and is simulated using meteorological and farming practice data and the following equation (Jensen et al., 1990).

\[ \text{NetIWR}(t) = PD(t) - D(t-1) + ETC(t) + DP(t) - ER(t) \cdots (2) \]

Where NetIWR is the daily net irrigation water requirement, PD is the reference ponding depth for each growth stage, D is the ponding depth, ETC is crop evapotranspiration, DP is deep percolation, ER is effective rainfall, and t is time step. ETC is determined by multiplying the reference crop evapotranspiration by the ten-day crop coefficients for paddy rice (Yoo et al., 2006). The reference crop evapotranspiration is computed by the FAO Penman-Monteith method (Allen et al., 1998).
2.3 Reservoir Vulnerability Assessment

Vulnerability assessment in irrigation reservoir is conducted with potential water supply (PWS) and irrigation water requirement (IWR). Vulnerability defines the extent of the differences between the threshold value and the unsatisfactory time-series values (Ashofteh et al., 2012). The risk and vulnerability analysis for water supply capacity in agricultural reservoirs is evaluated by calculating the probability of a water supply failure by applying the criteria to performance limitations. The potential water supply capacity and irrigation water requirements for the vulnerability assessment are estimated by the following equation:

\[
P_{\text{WS}} = R_C + \sum_{j=1}^{n} R_W t_{t+j} - \sum_{j=1}^{n} R_O t_{t+j} \quad (3)
\]

\[
I_{\text{WR}} = \sum_{j=1}^{n} P W R t_{t+j} \quad (4)
\]

Where PWS is the potential water supply capacity, RC is the reservoir water storage volume, RWI is the reservoir watershed inflow, RO is the reservoir overflow, IWR is the irrigation water requirement, PWR is the paddy water requirement, t is the unit of time, and n is the end of irrigation periods.

Elements of the irrigation vulnerability assessment model selected as supply and demand are displayed by the density of occurrence, and by a probability distribution. The two elements are combined to quantitatively estimate the probability of water supply failure from the probability density distribution of demand and supply. In this study, a reliability analysis was applied to assess the vulnerability of a water supply. The level of uncertainty can also be quantified through reliability analysis and is calculated by identifying the risks from the factors affecting the performance limit state of the water supply. To apply the reliability analysis to the vulnerability assessment, it is necessary first to determine the load, defined as irrigation demand, and the resistance capacity, defined as the water supply. The performance limit state of the water supply is defined as the point at which the availability of the water supply is equal to irrigation demand. When irrigation demand exceeds the capacity of the water supply, it is a failure state of the water supply. Therefore, the probability of failure is the probability that the water supply capacity of reservoirs reaches the limit, or failure, state. The reliability function can be described by the following equation:

\[
Z = P_{\text{WS}} - I_{\text{WR}} \quad (5)
\]

Where Z is the reliability function or performance limit equation, PWS is the potential water supply capacity, and IWR is the irrigation water requirement. Therefore, the reservoir vulnerability index is calculated by the following equation:

\[
R_v = 1 - R_t = P_{\text{failure}}(IWR > PWS) \quad (6)
\]

\[
P_{\text{failure}}(PWS - IWR < 0) = \int_{-\infty}^{\infty} \left[ \int_{-\infty}^{\infty} P_{\text{WS}}(x) dx \right] \times P_{IWR}(\tau) d\tau \quad (7)
\]

Where \( R_v \) is the risk index, \( R_t \) is the reliability index, \( P_{\text{failure}} \) is the probability of failure, \( P_{\text{PWS}} \) is the probability of potential water supply capacity, and \( P_{IWR} \) is the probability of irrigation water requirement.

3. RESULTS AND DISCUSSION

3.1 Analysis of The Agricultural Water Supply and Demand Model

PWS and IWR and basic statistics in each study reservoir were computed to analyze agricultural water supply and demand. Basic statistic annual average and deviation of PWS and IWR are shown in Table 2. Go-Sam reservoir has much larger effective
storage capacity compared to Go-Jan, so that mean, max., min., values of PWS and IWR have great difference. The results of annual watershed inflow, reservoir overflow, and paddy water requirement in the time series are shown in Figure 1 and 2. In many years, overflow exceeds other water potential components, and PWS was greater than IWR. It indicates that this study reservoir is not much vulnerable on April 1st.

**Table 2. Basic statistics on PWS and IWR for two reservoirs over 40 years**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Potential water supply capacity (PWS)</th>
<th>Irrigation water requirement (IWR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ((10^3 \text{m}^3))</td>
<td>Max. ((10^3 \text{m}^3))</td>
</tr>
<tr>
<td>Go-Sam</td>
<td>21,247</td>
<td>32,327</td>
</tr>
<tr>
<td>Go-Jan</td>
<td>598</td>
<td>962</td>
</tr>
</tbody>
</table>

**Figure 1.** Potential water supply and irrigation water requirement of Go-Sam reservoir

**Figure 2.** Potential water supply and irrigation water requirement of Go-Jan reservoir

### 3.2 Assessment of Reservoir Vulnerability

Daily reservoir vulnerability probability was computed from the water supply failure criteria using the probability distribution function of water supply and demand. As IWR and PWS are turned out that statistically distributed normally (Nam et al., 2014), the normal distribution function is determined to be applied in study reservoirs for the vulnerability analysis. Over 40-year weather data, reservoir water supply vulnerability
is calculated with. The real-time vulnerability was computed with daily reservoir storage data in 2013 when the drought occurred in South Korea.

![Figure 3. Vulnerability probability curve of Go-Sam reservoir](image1)

![Figure 4. Vulnerability probability curve of Go-Jan reservoir](image2)

Reservoir water supply vulnerability starts to increase at the beginning of transplanting period in both reservoirs. The transplanting period is the most critical time because the largest amount of water needs to be supplied in the paddy field based on ponding method. When transplant ends, the vulnerability decreases gradually after the transplanting season.

In Go-Jan reservoir vulnerability with real-time data started to decrease at the beginning of the period contrary to Go-Sam reservoir. Go-Jan reservoir has wide watershed and effective storage capacity. It seems that rain poured at the beginning of irrigation time on irrigation site of Go-Jan reservoir and it did not suffer from drought in 2013. Go-Sam reservoir, however, shows high vulnerability probability in early time in irrigation period. Real-time reservoir data started to decrease from May 7th, and it influenced vulnerability calculations. After a steep increase until May 23rd vulnerability probability dropped quickly to the general level. Therefore, a critical moment for stable water resources management in the agricultural reservoir is confirmed as the middle of transplanting period.
4. CONCLUSIONS

In this study, a practical method to assess vulnerability probability of agricultural reservoir was proposed. This method is based on probability theory and reliability analysis, and uses time-dependent change analysis of residual water supply and irrigation water requirements. The vulnerability curve starts to increase in transplanting period and decrease in the middle of the period. At the middle of the period vulnerability reached peak point and it is the critical point for the one-year irrigation system. The decision maker should pay attention to this period. Vulnerability using real-time data showed a very different trend from water supply vulnerability curve because of drought.

The reservoir vulnerability index is used to evaluate the present performance of the water supply and the current capacity of drought resistance within the agricultural reservoir system. These results can be utilized to establish a proper strategy for each reservoir depending on different characteristics.

5. ACKNOWLEDGEMENT

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6. REFERENCES


