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Evaluation of monthly drought prospect and reservoir operation rule for drought response using reservoir drought index (RDI)

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Abstract

Introduction: Recently, as climate change intensifies, the frequency and intensity of drought occurrence are increasing. Unlike floods, drought is challenging to know the beginning and end, so it is challenging to respond pre-emptively. In Korea, the vulnerability of agricultural reservoirs to disaster response is increasing due to climate change and the aging of facilities. So it is necessary to estimate an appropriate drought index to predict drought disasters and operate reservoirs that respond pre- emotively to drought.

Materials and Methods: Drought can be largely classified into meteorological, agricultural, hydrological, and socioeconomic drought. Various drought indeces have been researched and developed depending on the subject field. Each drought index uses different variables according to its focus subject. In Korea, more than 17,000 reservoirs have a total effective storage capacity of 31 tons approximately and contribute more than 75% of the total agricultural water. From June to August, precipitation is stored in the reservoirs as much as possible when rainfall is concentrated. Then water is supplied from April to

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September, the rice paddy growth period, to ensure stable crop cultivation. Hence if the reservoir storage is sufficient, it is possible to supply stable agricultural water to cultivate even in meteorological droughts. On the other hand, if the reservoir storage is insufficient, it is difficult to respond to a drought disaster. So the management of reservoir storage is a significant factor in the efficient management of agricultural water and stable crop production. In this study, the reservoir drought index (RDI), one of the hydrological drought indeces, was estimated and utilized to predict drought. Then the pre-emptive drought response operation rule was applied. First, monthly runoff and agricultural water demand were estimated. Then the multiple regression analysis was conducted to predict reservoir storage at the beginning of the following month. The reservoir storage at the beginning of the month, monthly runoff, and monthly agricultural water demand were used as independent variables. The RDI was calculated from estimated reservoir storage and annual reservoir storage. The estimated RDI was compared to the observed RDI to verify the applicability.

Results: The result of the multiple regression analysis showed above 0.65 coefficient of determination, and the RDI showed better performance because it was classified according to criteria range. In order to establish reservoir operation rules for drought response, this study conducted a survey of reservoir managers in Korea. As a result of the survey, the main factors influencing the suspension of reservoir water supply were rainfall, rainfall forecast, and reservoir storage rate. For the reservoir operation for drought response, the existing criteria of reservoir managers for stopping the supply of reservoir water were used. The agricultural water demand was always supplied considering the gross water requirement estimated by the Penman-Monteith equation when there were no suspension factors in the irrigation period. The result of the reservoir operation rules for drought response was evaluated by comparison to the result of reservoir operation according to theoretical water requirements.

Conclusions: In this research, a regression analysis was performed to predict the reservoir storage of the first day of the following month during the irrigation period using the reservoir storage, monthly inflow, and monthly water supply. Through this, the reservoir drought index, RDI, for the next month was estimated, and drought prospect was carried out. Despite the lack of collected monthly reservoir data, the prediction of the reservoir storage showed good performance, and the drought prospect through the RDI showed a higher accuracy than reservoir storage because it was performed by classifying the RDI values within a certain range into the same drought severity. For some RDI values, a lower level of drought prospect was shown compared to the actual drought severity. However, it might be supplemented considering the safety rate of the predicted RDI. So, it is thought that a drought prospect will be effective. However, the monthly inflow and supply for regression analysis were calculated assuming that future weather data are accessible. So the correct drought prospect can be expected when accurate forecast weather data are available. In addition, this study analyzed the factors that current reservoir managers in Korea to decide when to stop supplying water through a survey. Based on this, the reservoir operation rule for response to drought (ROD) was established. The effect of ROD was analyzed by comparing the results of reservoir operation by theoretical agricultural water requirement (TOM).

Keywords: Drought Response, Reservoir Operation, Reservoir Drought Index, Drought Prospect, Agricultural Water Supply.

1. Introduction

Recently, due to climate change, the frequency and intensity of drought in Korea are increasing, and severe drought is frequently occurring (Kim et al., 2016). Drought has enormous damage and influence, but it is difficult to establish and implement accurate responses because detecting the exact beginning and end of the drought is very challenging (Kim et al., 2013). Various drought indices are being developed to respond preemptively to drought and manage water resources. The research is being conducted to predict drought or analyze drought intensity and duration using the developed drought index (Kim et al., 2012). Drought can be classified into meteorological, agricultural, hydrological, and socioeconomic droughts, depending on the aspect of concentration (Wilhite & Glantz, 1985; Correia et al., 1991; Tate & Gustard, 2000). The hydrological drought index is defined by the amount of available water resources such as river flow, reservoir, and groundwater, focusing on water supply. In particular, the reservoir drought index is defined by an available water resource of the reservoir. It serves as a basis for determining whether irrigation can be stably performed.

There are more than 17,000 agricultural reservoirs in Korea. The total effective storage of the agricultural reservoirs is about 31 tons, accounting for more than 75% of the total agricultural water. Reservoirs are used as an essential agricultural water source for rice paddy farming in Korea. The agricultural reservoirs store water from October to March, which is a non-irrigation season, and supply agricultural water in the rice farming season to grow paddy rice stably. If the reservoir storage is sufficient, water can be stably supplied even in meteorological drought. So it is crucial to manage the available water of reservoirs to cope with the drought. Therefore, this study utilized the reservoir drought index (RDI) to prospect the drought focusing on the hydrological drought. Through multiple regression analyses, the reservoir storage of the first day of the month in the following month was calculated, and the RDI was predicted. Then drought prospects of the following month were conducted using predicted RDI. Monthly inflow and monthly supply were used as independent variables, and future weather data were assumed to be known. Also, in this study, a survey was conducted on current Korean reservoir managers to establish the reservoir operation rule to respond to the drought. Based on the survey results, the factors that affect stopping agricultural water supply were analysed. Then the criteria for reservoir operation to respond to the drought were established. The applicability of the RDI calculated using multiple regression analysis was evaluated by comparing it with the actual RDI. The established reservoir operation rule for drought response was compared to the reservoir operation results conducted by the theoretical agricultural water requirement.

2. Materials and methodology

The subject reservoirs of the study were the Gaeun reservoir and Geumsa reservoir. Meteorological data, land cover data, and watershed information were collected. Then the TANK model, a conceptual rainfall-runoff model, was applied to estimate the inflow amount of the reservoir from the upstream watershed. The evapotranspiration of the paddy rice was calculated by the FAO Penman-Monteith equation. The amount of agricultural water supply was estimated with the evapo-transpiration considering lot-management water requirements for crop growth, infiltration, conveyance loss, and distribution management loss. A regression equation was derived to calculate the reservoir storage of the first of the following month by utilizing monthly reservoir inflow, agricultural water supply, and the reservoir storage of the first of the month as independent variables. For the multi-regression analysis, reservoir water level data were collected, and reservoir storage and rate were calculated by the reservoir storage curve. The predicted reservoir storage was utilized to estimate the RDI, which was used for the prospect of the drought. The survey was conducted on current agricultural reservoir managers. From the survey results, the factors and standards for stopping agricultural water supply of the current reservoir operation rule. Then the reservoir operation rule of this study was established to respond to the drought. The predicted reservoir storage and RDI were compared with the observed reservoir storage and RDI calculated with the observed water level. The amount of water supply by the reservoir operation rule to respond to the drought were compared with theoretical water requirement.

2-1. Subject reservoir and data construction

The subject reservoirs of the study are Gaeun Reservoir, which is 37.65 degrees north latitude, and Geumsa Reservoir, which is 37.39 degrees north latitude. Each reservoir is located in Hongcheon-gun, Gangwon-do in Yeoju-si, Gyeonggi-do. The effective storage of Gaeun and Geumsa Reservoir are respectively 1,636,475 m3 and 3,312,909 m3, and the effective storage of Gaeun Reservoir before enlarging is 734,780 m3. The watershed area is 474 ha and 794 ha for Gaeun and Geumsa reservoirs, respectively. Figure 1 shows the location of the subject reservoir on the map.

Figure 1. Location of the subject reservoirs

Reservoir storage rate data calculated from reservoir water levels were used as the dependent variable for multi-regression analysis. The reservoir water level data were measured every 10 minutes with a water level instrument and collected by Korea Rural Community Corporation (KRC). In this study, the outliers of the water level data were removed, and the daily average water level data was used. The normal reservoir storage rate data were collected from KRC. Multiple regression analyses were carried out with monthly data for the irrigation period, excluding missing data. The TANK model and Penman-Monteith equation were applied to calculate monthly inflow and supply, which are independent variables of multiple regression analysis. The weather data were collected from the Thiessen station of each reservoir's upstream watershed. The land-use area ratio of the upstream watershed was calculated from the land cover map, and the TANK model parameters were calculated. The crop coefficient suggested by Yoo et al. (2006) was utilized to calculate the evapotranspiration of paddy rice. Table 1 and Table 2 are reservoir water level data, weather data, and land-use area ratio information.

Table 1. Properties of reservoir water level data

Reservoir	Data period	Total data number	Missing data number
Gaeun	2011.01.01.- 2018.06.12.	2,162	558
Geumsa	2012.03.20.- 2018.06.12.	2,276	196

Table 2. Thiessen weather station and land-use area ratio

Reservoir	Thiessen weather station	Ratio of land-use area (%)		
		Paddy	Upland	Forest
Gaeun	Hongchen	0.00	0.06	98.16
Geumsa	Icheon	2.57	3.83	88.57

2-2. Drought prospect

a) Estimation of monthly reservoir inflow

In this study, the daily runoff of the upstream watershed of the reservoir was estimated using the TANK model. Then the monthly inflow of the reservoir was calculated. The TANK model is a conceptual rainfall-runoff model developed by Sugawara (Sugawara, 1972). The TANK model has a simpler algorithm for interpreting rainfall-runoff phenomena and has fewer input data and parameters than other rainfall-runoff models (Koo et al., 2006). The TANK model assumes three to four conceptual reservoirs with two to three outlets and optimizes related parameters to perform runoff analysis on the watershed. Sugawara (1972) stated that the four- stage TANK model is suitable for the watershed in Japan, and the four to five-stage TANK is suitable for a large basin. In Korea, Kim & Park (1988) suggested a modified three-stage TANK model using three tanks and four outlet holes according to the characteristics of the upstream watershed of the agricultural reservoir (Kim & Kim, 2012; Ahn et al., 2015). In this study, the runoff of the upstream watershed was calculated by applying the modified three-stage TANK model proposed by Kim & Park (1988). The TANK model's construction parameters were estimated through the regression equation using the watershed area and land-use area ratio. Figure 2 is a schematic diagram of the runoff estimation process of the modified three-stage TANK model.

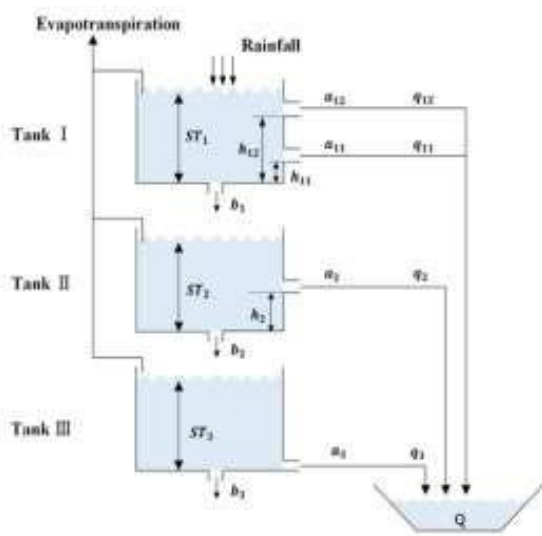


Figure 2. Schema of the modified 3-TANK model (Kim & Park, 1988; Song, 2017)

b) Estimation of monthly reservoir supply

In this study, the evapotranspiration of paddy rice was calculated using the FAO Penman-Monteith equation and the crop coefficient (Kc) proposed based on the observed evapo-transpiration by Yoo et al. (2006). The reservoir supply amount was calculated considering the estimated evapotranspiration, lot-management water requirements for crop growth, infiltration, and irrigation efficiency. Table 3 is the paddy rice crop coefficient applied in this study, and the crop coefficient was applied in units of 10 days after the transition period.

Table 3. Crop coefficient of paddy rice in Korea

Days	10	20	30	40	50	60	70
K_c	0.78	0.97	1.07	1.16	1.28	1.45	1.50
Days	80	90	100	110	120	Avg.	
K_c	1.58	1.46	1.45	1.25	1.01	1.27	

This study assumed that 10 mm/day of water was supplied for 14 days during the transplant period, and 70 mm of ponding depth was supplied after the 7-day midsummer drainage period for cultivation management. The infiltration amount was applied as 4 mm/day, and conveyance and distribution management loss rates were assumed to be 10% and 15%, respectively.

c) Estimation of reservoir drought index (RDI)

The reservoir drought index (RDI) proposed by Lee et al. (2018) was applied in this study. The RDI applied is as follows.

$$\mathrm{RDI} = \frac{\mathrm{SR_{obs}} - \mathrm{SR_{nor}}}{\mathrm{SR_{obs}}}$$

Where SRobs is observed storage rate and SRnor is normal storage rate for 30 years. The reservoir storage rate predicted through the regression equation was applied instead of the observed value to predict the RDI of the following month. Table 4 summarizes the criteria for the reservoir drought index to classify drought severity.

Table 4. RDI criteria for classification of drought severity

RDI	-∞ ~ -1	-1 ~ -0.5	-0.5 ~ 0.25	-0.25 ~ 0.25
Classification	Extremely Dry	Severely Dry	Moderately Dry	Normal
RDI	0.25 ~ 0.5	0.5 ~ 1.0	1.0 ~ +∞	
Classification	Moderately Wet	Severely Wet	Extremely Wet	

d) Reservoir operation rule for response to drought (ROD)

This study surveyed Korean reservoir managers to analyse the current reservoir operation rule. The survey was conducted on 15 branch offices that responded, and the criteria for stopping the supply of reservoirs were investigated for three reservoirs according to the size of the reservoir based on the effective storage for each branch. As a result of the survey, rainfall, reservoir storage rate, and rainfall forecast were the factors that stopped the supply of agricultural water in the reservoir. Table 5 summarizes the criteria for stopping agricultural water supply by factor excluding qualitative responses and the number of reservoirs to which the criteria are applied.

Table 5. Factors stopping supply from survey result

Stopping factors	Criteria	Number of reservoirs to be applied
Rainfall	More than 15 mm	3
	more than 25 mm	3
	more than 20~30 mm	3
	more than 30 mm	9
	more than 50 mm	3
Storage rate	less than 30%	12
	less than 60% compared to the normal year	3
Rainfall forecast for next day	more than 20 mm	3
	more than 30 mm	3
	more than 50 mm	3
	more than 60 mm	3
Rainfall forecast for two days later	more than 40 mm	3
	more than 50 mm	3

As a result of the survey, there was no difference in the criteria for stopping supply according to the size of the reservoir within the same branch office. Also, there were quite a few cases in which the criteria for two or more factors were applied together. In the case of rainfall, 30 mm was often the criteria for stopping water supply, and in the case of reservoir storage rate, 30% was the criteria for stopping water supply. In the case of rainfall forecast data, various water supply stopping criteria were applied depending on the reservoir manager. The criteria for the ROD were established based on the results of the survey. The reservoir supply amount was determined in consideration of the evaporation amount, lot-management water requirements for crop growth, infiltration, and irrigation efficiency, and the actual supply ratio of the reservoir supply amount was determined according to the water supply stopping factors. The ROD was applied through the reservoir water balance model. The effect was evaluated by comparing the reservoir operation results according to the theoretical agricultural water requirement (TOM). The reservoir water balance model applied in this study is as follows.

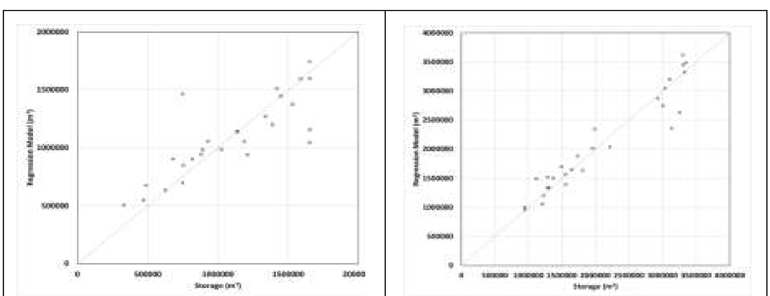
$$S_t+1 = S_t + I_t + P_t - AW_t - E_t - O_t$$

Where, S is the reservoir storage, It is reservoir inflow, P is the water surface rainfall, AW is the reservoir supply, E is the water surface evaporation, and O is the spillway release.

3. Results and discussion

a) Drought prospect

This study performed multiple regression analyses to predict the reservoir storage utilized to estimate the reservoir drought index (RDI). The monthly inflow and supply of reservoirs were calculated using the TANK model and Penman-Monteith equation, and drought prospect was conducted using RDI. As a result of multiple regression analyses predicting reservoir storage, the coefficient of determination was 0.66 for the Gaeun reservoir and 0.92 for the Geumsa reservoir. It confirms that the reservoir storage of the first day of the following month was properly simulated. Figure 3 shows the results of the reservoir storage estimated by the regression equation as a scatter plot at the Gaeun and Geumsa reservoirs.



(a) Gaeun reservoir (b) Geumsa reservoir

Figure 3. Scatter plot of the actual reservoir storage and result of regression equation

In the scatter plot, it can be seen that multiple regression analysis predicts the storage amount well except for some values. The RDI is estimated through the reservoir storage rate calculated through the reservoir storage from the regression equation, and the drought prospect is conducted by classifying the RDI according to the criteria. Hence, even if there is a difference in the prediction of the reservoir storage through the regression equation, it can be classified as the same drought severity in the drought prospect. Figure 4 shows the RDI for the actual and estimated reservoir storage rate as a scatter plot. The dividing line indicated by the dotted line means the criteria for classifying drought severity.

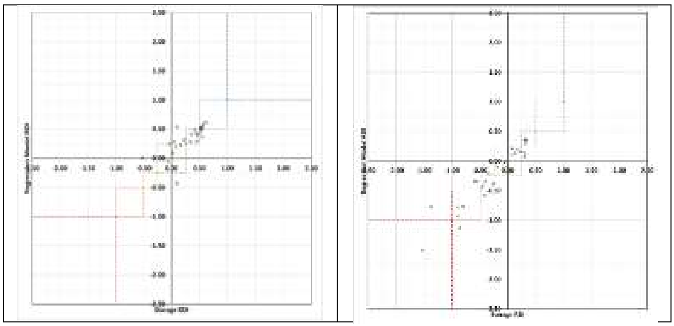


Figure 4. Scatter plot of the actual and estimated RDI

The fact that it falls within the same range in Figure 4 means that the actual and predicted RDI are classified as the same drought severity. From the scatter plot, it can be seen that reservoirs were classified as generally the same drought severity in Gaeun and Geumsa reservoirs.

b) Application of reservoir operation rule for response to drought (ROD)

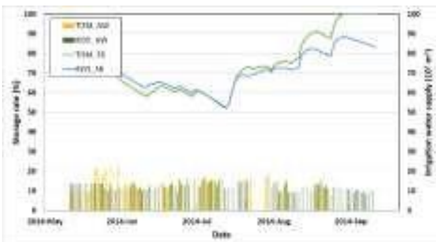
In this study, reservoir operation rules for response to drought (ROD) were established based on the survey results. As a result of the survey, a ROD was established to determine the ratio of agricultural water supply based on rainfall, rainfall forecast, and reservoir storage rate. At this time, the amount of agricultural water supply is estimated considering the paddy rice evapotranspiration, lot- management water requirements for crop growth, infiltration, and irrigation efficiency. Table 6 summarizes the criteria of ROD for adjusting the supply ratio.

Table 6 Criteria of ROD for adjusting the supply ratio

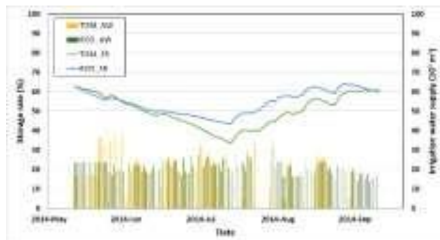
Factors	Criteria	Adjusting supply ratio
Rainfall	Above 50 mm	Stopping supply (0 %)
	Above 15 mm	50 % supply
Reservoir storage	Below 30 %	Stopping supply (0 %)
	Below 50 %	50 % supply
Rainfall forecast	above 50 mm (for next day)	Stopping supply (0 %)

* Supply ratio of each factor was applied in duplicated
** The supply ratio is not applied to the transplant and midsummer drainage period

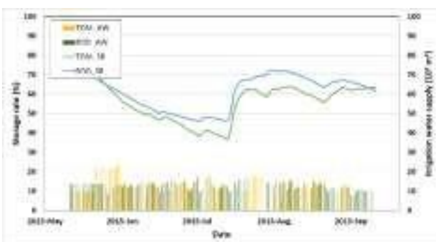
In order to compare the preemptive drought response effect of the reservoir operation according to the ROD, the results of the reservoir operation according to ROD and theoretical agricultural water requirement (TOM) were compared under the same initial reservoir rate condition at the start of irrigation. Figure 5 shows the storage rate and supply of the Gaeun and Geumsa reservoir from 2014 to 2016.



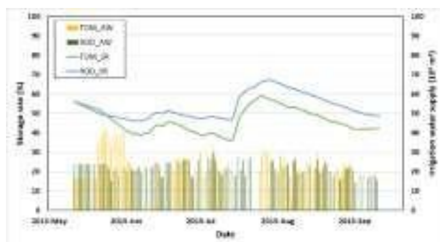
(a) Gaeun reservoir (2014)



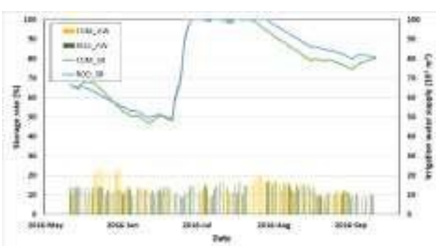
(b) Geumsa reservoir (2014)



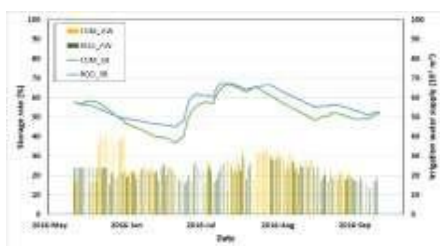
(c) Gaeun reservoir (2015)



(d) Geumsa reservoir (2015)



(e) Gaeun reservoir (2016)

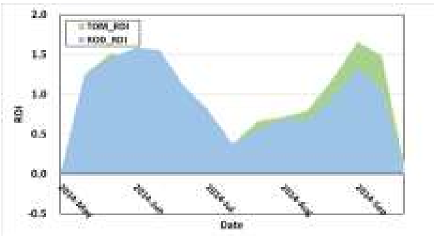


(f) Geumsa reservoir (2016)

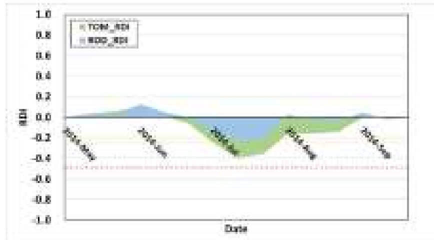
Figure 5. Reservoir storage rate and amount of supply (2014-2016)

In Figure 5, when ROD was applied, it maintained a relatively higher reservoir storage rate than the result of TOM applied. It means that the reservoir storage of ROD is secured more than TOM, so ROD is more stable against drought than TOM when drought is predicted. Figure 6 shows the change in the reservoir drought index at the beginning of the month when

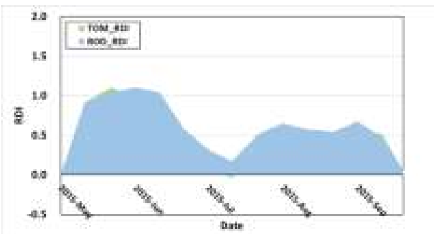
ROD and TOM are applied to the reservoir operation.



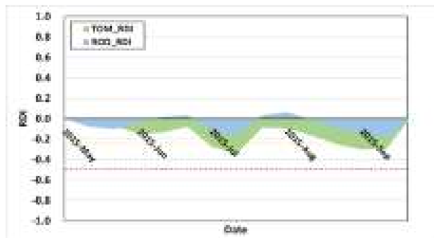
(a) Gaeun reservoir (2014)



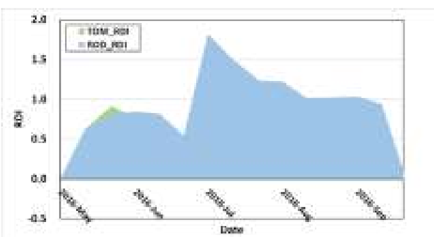
(b) Geumsa reservoir (2014)



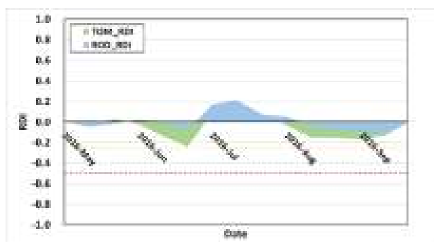
(c) Gaeun reservoir (2015)



(d) (b) Geumsa reservoir (2015)



(e) Gaeun reservoir (2016)



(f) (b) Geumsa reservoir (2016)

Figure 6. Reservoir drought index (2014-2016)

In Figure 6, when the inflow was sufficient, such as the Gaeun Reservoir, the RDI was above 0. Both the ROD and TOM application results showed stable reservoir operation results for the reservoir drought index at the Gaeun reservoir. In the case of Geumsa reservoir, when TOM was applied, the RDI was lower, and it was classified as a more severe drought than when ROD was applied. When ROD is applied, a relatively weak reservoir drought can be maintained compared to TOM. So it is thought that more stable irrigation can be performed compared to TOM when the drought is prolonged.

4. Conclusions

In this study, a regression analysis was performed to predict the reservoir storage of the first day of the following month during the irrigation period using the reservoir storage, monthly inflow, and monthly water supply. Through this, the reservoir drought index, RDI, for the next month was estimated, and drought prospect was carried out. Despite the lack of collected monthly reservoir data, the prediction of the reservoir storage showed good performance, and the drought prospect through the RDI showed higher accuracy than reservoir storage because it was performed by classifying RDI values within a certain range into the same drought severity. For some RDI values, a lower level of drought prospect was shown compared to the actual drought severity.

However, it might be supplemented considering the safety rate of the predicted RDI. So, it is thought that a drought prospect will be effective. However, the monthly inflow and supply for regression analysis were calculated assuming that future weather data are accessible. So the correct drought prospect can be expected when accurate forecast weather data are available. In addition, this study analyzed the factors that current reservoir managers in Korea to decide when to stop supplying water through a survey. Based on this, the reservoir operation rule for response to drought (ROD) was established. The effect of ROD was analyzed by comparing the results of reservoir operation by theoretical agricultural water requirement (TOM). When applying ROD, the reservoir storage rate was maintained higher than TOM. In the case of TOM applied, the water storage rate fell below 50% and 40%, which means the discontinuation of supply in the current operating standards. When analyzed as the RDI, the application of TOM was found to suffer more from a reservoir drought than ROD. It means more reservoir storage was retained in case of the ROM applied. Therefore, when the drought is prolonged, it is expected that the operation of the reservoir with ROM will be able to cope more stable than TOM.

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