Article

Improving Reservoir Operation Criteria to Stabilize Water Supplies in a Multi-Purpose Dam

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Abstract: Recently, torrential rain and drought have occurred in close temporal proximity and for similar durations due to changes in the spatiotemporal patterns of rainfall owing to climate change. In particular, when a drought occurs, it tends to be prolonged, making it necessary to improve the operation of multi-purpose dams that not only control flooding but also serve as water supplies. In this study, standard water volume lines and action plans by response stage were improved so that water could be stored in advance of a drought instead of reservoir operation criteria set based on data from the past. The minimum water demand by use (domestic water, industrial water, and agricultural water) was also calculated. The improved reservoir operation criteria were applied to multi-purpose dams in the Nakdong River Basin, and their effects were analyzed by calculating additionally secured water volumes. In the future, in case of lowered water volumes in multi-purpose dams owing to a drought, the application of these improved reservoir operation criteria is expected to contribute to water supply stability by delaying entry into the drought stage, and minimizing the damages caused by limited water supplies.

Keywords: drought; multi-purpose dam; water supply; reservoir operation criteria; standard water volume lines

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1. Introduction

The functional definition of a drought is a prolonged shortage of rainfall resulting in serious damage to crops and their production. A drought occurs when a shortage in rainfall continues for a long period of time, thereby decreasing soil moisture and the flow rates of rivers and dams. A meteorological drought that occurs because of a long-term rainfall shortage or an extended period of no rainfall develops into an agricultural drought owing to a lack of moisture in the soil, which then develops into a hydrological drought in which there are shortages in major water resources, such as dams and rivers. Such water shortages may ultimately develop into a socioeconomic drought, causing damages to society at large [1].

Unlike many other natural disasters, it is difficult to accurately predict the start and end of a drought, and a drought may occur over an extensive area. Therefore, negative impacts are felt throughout the society. Additionally, differences in precipitation between regions have increased due to anthropogenic climate change, and the resulting local droughts have caused extreme water shortages when they lasted for prolonged periods of time. As such, the South Korean government has pursued short-term countermeasures against droughts, including the development and securing of temporary water sources for drought-stricken areas, appropriate distribution of water, and management of water demands [2].

California in the United States suffered water shortages for as much as five years from 2012 to 2017 owing to a drought. In California, the precipitation between November and February accounts for ~62% of the annual precipitation. During this period, snow in the Sierra Nevada Mountains in

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winter provides ~30% of the total water supply. However, in the winter of 2014, only ~5% of the normal snowfall was recorded. In 2015, an extreme drought, which has the probability of occurring once every 1,200 years, occurred due to a severe lack of rainfall. This lasted for five years, until the end of the drought was declared in 2017 [3]. However, water shortages persist throughout much of California.

In South Korea, droughts occur approximately every seven years, but this periodicity has been shortened since 2010, and the duration of a drought has been extended. For Boryeong Dam, located in the western region of Chungnam, only 38% of the normal rainfall combined with only 18% of the normal inflow during the flood season of 2015 caused an extreme drought, and a lack of rainfall for three years resulted in the lowest recorded water volume (8%) in May of 2017. The inflow reduction, due to the shortage of rainfall in the winter of 2016, caused the water volumes of the dams located in the southern region of Chungnam to drop below 30% in February of 2017. Miryang Dam announced a drought alert stage, Juam Dam, and Hapcheon Dam announced a caution stage, and Buan Dam announced an attention stage.

For multi-purpose dams, effective dam operation is essential to overcome the water supply conditions caused by changes in climate as well as the uncertainties of future water management. Many studies have assessed the performances of the water resource systems of multi-purpose dams, and most have applied decision-making methods to establish water supply plans [4] or assessed the water supply capacities and reliability of multi-purpose dams using operation methods [5–7] or assessment indices [8–10] for multi-purpose dams. No et al. [11] and Choi [12] assessed the water supply capacity of a prospective multi-purpose dam using future climate change scenarios. However, most of these studies assessed the water supply capacity of a single dam or the effects of optimal operation criteria capable of maximizing benefits, such as power generation [7]. Therefore, research on dam operation capabilities for preventing or minimizing damages during times when general operation is not possible, such as a drought, remains necessary.

A suite of "water supply adjustment criteria against dam water shortage" were suggested in 2015 [2], and improvements were suggested in 2016 through a pilot application at 15 multi-purpose dams to prepare multi-purpose dams for water shortages caused by future droughts [2]. In this study, the past operation criteria and the improved criteria were applied to six multi-purpose dams in Nakdong River, where drought events have frequently occurred in the past, and the effects of these two operational conditions were analyzed. For this, the water volume of the dams in the past were compared with those under the improved criteria on April 1, when the use of agricultural water starts to increase for the year, and when a drought occurred in the past. The additionally secured water volumes were then analyzed.

2. Water Supply Adjustment Criteria against Dam Water Shortage

2.1. Problems with the existing water supply adjustment criteria

For the water supply adjustment criteria before 2015, the normal state was determined based the possibility of water supply volumes until the flood season of the next year (i.e., June 20). A 20-year frequency flow rate was introduced based on the basic plan supply amount for each dam. Additionally, a limited water supply scenario was used for attention (80–90% of the basic plan), caution (60–80% of the basic plan), alert (50–60% of the basic plan), and serious (below 50% of the basic plan) drought stages. However, because the reduction supply amounts and water volume storages were determined only when it was predicted to be difficult to secure the standard low water level until June 20 (i.e., the flood season), preemptive responses were difficult to employ when a drought continued after the flood season. Considerations for the current inflow situation and future inflow uncertainties were insufficient because only the single condition of the 20-year frequency flow rate was reflected. Furthermore, dam-dam and dam-weir link operations, such as Soyang River-Chungju Dam, Andong-Imha Dam, and Geum River-Boryeong Dam, were not considered. When the drought stage was entered, it was difficult to store the required amount of water at the right time owing to complicated procedures in determining the dam water supply amount reduction, such as

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the discussions required among related agencies and decisions by the dam-weir link operation council.

2.2. Water supply adjustment criteria against dam water shortage (draft)

In the improved water supply adjustment criteria against dam water shortage, response stages were classified into four stages, attention, caution, alert, and serious, for each multi-purpose dam. Domestic and industrial water was supplied in a stable manner by decreasing the water supply amount when water availability was insufficient. Table 1 shows the major improvements to the dam operation criteria.

Table 1. Improvements to reservoir operation criteria.

Division	Original Criteria	Revised Criteria
Water supply	General planning for water supply from dam	Actual demand for water supply from dam
Projected inflow condition	Inflow (drought frequency, 20-year)	Stochastically generated daily inflow for 500 years
Standard water volume lines	Single operation	Coupled operation (Soyanggang-Chungju, Andong-Imha)
Reference condition	Satisfy the projected water demand until June 20 (Water level: above low water level)	Water supply reliability of 95% for water demand at each drought response stage
Stage of drought	4 Stages (Attention, Caution, Alert, Serious)	Same as original
Reduction order	River maintenance → Agriculture → Domestic and Industrial	Same as original

In the case of the attention stage the supply period was extended from 10 days to 15 days for setting standard water volume lines when there was no inflow for the caution-stage water volume in the operation period of the dam-weir link operation council. In case of a drought, the response time was insufficient because stage elevation occurred due to rapid water volume decreases caused by small differences between water volumes by drought stage. To supplement this, the response time of 15 days was set to secure the response time as well as the lead time in which drought stage elevation does not occur in case there is no inflow. Figure 1 compares the existing standard water volume lines and the improved volumes.

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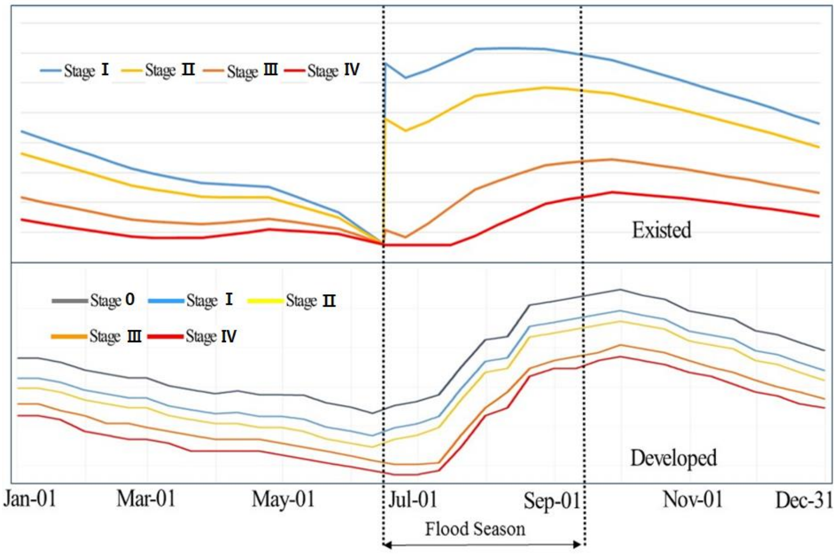

Figure 1. Comparison of standard daily water volume lines by five drought response stages: Stage 0 (no drought; gray); Stage I (attention; blue); Stage II (caution; yellow); Stage III (alert; orange); Stage IV (serious; red).

The action plan for each drought response stage was improved by reducing the total available amount of water and considering link operations so that water storages were possible in the caution stage when the water volumes decreased. To calculate the minimum required demand, the reduction amount for each use was calculated, and the minimum initial reduction amount for each response stage was determined. Based on this required demand, the practical reduction in domestic and industrial water (initial reduction rate of 20%) as well as agricultural water was used in the alert and serious stages (Table 2). This procedure was continued until the dam water volumes reached the normal water supply return criteria. It was adjusted and implemented through the discussion of the dam-weir link operation council when there was a request to adjust the reduction amount. Finally, after the reduction adjustment of water, the dam water volumes were constantly monitored and the contents were posted on the websites of the K-water and the flood control offices, and water supplies returned to the normal state when the dam water volumes reached the normal water supply return criteria [2].

Table 2. Description of water supply conditions by each drought response stage.

Drought Stage		Original Criteria	Revised Criteria
Water Supply Condition	Normal (Stage 0)	-	Satisfying the water demand for the significant stage should satisfy the water demand for 30 days w/o inflow
	Attention (Stage I)	Projected water demand: 80~90%	Satisfying the water demand for the significant stage should satisfy the water demand for 15 days w/o inflow
	Caution (Stage II)	Projected water demand: 60~80%	Satisfy the water demand for domestic, industrial, agricultural, and ecological water
	Alert (Stage III)	Projected water demand: 50~60%	Satisfy the water demand for domestic, industrial, and agricultural water
	Serious (Stage IV)	Projected water demand: < 50%	Satisfy the water demand for domestic ,and industrial water

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3. Results

3.1. Target river basin

The total water resources of South Korea amount to 129.7 billion m³/year, but the usage is just 26% of this total (i.e., 33.3 billion m³/year). The water supplies provided by dams represent 56% of the usage (i.e., 18.9 billion m³/year), and multi-purpose dams alone supply 67.2% of the total amount (i.e., 11 billion m³/year). The total water volume and valid water volume of multi-purpose dams in the Nakdong River Basin, which is the target river basin of this study, are 3.2 billion m³ and 2.5 billion m³, respectively, and represent 25% of the total water volume and 28% of the total valid water volume [13]. For the six target dams (Andong Dam, Imha Dam, Hapcheon Dam, Miryang Dam, Gunwi Dam, and Gimcheonbuhang Dam) where the water supply adjustment criteria were implemented to prevent water shortages, the revised standard water volume lines, the water volumes by dam operation with the action plans, and the water volumes by the past dam operation were compared, and the additionally secured water volumes were calculated. Table 3 shows the summarized reservoir capacities of the six dams, which are listed in the dam operation handbook [14].

Table 3. Storage (Unit: $10^6 m^3$) of six multi-purpose dams [13].

	Reservoir	Total storage	Effective storage	Flood control storage	Emergency storage	Dead storage
Nakdong River	Andong	1,248.0	1,000.0	110.0	130.0	118.0
	Imha	595.0	424.0	80.0	84.0	40.0
	Hapcheon	790.0	560.0	80.0	130.0	20.0
	Miryang	73.6	69.8	6.0	3.6	0.2
	Gunwi	48.7	40.1	3.1	1.3	4.2
	Gimcheon buhang	54.3	42.6	12.3	1.6	2.1

3.2. Assessment of the improved adjustment criteria

For each of the six multi-purpose dams in the Nakdong River Basin, the water volumes from the completion year to 2015 under the existing dam operation criteria were compared with those under the adjusted criteria to analyze their effects. For Andong Dam and Imha Dam, link operations through waterways were reflected, and the surplus of the current daily inflow for the a mean daily inflow was analyzed for each dam.

The water volumes under the past dam operation criteria are compared with those under the improved criteria for Andong Dam and Imha Dam wherein link operations are conducted through connected waterways (Figure 2). Additionally, the surplus was also analyzed. The past dam operation shows that the inflow continuously decreased from 1994 to 1996, which lowered the water volume in the serious stage (Stage IV) of the drought. Furthermore, the inflow decreased from 2008 to 2009, and a similar pattern was observed from the middle of 2013 to 2015. When the inflow decreased, the water volume also decreased, thereby reaching the alert (Stage III) or serious stage. However, when the improved reservoir operation criteria were applied, the onset of the water volume reduction during the drought between 1994 and 1995 was delayed, and the water volume also exhibited larger differences than that observed using the existing dam operation criteria. Under

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the adjusted criteria, the alert stage was not reached. Similar results were also observed for 2008–2009 and 2013–2015.

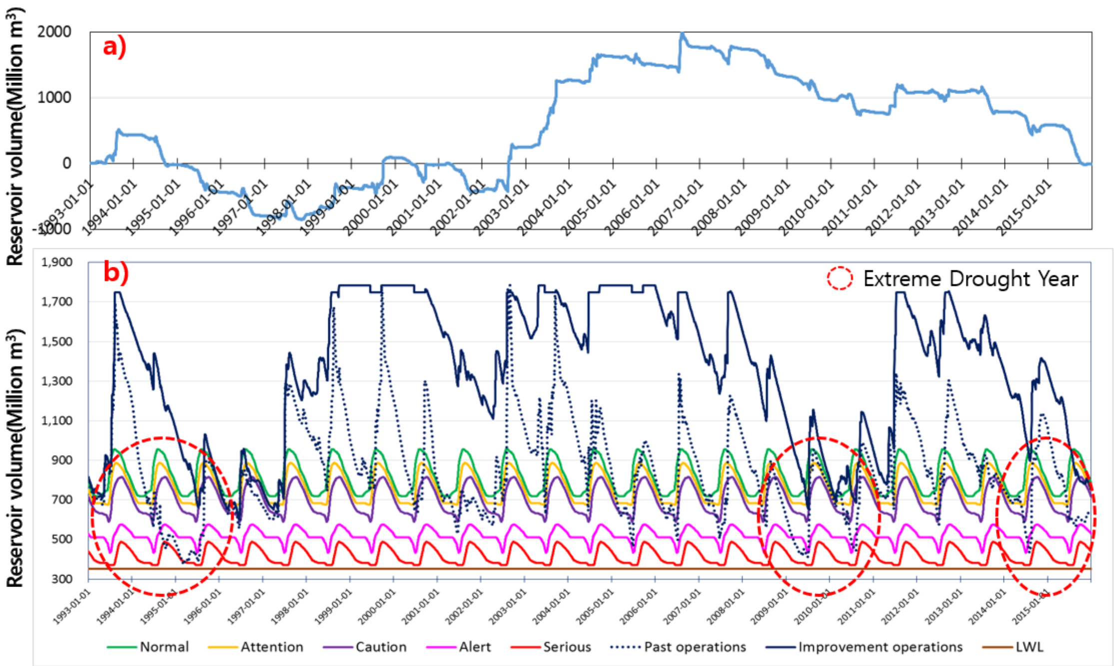

Figure 2. Application results of reservoir operation criteria on Andong-Imha Dams in the Nakdong River Basin. (**a**) Reservoir volume (m³) based on the current daily inflow minus the average daily inflow (i.e., the surplus); (**b**) Reservoir volume (m³) with respect to past (gray dotted line) and improved (solid black line) operation criteria. Drought stages are presented as normal (Stage 0; green); attention (Stage I; yellow); caution (Stage II; purple); alert (Stage III; pink); serious (Stage IV; red). Extreme drought years are circled in red.

Changes in the total water volume in Nakdong River were compared and analyzed for each completion year by reflecting the characteristics of multi-purpose dams connected in parallel around the Nakdong River (Figure 3). Owing to the influence of Andong-Imha Dam, which has the largest water volume in the Nakdong River Basin, the trends in water volume are similar to those of Andong-Imha Dam. From 2008 to 2009 and again from 2013 to 2015, a state of drought began owing to the water volume decreases in the Andong-Imha Dam and Hapcheon Dam, which represented most of the dam water volume in the Nakdong River Basin. Similar to the results of the single dam, the dam water volume using the improved operation criteria was different from that founding using the past dam operation criteria. For 1994–1995, 2001, 2009, and 2014–2015, which were the representative drought years in the past, the water volumes on April 1 (i.e., when agricultural water is required for paddy farming) were compared, and additionally secured water volumes were calculated (Table 4).

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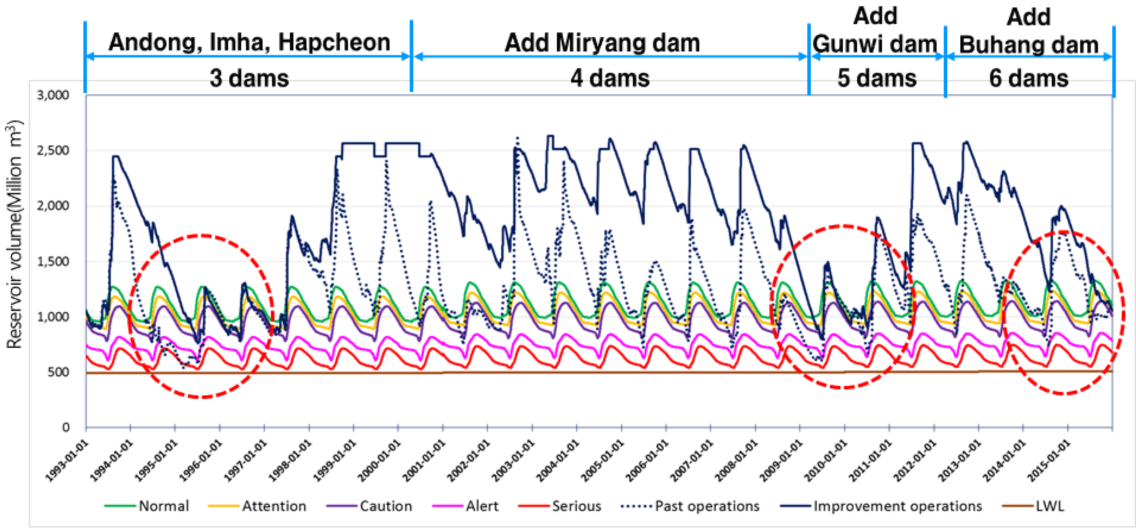

Figure 3. Reservoir volume (m^3) results of reservoir operation criteria for six multi-purpose dams in the Nakdong River Basin: Past (gray dotted line) and improved (solid black line) operation criteria. Drought stages are presented as normal (Stage 0; green); attention (Stage I; yellow); caution (Stage II; purple); alert (Stage III; pink); serious (Stage IV; red). Extreme drought years are circled in red.

Table 4. Evaluation of improved operation criteria of the reservoir for six multi-purpose dams on April 1.

Reservoir	Andong-Imha						Hapcheon					
Volume (10^6m^3)	'94	'95	'01	'09	'14	'15	'94	'95	'01	'09	'14	'15
1	801.9	399.2	727.7	461.8	704.1	802.7	285.5	177.4	314.4	171.7	294.7	443.6
2	1,416.3	891.0	1,530.9	907.0	1,231.3	1,193.9	409.7	222.8	563.6	207.2	411.3	370.8
3	614.4	491.8	803.2	445.2	527.2	391.2	124.2	45.4	249.2	35.5	116.6	-72.8
Reservoir	Miryang						Gunwi					
Volume (10^6m^3)	'94	'95	'01	'09	'14	'15	'94	'95	'01	'09	'14	'15
1	-	-	9.2	32.3	30.6	43.4	-	-	-	-	7.6	27.7
2	-	-	3.8	20.0	46.1	67.6	-	-	-	-	5.8	22.0
3	-	-	-5.4	-12.3	15.5	24.2	-	-	-	-	-1.8	-5.7
Reservoir	Buhang						Total					
Volume (10^6m^3)	'94	'95	'01	'09	'14	'15	'94	'95	'01	'09	'14	'15
1	-	-	-	-	17.6	22.1	1,087.4	576.6	1,051.3	665.8	1,054.6	1,357.5
2	-	-	-	-	18.6	18.9	1,931.8	1,010.0	2,087.6	1,056.2	1,685.9	1,640.4
3	-	-	-	-	1.0	-3.2	844.4	433.4	1,036.3	390.4	631.3	282.9

1: Past operations; 2: Improvement operations; 3 : 2 - 1

As a result of calculating the additionally secured water volumes by applying the improved reservoir operation criteria, the maximum additional water volume of all multi-purpose dams in Nakdong River was 1.36 billion m^3 in 2001. For Andong-Imha Dam, the maximum additional water volume was 803.2 million m^3 in 2001. Hapcheon Dam was found to have secured an additional 249.2

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million m^3 in the same year. However, the additional water volume decreased for Miryang, Gunwi, and Buhang Dams. This is likely because advanced reductions at the time of the rain forecast as well as decision-making issues through the discussion of related agencies during the period of limited water supply, were not reflected.

4. Discussion and Conclusion

In this study, the water supply criteria for multi-purpose dams were adjusted to prevent water shortages. The criteria were improved to avoid the existing operation criteria, which are dependent on the past flood season inflow in multi-purpose dams, to prepare for future dam water shortages in advance, and to store the maximum water supply through appropriate limitation of the water supply in case of a drought. The improved adjustment criteria were applied to multi-purpose dams in the Nakdong River basin to analyze their effects and to calculate the additional water volumes secured by employing the new criteria. Below are the major conclusions of this study.

For preemptive responses in multi-purpose dams in case of a drought, the setting of standard water volume lines was reinforced. The dam supply amount (actual dam demand) and dam inflow amount (stochastic 500-year simulated inflow amount) were modified, and dam-dam or river-dam link operations were considered. Securing the standard water volume lines by season was set as the reduction criterion, and the minimum response time (15 days) was set to prevent the drought stage adjustment owing to the rapid changes in the water volume.

Action plans were reinforced so that preemptive water storage measures would be possible when the water volumes of multi-purpose dams enter the drought stage. The total available amount of water is reduced in the caution (Stage II) stage, agricultural water is practically reduced in the alert stage (i.e., a 20% reduction for April–June and a 30% reduction for July–September in Stage III), and domestic and industrial water is practically reduced (i.e., 20% reduction) in the serious stage (Stage IV).

Water volumes under the past operation criteria were compared with those under the improved reservoir operation criteria. Surplus was analyzed by comparing the current daily inflow with the average daily inflow for multi-purpose dams in the Nakdong River Basin where the adjusted water supply criteria were applied. Consequently, the long period of the inflow reduction significantly decreased the water volumes and the water volumes could be additionally secured when the improved reservoir operation criteria were applied in cases of drought.

For each dam, the water volumes of April 1, when the usage of agricultural water increases, were compared for 1994–1995, 2001, 2009, and 2014–2015 when there were serious droughts. Additionally, the water volumes of all multi-purpose dams in Nakdong River were compared. It was found that the water volume of 433.4 million m^3 to 1.36 billion m^3 was additionally secured. However, further research is required to develop accurate criteria because the artificial operations of dam operators, such as advanced discharge at the time of rain forecast and the discharge amount control according to the dam group operation, are not reflected in this study. The application of the water supply adjustment criteria to prevent water shortages at multi-purpose dams in the future is expected to contribute to the stability of the water supply through the storage of the required water in advance of droughts, as well as the adjustment of the water supply during periods of drought.

Acknowledgments: This work is funded by the Ministry of Land, Infrastructure and Transport grant number 18AWMP-B083066-05 through the Korea Agency for Infrastructure Technology Advancement (KAIA).

Conflicts of Interest: The author declares no conflict of interest.

References

1. Kang, B.M. Occurrence of agriculture drought and effort of conquest. *J Disaster Prev.* **2015**, *17*, 47–57.
2. K-water. *Handbook of Dam Operation Working-level*; Kwater, Korea, 2016b.
3. MLTM *Development of Technology for Water Surface Connection Based on Groundwater Resources for Drought Response*; Ministry of Land, Infrastructure and Transport (MOLIT), Korea, 2017.

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4. Kang, N.; Kim, Y.O.; Jung, E.S.; Park, J. Applicability of Robust Decision Making for a Water Supply Planning under Climate Change Uncertainty. *J. Clim. Change Res.* **2013**, *4*, 11–26.
5. Kang, M.G.; Park, S.W. Assessment of additional water supply capacity using a reservoir optimal operation model. *J. Korea Water Resources Association* (KWRA) **2005**, *38*, 937–946.
6. Lee, S.H., and Kang, T.U. An evaluation method of water supply reliability for a dam by firm yield analysis. *Journal of Korea Water Resources Association* (KWRA) **2006**, *39*(5), 467–478.
7. Lee, D.R., Moon, J.W., and Choi, S.J. Performance Evaluation of Water Supply for a Multi-purpose Dam by Deficit-Supply Operation. *J. Korea Water Resour. Assoc.* (KWRA) **2014**, *47*(2), 195–206.
8. Cha, S.H., and Park K.B. A Study on Estimate of Evaluation Indices of Water Supply Capacity for Multipurpose Dam. *J. Environ. Sci.* **2004**, *13*(3), 197–204.
9. Nam, W.H., and Choi, J.Y. Development of Operation Rules in Agricultural Reservoirs using Real-Time WaterLevel and Irrigation Vulnerability Index. *J. Korean Soc. Agricult. Eng*. **2013**, *55* (6), 77–85.
10. Yu, J.S., Shin, J.Y., Kwon, M., and Kim, T.W. Bivariate Drought Frequency Analysis to Evaluate Water Supply Capacity of Multi-Purpose Dam. *J. Korean Soc. Civil Eng.* (JKSCE) **2017**, *37*(1), 231–238.
11. No. S.H., Jung, K.S., Park, J.H., and Ryoo, K.S. Water Supply Change Outlook for Geum River Basin Considering RCP Climate Change Scenario. *J. Korea Water Resour. Assoc.* **2013**, ı(5), 505–517.
12. Choi, S.G. Evaluation of Available Water Resources of Multi-purpose Dam according to Climate Change Scenarios and Research on Optimal Reservoir Operation, Ajou University Press 2013, Ajou University, Korea.
13. MLTM. *National Water Resources Plan (2011 ~2020)*; Ministry of Land, Infrastructure and Transport (MOLIT), Korea, 2011.
14. K-water. *Practical Manual of Dam Operation;* K-water, Korea, 2016a.

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