Utilizing inactive storage in a dam reservoir during extreme drought periods

Utilisation du stockage inactif dans le réservoir d'un barrage pendant les périodes de sécheresse extrême

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Abstract. The purpose of this study is to suggest a structural plan for improving the utilization of inactive storage in dam reservoirs, to mitigate extreme drought. Inactive storage in the dam is composed of emergency storage and dead storage. The emergency storage can be used in emergencies such as drought. But, in general, the dead storage for sedimentation is not used, even in an emergency. Therefore, we developed a methodology to determine how the dead storage space can be partially used during extreme drought periods when the sedimentation has not occurred yet. We call this partial space in a dam reservoir "drought storage". An accurate analysis of sediment levels needs to be performed before calculating drought storage, and so the present sediment level in the dam reservoir was estimated using SED-2D linked with the RMA-2 model of SMS. After considering the additional available storage capacity based on the estimated sediment level, drought storage was finally determined. We also predicted future sediment levels after 100 years and suggest the amount of drought storage available in the future. As a result, we found that the available drought storage will be lower in the future compared to present drought storage, due to the gradual increase in reservoir sedimentation over time in the dam. Further research may be needed to effectively reduce sedimentation in order to increase the drought storage capacity.

Résumé. L'objectif de cette étude est de proposer un plan structurel pour améliorer l'utilisation du stockage inactif dans les réservoirs des barrages, afin d'atténuer la sécheresse extrême. Le stockage inactif dans le barrage est

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composé d'un stockage d'urgence et d'un stockage mort. Le stockage d'urgence peut être utilisé dans des situations d'urgence telles que la sécheresse. Mais en général, le stockage mort pour la sédimentation n'est pas utilisé, même en cas d'urgence. Nous avons donc développé une méthodologie pour déterminer comment l'espace de stockage mort peut être partiellement utilisé pendant les périodes de sécheresse extrême où la sédimentation n'a pas encore eu lieu. Nous appelons cet espace partiel dans un réservoir de barrage « stockage de sécheresse ». Une analyse précise des niveaux de sédiments doit être effectuée avant de calculer le stockage de sécheresse. Le niveau actuel de sédiments dans le réservoir du barrage a donc été estimé à l'aide de SED-2D lié au modèle RMA-2 du SMS. Après avoir considéré la capacité de stockage supplémentaire disponible sur la base du niveau estimé des sédiments, le stockage de sécheresse a finalement été déterminé. Nous avons également prédit les niveaux de sédiments futurs après 100 ans. Nous suggérons également la quantité de stockage de sécheresse disponible à l'avenir. Ainsi, nous avons constaté que le stockage de sécheresse disponible sera plus faible à l'avenir par rapport au stockage de sécheresse actuel, en raison de l'augmentation progressive de la sédimentation du réservoir au fil du temps dans le barrage. Des recherches supplémentaires pourraient être nécessaires pour réduire efficacement la sédimentation afin d'augmenter la capacité de stockage de sécheresse.

1 Introduction

Climate change and abnormal weather conditions across the globe have recently led to an increase in the number of natural disasters, such as droughts and floods. Dams are one of the methods that can be used to address and mitigate problems involving limited water and flood control. Dams provide a reasonable way to manage these ever-increasing water problems, and provide new water resources, so that water resource utilization rates can be further improved. However, building new dams is difficult for various reasons, such as the limited number of suitable areas available for the construction of new dams, disparities in water resource consumption between regions, and social conflicts arising from different issues, such as environmental conservation. Against this backdrop, various measures have been proposed for existing dams, but most of them have been limited to flood control. Less attention has been paid to water use applications, and this has led to inadequate preparations for water shortages and drought. The available water resources in Korea total 75.3 billion m^3 on an annual basis, which is about 58% of the total annual amount of water resources, at 127.9 billion m^3. The failure to store a sufficient amount of water using dams or other means in the summer can lead to disruptions of water supply during drought periods, such as winter and spring (MOLIT, 2011). Notably, in Korea, the intensity of drought has been gradually on the rise, and recent extreme droughts have brought significant hardship. All these events should be a wake-up call for better preparedness and response.

Among previous studies on dam projects to address droughts, Hashimoto et al. (1982) examined and evaluated how deficient or satisfactory a water supply was during a specific period of time, how quickly the system was able to return to the satisfactory state after it became unsatisfactory, and how severe actual water shortage events were, especially with regards to reliability, resilience, and vulnerability. These indexes are frequently used in Korea as well to reexamine existing dams, but the method has limitations when evaluating the degree of damage caused by water shortages, e.g., extreme droughts, beyond safety criteria, because they are based on the statistical analysis of water shortage events.

Kelly et al. (1986) examined alternative measures to respond to urgent water shortages caused by extreme droughts, where reservoir operation methods are modified. They investigated, for example, introducing water supply lending systems, integrating reservoir storage, and modifying the minimum discharge volume and business purposes. USACE (1996) proposed long-term reservoir operation rules in an attempt to implement water supply, by considering the amount of storage and inflow during dam operation.

Long-term reservoir operating rules include the Standard Operation Policy (SOP), the hedging rule, and pack rule. In drought periods, dams in Korea have been operated under these rules as well. Also, Kull (2006) studied the cause of the lowered level of Lake Victoria, located between Uganda and Egypt. They attributed it to the integrated operation of the Nalubbale Dam and Kiira Dam coupled with droughts. Lee et al. (2012) examined an approach where the reservoir storage of existing multi-purpose dams was used as an emergency water supply source based on water supply indexes. Kim et al. (2014) conducted a water budget analysis of the Chungju Dam based on rainfall-runoff simulation results, using climate modeling data to evaluate water use efficiency. As a result, it was predicted that drought risks would increase in June, the month where the maximum water demand was found. In MOLIT (2016), the water supply capacities of current multi-purpose dams and water supply systems were evaluated based on the AR5 RCP scenarios in an attempt to develop a reliable water supply system that would be adaptive to climate change. Also, the concept of dam reserve rates and the implementation of optimal integrated operating systems for water supply facilities were considered.

Likewise, there have been many studies on the design and operation of dams to manage droughts, but most of them have involved non-structural measures and academic approaches only, thus failing to provide fundamental solutions. As a result, people have relied only on rainfall to relieve droughts year after year. In the current conditions, this means present dam systems and operating strategies are approaching their limit. However, raising or redeveloping existing dams to address drought issues is as difficult as building new ones, as mentioned above. This makes it necessary to find ways of implementing such tasks while minimizing social conflict and costs.

The goal of the present study was to identify measures that would make better use of the structure of dams as a way to help fight droughts, while causing the least controversy. In principle, emergency storage, which is as part of the inactive storage capacity of a dam, is supposed to be used when a drought occurs. However, this emergency storage alone cannot fully relieve drought conditions. Given that dead storage must be higher than the sediment level, the present study proposes using part of the dead storage as part of the inactive storage. This amount is called drought storage. To determine the sediment level, a tank model and RMA-2 & SED-2D models were used. Based on these models, the drought storage now and 100 years from now were estimated, respectively, and the expected overall trend in drought storage was investigated.

2 Measures to Improve the Use of Inactive Dam Storage

2.1 Overview of inactive dam storage

Inactive storage is generally defined as the volume capable of being stored in a dam, especially from the bottom of the dam to the low water level (LWL). In normal times, this space is not used for water supply purposes. The inactive storage is composed of dead storage and emergency storage. The dead storage is located below the water intake and thus cannot be normally used, while the emergency storage is located above the water intake and can be used in an emergency, such as drought (MOLIT, 2011).

In the US, the inactive storage is defined as the reservoir storage present above the dead storage level, which cannot be normally used due to operating policies or physical constraints. It is considered that this inactive storage can be discharged in abnormal conditions, such as water shortages or structural problems (US. Dept. of the Interior, 1987).

It has been reported that the inactive storage in Korea's multi-purpose dams, 2.5 billion m^3, amounted to nearly 20% of the total reservoir storage of 12.742 billion m^3 (K-water, 2017) (Table 1). It is worth noting that this figure is as large as the total reservoir storage of the Soyang-gang Dam. This makes it reasonable to seek methods that would proactively allow the use of this inactive storage in case of a drought.

Table 1. Total storage and inactive storage in multi-purpose dams, Korea.

Multi-purpose Dam	Total storage (million m^3)	Inactive storage (million m^3)	Multi-purpose Dam	Total storage (million m^3)	Inactive storage (million m^3)
Soyang-gang	2,900.00	650	Seongduck	27.9	2.2
Chungju	2,750.00	596	Bohyun-san	22	0.8
Hoengseong	86.9	13.5	Daecheong	1,490.00	450
Andong	1,248.00	248	Yongdam	815	70
Imha	595	124	Boryeong	116.9	8.2
Hapcheon	790	150	Buan	50.3	5.7
Namgang	309.2	9.5	Seomjin-gang	466	82
Miryang	73.6	3.8	Juam(main)	457	45
Gunwi	48.7	5.5	Juam(regulation)	250	20
Buhang	54.3	3.7	Jangheung	191	12
Total				12,741	2,499 (20%)

2.2 Drought storage proposal

In an effort to improve the use of dams' inactive storage during droughts, the present study newly proposes using part of the inactive storage for water supply purposes. Here, dam drought storage refers to the inactive part of the reservoir storage, which has supply facilities and plans and thus can be used in case of a drought. Conventionally, only the emergency storage portion of this inactive storage has been available for use during droughts, but the drought storage proposed in this study allow operators to use part of the dead storage as well, along with the emergency storage, when droughts occur (Table 2 & Figure 1). This concept of drought storage contradicts the general notion that dead storage cannot be used for water supply purposes. Since it is assumed that only the portion of the dead storage above the sediment level can be used, to exactly determine drought storage it is necessary to first analyze the sediment level (SL) of a dam.

Table 2. Comparison of inactive storage and drought storage.

Classification	Definition	Structure
Inactive storage	Emergency storage: Use of storage during drought Dead storage: Unavailable storage	Emergency storage + Dead storage (Emergency storage only available)
Drought storage	Usable storage in inactive storage	Emergency storage + Usable storage in dead storage

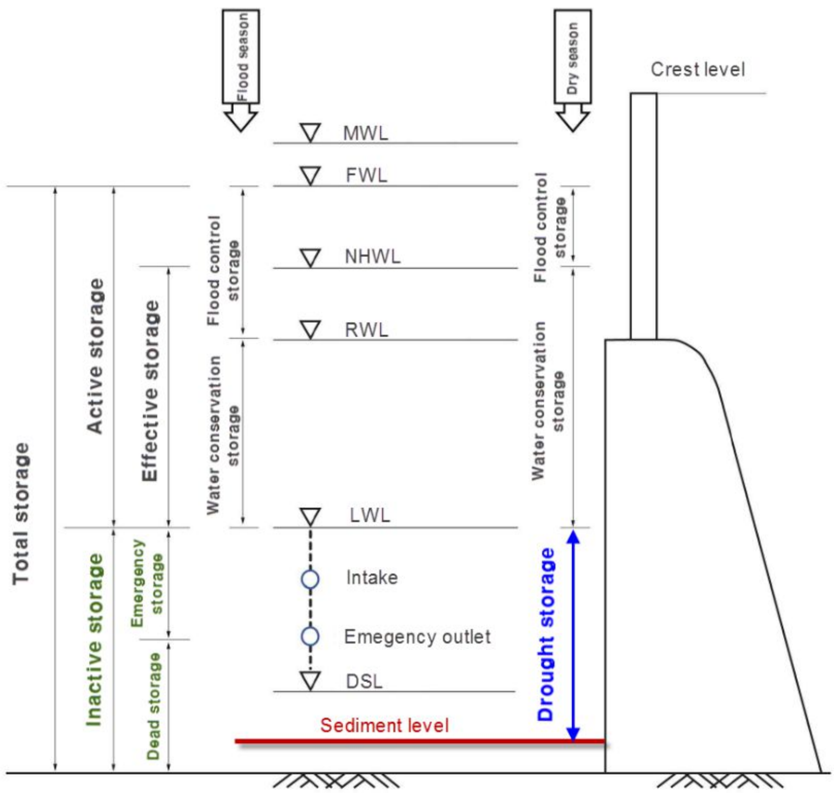


Fig. 1. Definition of drought storage in the dam.

3 Model Selection for Sediment Level Analysis

Models suitable for determining the sediment level in reservoir areas, including inundated dam areas, include HEC-6 (one dimensional) of the US Army Corps of Engineers (USACE) and RMA-2 & SED-2D models (two dimensional) related to SMS. HEC-6 is usually considered to be more effective for simply determining sediment levels because the model allows the simulation of river profile changes. However, in the present study, SMS's RMA-

2 and SED-2D models were selected and used because the models were deemed to be able to provide a better simulation of dam reservoir conditions.

4 Determination of Sediment Level and Drought storage of Dams

4.1 Selection of dams

In the present study, an analysis to determine the drought storage was conducted on the inundated areas of the Imha Dam, as shown in Figure 2. The Imha Dam is one of Korea's major multi-purpose dams, and the ninth constructed in the country. It is located about 18 km upstream of the Banbyeoncheon Stream, which merges with the Nakdong River about 347 km from the mouth of the river, as its first branch. The basin area is 1,361 km2, which accounts for about 5.8% of the Nakdong River basin. The total reservoir storage is 595.0 million m^3, the effective storage is 424.0 million m^3, the design flood level is 164.7 m, the normal high water level is 163.0 m, the low water level is 137.0 m, the emergency storage is 84.5 million m^3, and the dead storage is 40.0 m^3. The inactive storage, which is the sum of the emergency storage and dead storage, is estimated to be 124.5 million m^3 (k-water, 2017).

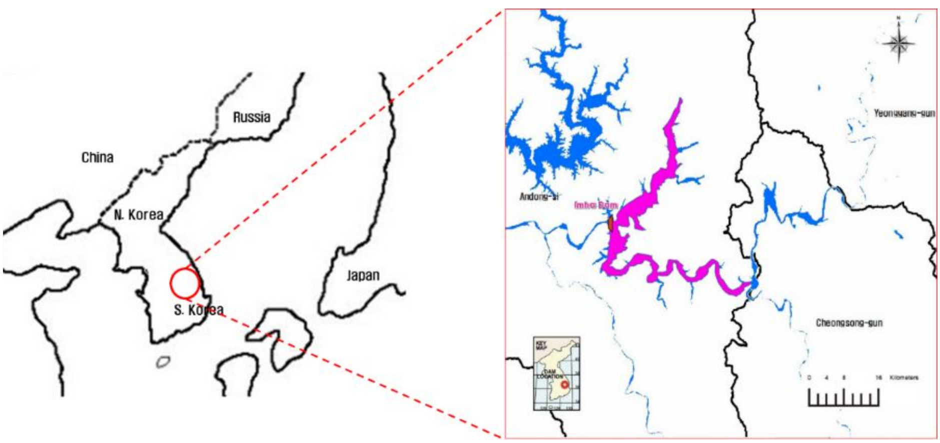


Fig. 2. Location map of the Imha dam in Korea.

4.2 Sediment level analysis for determining drought storage

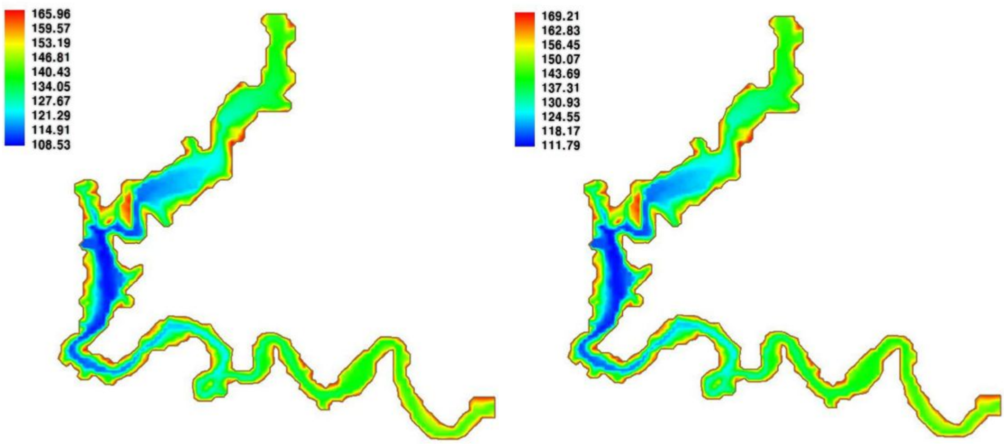
SMS's RMA-2 & SED-2D models were used to determine and analyze the sediment level of the Imha Dam. The sediment levels of most dams have been measured in previous examinations, but current data are not available. To estimate the current sediment level, the actual measurement of 110.00 EL.m was used as reference data. That measurement was obtained during the second sediment survey (2007). The parameters used were corrected and calibrated based on the data obtained from 1995 to 1997 during the first sediment survey of the Imha Dam (1995). Data measured after the year 2007 were also collected and used. All of the data used here were based on existing survey data. The reservoir inflow was referenced to the daily reservoir runoff data obtained from 2008 to 2017. The sediment concentration was estimated using a streamflow-sediment relationship obtained from the *Wolpo* area near the Imha Dam, based on the daily reservoir runoff data obtained during the same period (MOLIT, 2002) (Eq. 5).

$$Qs = 3.7419 \times Q^{1.4292} \tag{5}$$

In practice, drought storage must be estimated after considering the sediment level, which can vary depending on the distance from the dam reservoir. However, given that the water intake is located in the main body of the dam, the present study examined only the upstream portion of the dam when estimating the sediment level, which corresponds to its typical definition. As a result, the sediment level of the dam was estimated to be about 111.21 m, as shown in Figure 3 & Table 3.

Predicting future drought storage requires predicting future sediment levels. This was accomplished using the RAM-2 & SED-2D models based on existing data. The time period was set from 2017 to 100 years from now (2117).

The future sediment level was estimated by further extending the period of the existing reservoir inflow and sediment concentration data from 2008 to 2017 by 100 years. As a result, the sediment level 100 years from now was estimated to be about 114.22 m, which is about 3.6 m higher than the current level, as shown in Figure 3 & Table 3.



(a) 2017 (b) 2117

Fig. 3. Simulated sediment level in Imha dam reservoir by RMA-2 & SED-2D model.

Table 3. Calculation of the present (2017) and future (2117) sediment levels.

Sediment level (El.m) (RMA-2 & SED-2D model)		Remark
Present (2017)	After 100 years (2117)	
111.21	114.22	Upstream of dam

4.3 Estimation and comparison of the present and future drought storage

In the present study, a drought storage concept is proposed as a way to help improve the use of existing inactive storage, estimated based on sediment level data. Storage capacity with respect to the dam's water level was determined based on the dam's dimensions and construction site. The portion of the inactive storage that can be additionally made available corresponds to the section ranging from the dead storage level (124 EL.m) to the sediment level (111.21m), i.e., part of the dead storage. Simply put, this portion, corresponding to the storage volume between the dead storage level and the sediment level, was determined to be 33.52 million m^3. The drought storage can then be estimated to be 118.02 million m^3 by adding the emergency storage of 84.5 million and the additional storage, as described above, of 33.52 million m^3 (Table 4 & Table 5).

The future drought storage volume can be determined based on the future sediment level estimated above. The portion of the inactive storage that can be additionally made available 100 years from now corresponds to the section between the dead storage level (124 EL.m) and the sediment level (114.22 m), i.e., about 8.2 million m^3, as shown in Table 5. The figure is about 25.32 million m^3 smaller than the dead storage that is currently available now.

The drought storage 100 years from now was estimated by adding the emergency storage and the portion that can be additionally available, i.e., 92.35 million m^3. Given that the sediment level of a dam tends to gradually increase over time from the moment its construction was complete, the future drought storage must always be smaller than that of the past or present. It was found that as sedimentation proceeded in the dam reservoir, the dead storage decreased, leading to a decrease in drought storage, as shown in Table 4 & Figure 4. Therefore, it is necessary to find ways to reduce the amount of sediment, for example, by dam reservoir dredging and conduct more research so that measures to further increase the drought storage can be sought. Also, water quality issues associated with the drought storage need to be examined because the drought storage portion starts from the sediment level. In addition, to make better use of the drought storage, it is necessary to find ways to take in water between the emergency outlets and the sediment level, for example, by installing portable emergency outlets.

Above all, using the drought storage is a way of making better use of existing dam structures, and this is consistent with the intent of the present study, which aimed to find ways to fight droughts in a decisive manner while minimizing social conflict and costs.

Table 4. Drought storage of the Imha Dam (2017 VS 2117).

L.W.L (EL.m)	Capacity by L.W.L (million m³)		Remarks		L.W.L (EL.m)	Capacity by L.W.L (million m³)		Remarks	
	Present (2017)	Future (2117)	Present (2017)	Future (2117)		Present (2017)	Future (2117)	Present (2017)	Future (2117)
137	118.02	92.35	L.W.L	L.W.L	120	17.97	5.0		
136	109.14	79.42			119	14.56	4.2		
135	100.65	71.23			118	11.38	3.4		
134	92.99	63.32			117	8.68	2.6		
133	85.53	55.89			116	6.25	1.8		
132	78.21	48.79			115	4.01	0.9		
131	71.54	41.97			114	2.23	-		Sediment level
130	65.13	35.53			113	1.98	-		
129	59.25	29.62			112	0.9	-		

128	53.42	23.81			111.21	-	-	Sediment level	
127	48.15	18.45			111	-	-		
126	43.05	13.32			110	-	-		
125	38.18	9.0			109	-	-		
124	33.52	8.2	D.S.L	D.S.L	108	-	-		
123	29.21	7.4			107	-	-		
122	25.23	6.6			106	-	-		
121	21.41				104.5	-	-	Bottom level	Bottom level

Table 5. Comparison of present (2017) and future (2117) drought storage in the Imha Dam.

Drought storage (million m³) (present)			**Drought storage (million m³) (after 100 years)**		
Emergency storage	Available capacity in dead storage	Total available storage	Emergency storage	Available capacity in dead storage	Total available storage
84.5	33.52	118.02	84.5	8.2	92.35

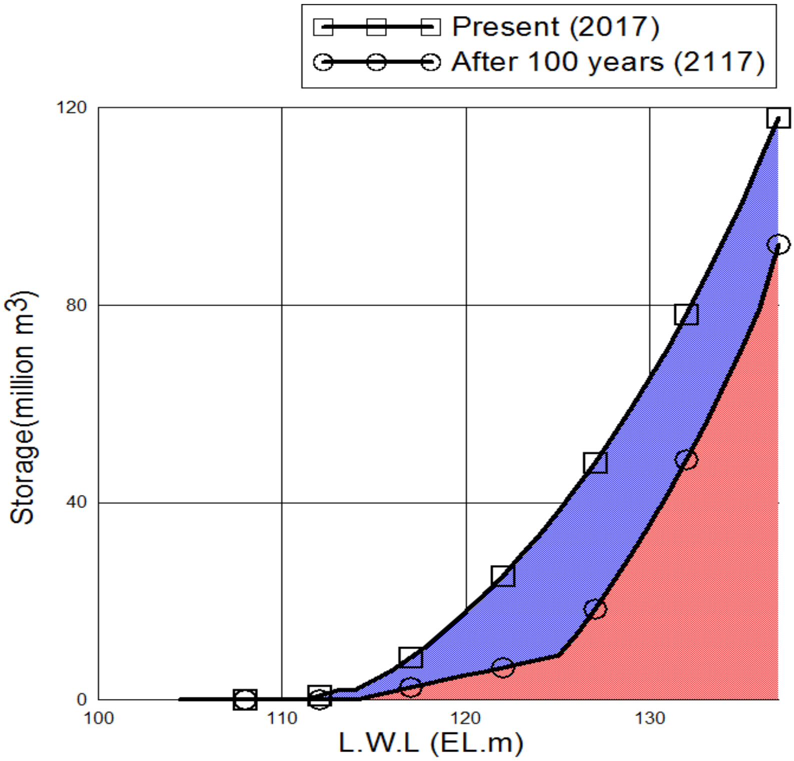


Fig. 4. Comparison of present (2017) and future (2117) drought storage in the Imha Dam.

5 Conclusions

The present study sought to find ways of make better use of the inactive storage of the Imha Dam in Korea, in an attempt to fight droughts. A new portion that can be made available for use as part of the inactive storage was proposed, i.e., drought storage. The concept of drought storage was proposed assuming that the existing inactive storage, and part of the dead storage present above the sediment level, could be used. The RMA-2 & SED-2D models were used to estimate the sediment level of the upstream portion of the dam, and the present and future drought storage were then calculated and compared. The major findings can be summarized as follows.

1) As of 2017, the portion of dead storage that can be additionally made available corresponds to the section between the dead storage level (124 EL.m) and the sediment level (111.21m), which was estimated to be 33.52 million m^3. This figure is even larger than the total reservoir storage of small-scale multi-purpose dams. The drought storage of the Imha Dam was then estimated to be 118.02 million m^3 by adding the emergency storage at 84.5 million and the additional storage, described above, of 33.52 million m^3.

2) The portion of the dead storage that could be additionally made available 100 years from now (2117) was estimated to be about 8.2 million m^3. The figure was about 25.32 million m^3 smaller than the dead storage that is currently available. The future drought storage was estimated in the same way as that for the present, by adding the emergency storage and the portion of the dead storage that could be made available, i.e., 92.35 million m^3. Given that the sediment level of a dam tends to gradually increase over time, it is necessary to find

ways to reduce the amount of sediment, for example, by dam reservoir dredging. Additional research should investigate measures to further increase the drought storage. Water quality issues associated with drought storage also need to be examined because the drought storage portion starts from the sediment level.

Thus far, many of the measures used or proposed to fight droughts have been short-term and somewhat passive solutions. As a result, people have suffered from droughts year after year, and left to rely on the arrival of rainfall to mitigate the effect of droughts. Although it may be difficult to completely eliminate the effects of droughts for various reasons, long-term and proactive countermeasures must be developed.

The concept of drought storage proposed in the present research conforms to the study's intent stated above. Lowering the dead storage level may also be considered when designing and operating dams going forward. Also, to make better use of drought storage, it is still necessary to repair existing dams, for example, by installing portable emergency outlets based on construction plans that reflect each country's actual situation.

Acknowledgments

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