On Hypsometric Curve and Morphological Analysis of The Collapsed Irrigation Reservoirs

Donghyun Kim

Inha University <https://orcid.org/0000-0002-9785-8657>

Jongsung Kim

Inha University

Wonjoon Wang

Inha University

Haneul Lee

Inha University

Myungjin Lee

Inha University

Hung Soo Kim (✉ sookim@inha.ac.kr)

Inha University

Research Letter

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On hypsometric curve and morphological analysis of the collapsed irrigation reservoirs

Donghyun Kim¹, Jongsung Kim², Wonjoon Wang¹, Haneul Lee¹, Myungjin Lee², Hung Soo
Kim^{1*}

¹ Department of Civil Engineering, Inha University, Incheon 22212, Korea

² Institute of Water Resources System, Inha University, Incheon 22212, Korea

Correspondence: Hung Soo Kim (sookim@inha.ac.kr)

Abstract

To identify the drought and flood control functions of an irrigation reservoir, research on hydrological analysis and its impact needs to be conducted. To this end, geographical characteristics, such as the cross section of the reservoir, are important, but such information is insufficient. Therefore, this study aimed to identify the topographic and morphological characteristics of reservoirs without measured data using their geographical information. In addition, an attempt was made to identify the morphological characteristics of reservoirs that had collapsed due to aging and the increased frequency of occurrence of strong rainfall intensity caused by climate change. Ten reservoirs, including the Ga-Gog Reservoir located in Miryang city, Gyeongsangnam province, South Korea with measured data, were selected as target reservoirs. The topographic information of the target reservoirs was constructed using topographical maps and GIS techniques. Based on the information, the volume (V)-area (A)-depth (H) relationship and the hypsometric curve (HC) according to the relative height (h/H) and relative area (a/A) were created. When the volume of each reservoir estimated using topographic information was compared with the measured volume, the error rate was found to be between 0.23 and 14.27%. In addition, two reservoirs that had collapsed near Miryang city were added, and the V-A-H relationship and HCs were created based on the topographic information. In addition, the morphology index, storage-area of full water-levee height relationship, and storage-area of full water relationship were analyzed to identify the morphological characteristics of the reservoirs. The analysis results showed that the collapsed reservoirs had a relatively high water depth and a large area. In addition, similar types of reservoirs were grouped by conducting cluster analysis using basic specifications, such as the reservoir watershed, storage, and area of full water. When the cluster analysis results were analyzed based on HC, the reservoirs were grouped into three shapes: convex upward shape (youthful stage), relatively flat shape (mature stage), and convex

43 downward shape (old stage). The HCs of the collapsed reservoirs exhibited the convex downward
44 shape (old stage), indicating that they were subjected to considerable erosion due to aging. In
45 other words, considerable erosion makes the allowable storage capacity insufficient due to the
46 large amount of sediment accumulated in reservoirs and reduces their flood control capacity,
47 which may cause them to collapse during heavy rainfall. Therefore, it is expected that identifying
48 the potential causes of reservoir collapse through the morphological characteristics and HCs of
49 reservoirs will support the operation and management of reservoirs for reducing flood damage.

50
51 Keywords: hypsometric curve, cluster analysis, volume(V)-area(A)-depth(H), morphology index
52

1. Introduction

The precipitation by heavy rainfall, monsoon rains, and typhoons, which occur during the summer rainy season, is stored and used in the next year. To this end, water is secured and water resources are managed through hydraulic facilities, such as dam reservoirs for various types of water and irrigation reservoirs for agriculture. Owing to the increasing variability of precipitation under the influence of climate change and an imbalance in precipitation by region, however, reservoirs are becoming more vulnerable to droughts and floods depending on the region. In particular, the flood damage caused by the collapse of irrigation reservoirs has occurred because high rainfall intensity and heavy rainfall have occurred more frequently (Kim et al, 2019). According to the National Disaster Management Research Institute, there are 16,791 reservoirs in South Korea, including 3,406 reservoirs managed by the Korea Rural Community Corporation and 13,385 reservoirs managed by local governments, and their specifications vary depending on the topographic characteristics at the time of their completion (National Disaster Management Research Institute, 2019).

To respond to drought and flood control functions, among the several functions of reservoirs, it is necessary to conduct research on hydraulic and hydrological analysis and its impact. For accurate research, basic research on the topographic and morphological characteristics of reservoirs is important. While the reservoir storage rate has been monitored and systematic management has been performed for the reservoirs managed by the Korea Rural Community Corporation, significantly insufficient management has been performed for the small irrigation reservoirs managed by local governments (Kim et al, 2020). Many of the existing irrigation reservoirs in Korea are aged more than 50 years (Hong et al., 2004; Kim et al., 2019), and they are small reservoirs with an irrigation scale of 100 ha (0.01km^2) or less. In addition, reservoirs have been inefficiently managed because management personnel are limited and considerable cost

is required (You et al., 2007). Since reservoirs located throughout the country have different shapes and characteristics, they also exhibit different damage patterns during heavy rainfall. Since the flood damage patterns of irrigation reservoirs by heavy rainfall are correlated with the topographic and physical factors of the reservoirs, it is necessary to analyze the topographic characteristics of the reservoirs and identify their morphological or physical characteristics (Graf, 1999; McDonald et al., 2012; Kim et al., 2020).

In recent years, precision measuring instruments have been used for efficient management of reservoirs through accurate specifications, such as the area by water level and the storage capacity. According to previous studies, reservoirs are measured using manned and unmanned boats equipped with GPS and water depth sensors to measure the topography, area by water level, and storage capacity in reservoirs (Chang et al., 2003; Park and Jeong., 2005; Choi and Lee., 2007; Guerrero and Lamberti., 2011; Song et al., 2018; Ilci et al., 2019). Considerable time and cost, however, are required inefficiently to measure accurate specifications, such as the area by water level and storage capacity, for all reservoirs. In addition, as reservoirs are located in mountainous areas, it is difficult for water depth measuring instruments to access them. Therefore, in this study, the depth of water and the area were obtained using topographical maps and GIS techniques. To quantitatively analyze the topographic and morphological characteristics of reservoirs using these data, an attempt was made to apply the hypsometric curve (HC), which is used for river basins, to reservoirs.

Langbein et al. (1947) utilized HC to identify the topographic characteristics of the basins in the northeastern United States. In addition, HCs were created by identifying the area by water level and the storage capacity using the topographic information of river basins, reservoirs, and wetlands, and the topographic and morphological characteristics of basins were identified and utilized as basic data (Hayashi et al, 2000; Park et al., 2000; Oertel et al., 2000; Kim et al., 2002;

Kang et al., 2005; Nam et al., 2015). For reservoirs, the morphology index and HC are important information for research on topographic characteristics, and studies that can quantitatively present topographic characteristics are also required (Takeuchi , 1997; Leonard et al., 1999; Lehner et al., 2004; Dargahi & Setegn., 2011; Li et al., 2014; Zhang et al., 2017; Lopes et al., 2018; Munar et al., 2018; Andrade et al., 2020).

If the topographic and morphological characteristics of reservoirs with the reliability of quantitative data can be identified using topographical maps and GIS techniques, it will be possible to indirectly secure topographic information on reservoirs located in mountainous or remote areas with poor accessibility. In addition, the secured topographic information can be utilized for the hydraulic and hydrological analysis and management of reservoirs.

Therefore, the purpose of this study is to construct the geometry of reservoirs using their topographic information and to evaluate its accuracy through a comparison with the measured data and volumes of the reservoirs. In addition, HCs were created for reservoirs to understand the geometry of the reservoirs and to identify the area by elevation and storage capacity. In addition, an attempt was made to quantitatively present the morphology index through relational analysis that used the basic specifications of reservoirs, such as the storage capacity and area of full water, and to group similar types of reservoirs through cluster analysis. Based on this, the topographic and morphological analysis of reservoirs that had collapsed due to flooding was conducted to identify the potential causes of collapse.

2. Research Method

2.1 The area-volume relationship for reservoirs according to the depth of water

To identify HC for a reservoir using the volume (V)-area (A)-depth (H) relationship, the geometry of the reservoir is very important. Reservoirs, however, have different geometry, and it

is not possible to accurately express the geometry of a reservoir with a cross section. In this study, it was assumed that the A-h and V-h relationships can be expressed with inverse functions. In addition, a basic mathematical theory was developed based on previous studies to induce first-order equations for these relationships. Here, it can be inferred that the A-h and V-h relationships are interdependent. Thus, based on this, the equations were induced (Hayashi et al, 2000; Kim et al, 2002).

Figure. 1 The structure of reservoir

The volume of the reservoir can be obtained by integrating the area along the water depth as shown in Eq. (1).

$$V = \int_0^h A(\eta) d\eta \quad (1)$$

where η is an arbitrary variable for water depth, V is the volume of the reservoir, h is the water depth from the lowest point of the reservoir to the water surface, h_0 is the water depth to the infinitesimal area of the reservoir, and A is the surface area of the wetland.

A is assumed to be flat and can be obtained considering the wetland slope between dh , which can be expressed as Eq. (2).

$$\frac{y}{y_0} = \left(\frac{r}{r_0}\right)^p \quad (2)$$

148

149 where y is the altitude of the ground surface corresponding to h , y_0 is the unit altitude of the
 150 ground surface, r is the radius of the wetland, r_0 is the radius of an arbitrary infinitesimal area of
 151 the wetland, and p is the shape factor for the side slope of the wetland.

152

153 Since the area is $A = \pi r^2$ if it is obtained using a conventional method without considering the
 154 slope of the reservoir, the change in area depending on the water depth is $\pi r_0^2 \propto h_0$ and $\pi r^2 \propto$
 155 h_0 . Therefore, Eq. (3) can be expressed from $h_0 \pi r^2 = h \pi r_0^2$.

156

$$\frac{r^2}{r_0^2} = \frac{h}{h_0} \quad (3)$$

158

159 In addition, from Eq. (2) and (3), the relationship of $\frac{y}{y_0} = \left(\frac{r}{r_0}\right)^p \rightarrow \left(\frac{h}{h_0}\right)^{\frac{2}{p}}$ and Eq. (4) can be
 160 inferred.

161

$$r^2 \sim \left(\frac{r}{r_0}\right)^p \pi r_0^2 \quad (4)$$

163

164 The area can be expressed using Eq. (4) as shown in Eq. (5).

165

$$A = \pi r^2 = \pi r_0^2 \left(\frac{h}{h_0}\right)^{\frac{2}{p}} \quad (5)$$

167

168 Therefore, the change in area depending on the slope can be expressed as Eq. (6).

169

170 $A = \pi r_0^2 \left(\frac{h}{h_0}\right)^{\frac{2}{p}} = S \left(\frac{h}{h_0}\right)^{\frac{2}{p}} \quad (6)$

171

172 The volume that applied the shape factor of the sloped cross section of the reservoir can be
173 expressed as Eq. (7).

174

175 $V = \int_0^h A(\eta) d\eta \quad (7)$

176

177 $A(\eta)$ can be introduced from Eq. (6), and Eq. (6) can be expressed as Eq. (8).

178

179 $V = \frac{s}{(1+2/p)} \frac{h^{1+(\frac{2}{p})}}{h_0^{2/p}} \quad (8)$

180

181 **2.2 Morphology index and equations for relationships between basic specifications**

182 **2.2.1 Morphology index**

183 The morphology index of a reservoir is quantified using the average depth and area of full water of the reservoir.
184 According to Leonard and Crouzet (1999), a morphology index of 10.5 or higher belongs to a deep lake and a
185 morphology index of 0.6 to 10.4 represents a normal lake. A morphology index of 0.5 or less is classified as a shallow
186 lake. Eq. (9) shows the morphology index applied to reservoirs.

187

188 Morphology index = $1,000 \times \text{average depth(m)} \times \text{area of full water(m}^2\text{)}^{-0.5} \quad (9)$
189

190 **2.2.2 Storage-area of full water-levee height relationship**

191 Lehner et al. (2004) estimated the storage-area of full water-levee height relationship for reservoirs and lakes in the world as
192 shown in Eq. (10), and showed that the storage is approximately 29% ($\approx 1/3.42$) of the product of the area of full water and the levee
193 height.

194

195 $\text{area of full water(m}^2\text{)} = 3.42 \times \frac{\text{storage(m}^3\text{)}}{\text{levee height(m)}} \quad (10)$
196

2.2.3 Storage-area of full water relationship

Takeuchi (1997) estimated the storage-area of full water relationship for reservoirs in the world with an area of full water of 36.1km^2 or high and a storage of 0.5km^3 or higher as shown in Eq. (11).

$$\text{storage}(10^6 \times \text{m}^3) = 9.208 \times \text{area of full water}^{1.114}(\text{km}^2) \quad (11)$$

2.3 Cluster analysis

Cluster analysis is a method of classifying data with similar characteristics into groups based on the characteristics possessed by multiple subjects. It is divided into hierarchical cluster analysis and non-hierarchical cluster analysis (Kyoung et al., 2007; Han et al., 2014; Nam et al., 2015). Representative methods for hierarchical cluster analysis include clustering methods that use the distance between data, such as shortest connection and longest connection. A representative method for non-hierarchical cluster analysis is K-means clustering. K-means cluster analysis classifies data with similar characteristics into K groups. It is a method of grouping data in the close distance from a centerpoint, which is the average of the data in each cluster. In this study, K-means cluster analysis was conducted to determine optimal clusters by minimizing the distance between data in each cluster based on the centerpoint, and the cluster analysis process was terminated at the stage where the arbitrarily defined centerpoint of each cluster could no longer minimize the error. Figure. 2 shows the concept of cluster analysis among unsupervised methods.

Figure. 2 Concept of cluster analysis

3. Target Basin Selection and HC Calculation

3.1 Target basin selection

Ten reservoirs, including the Ga-Gog Reservoir located in Miryang city, Gyeongsangnam province, were selected as target reservoirs in this study. They were measured using unmanned water depth measuring equipment by the National Disaster Management Research Institute. The total storage capacity is the height from the reservoir bottom to the full water level. Since the dead storage level could not be identified, the total storage was compared and analyzed. In this study, the reservoir data measured by the National Disaster Management Research Institute were used. The locations of the ten reservoirs, including the Ga-Gog Reservoir, are shown in Figure. 3. The names of the ten reservoirs are R(1): Ga-Gog, R(2): Nae-Gog, R(3): Dae-Gog, R(4): Sam-Son, R(5): Deog-Am, R(6): Un-Jeong, R(7): Yong-Po, R(8): O-Cho, R(9): Ga-Gog2, and R(10): U-Gog2 (Table 1).

Figure. 3 Study area

Table 1. Reservoir name

Classification	Name
R1	Ga-Gog
R2	Nae-Gog
R3	Dae-Gog
R4	Sam-Son
R5	Deog-Am
R6	Un-Jeong
R7	Yong-Po
R8	O-Cho
R9	Ga-Gog2
R10	U-Gog2

3.2 Creation of digital elevation models (DEMs) for the target reservoirs

The target reservoirs were modeled based on the digital topographic maps (1:25,000) of Miryang city, Gyeongsangnam province provided by the National Spatial Information Portal. To quantitatively identify the altitude and topographic characteristics of the reservoirs, the procedure of (1) to (6) in Figure. 4 was performed. In other words, (1) the contour line layer is extracted. (2) Watershed boundaries are added. (3) A digital topographic map is built for each reservoir watershed. (4) TIN data are generated for each reservoir watershed. (5) Numerical data are extracted. (6) Cell interval 5m X 5m DEM is created for each reservoir watershed. For the ten reservoirs, including the Ga-Gog Reservoir, topographic information was constructed using topographical maps and GIS techniques, and the location and the area by water depth were modeled for each reservoir as shown in Figure. 5.

Figure. 4 Reservoir modeling flow chart

Figure. 5 Study reservoir location and modeling

4. Characteristics Analysis according to the HCs of the Reservoirs

4.1 HC calculation

Figure. 6 shows HCs for river basins. In this study, an attempt was made to apply HC to reservoirs. HC can be mainly divided into the youthful stage, mature stage, and old stage. The youthful stage has the characteristics of a basin where the original ground surface is not significantly eroded. The mature stage has the characteristics of a basin where the ground surface is significantly eroded. The old stage has characteristics close to those of a peneplain because the ground surface is further eroded. In other words, for reservoirs, the old stage exhibits the highest level of erosion, followed by the mature stage

and youthful stage (Sarp et al., 2011). Erosion causes the allowable storage capacity to be insufficient due to the accumulated sediment in reservoirs, which reduces the flood control capacity of reservoirs and may lead to their collapse during heavy rainfall.

Figure. 6 Interpretation of Hypsometric Curve

Based on the topographic information constructed using topographical maps and GIS techniques, HC according to the relative height (h/H) and relative area (a/A) was created for each reservoir. The HC of a reservoir is created by calculating the area by elevation and then connecting the altitude of the reservoir above sea level to the cumulative area above a certain altitude. In this instance, the Y-axis was defined as the ratio of a certain height (h) to the total height of the reservoir watershed (H) and X-axis as the ratio of the cumulative area (a) above a certain height (h) to the total area of the reservoir watershed (A). In other words, the relative height was set to h/H and the relative area to a/A . Since h/H and a/A are relative values for each reservoir watershed, the volume and area were calculated for each reservoir while h was increased from zero by 0.5 m.

Tables 2, 3, 4, and 5 show the area and volume according to the change in h for each reservoir. For the reservoirs, the A-h relationship curves are shown in Figure. 7 and the V-h relationship curves in Figure. 8. In addition, HC was created for each reservoir using the a/A and h/H ratios (Figure. 9). A comparison with the volumes of the reservoirs measured using unmanned water depth measuring equipment by the National Disaster Management Research Institute revealed that the error rate ranged from 0.23 to 14.27% and the average error rate was 5.03% (Table 6).

4.2 Analysis of the morphological characteristics of the reservoirs

To identify the characteristics of the reservoirs, the morphology index and the storage-area of full water-levee height relationship used by Leonard and Crouzet (1999) and Lehner et al. (2004) were utilized. Leonard and Crouzet (1999) quantified the morphology index for a reservoir using the average depth and area of full water of the reservoir. In this study, the average morphology index of the ten reservoirs, including the Ga-Gog Reservoir, was found to be approximately 4.36, and thus they were classified as normal lakes. The R3, R4, R5, R7, R8, R9, and R10 reservoirs exhibited low morphology index values, indicating that they had lower depths compared to other reservoirs. The morphology index results also showed that the R1, R2, and R6 reservoirs had high depths.

Lehner et al. (2004) estimated the relationship for reservoirs and lakes in the world. In this study, the storage-area of full water-levee height relationship was analyzed for the target reservoirs and the relationship between the storage and the product of the area of full water and the levee height was derived as shown in Eq. (12).

$$\text{area of full water}(m^2) = 3.98 \times \frac{\text{storage}(m^3)}{\text{levee height}(m)} \quad (12)$$

The analysis results showed that the R3, R4, R5, R7, R8, R9, and R10 reservoirs had a relatively smaller area of full water compared to the R1, R2, and R6 reservoirs.

Takeuchi (1997) estimated the relationship between the area of full water and the storage for reservoirs in the world with an area of full water of 36.1 km^2 or higher and a storage of 0.5 km^3 or higher. In this study, the relationship was analyzed for reservoirs in Korea and Eq. (13) was derived.

$$\text{storage}(10^6 \times m^3) = 2.63 \times \text{area of full water}^{1.114}(km^2) \quad (13)$$

The results of the storage-area of full water relationship showed that the R3, R4, R5, R7, R8, R9, and R10 reservoirs had a relatively smaller storage compared to the R1, R2, and R6 reservoirs (Table. 7).

Table 2. Area according to the change in reservoir height, Measurement

h(m)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
	A(m ²)									
0	0	0	0	0	0	0	0	0	0	0
0.5	1,012	59	4,033	1,488	107	7	18	1,073	53	4,299
1	1,542	227	5,000	4,177	2,554	151	3,385	1,704	1,467	6,950
1.5	2,088	433	5,350	5,510	3,767	1,060	11,230	2,330	2,071	8,360
2	2,634	809	5,670	6,180	5,020	3,053	14,660	2,984	2,628	9,020
2.5	3,164	1,646	5,960	6,760	6,390	6,310	16,560	3,679	3,151	9,640
3	3,694	3,402	6,220	7,360	7,770	10,370	18,380	4,332	3,752	10,270
3.5	4,477	6,260	6,300	7,920	9,030	14,330	20,290	5,880	4,354	10,910
4	5,260	7,870		8,480	10,200	17,230	20,760	6,690	4,910	11,550
4.5	5,905	9,080		9,030	11,190	20,840		7,270	5,480	12,210
5	6,550	10,230		9,580	12,130	25,910		7,830	6,010	12,590
5.5	7,235	11,250		10,150	12,990	30,470		8,440	6,560	
6	7,920	12,180		10,970	13,690	34,170		9,170	7,180	
6.5	8,720	12,950			14,410	38,610		10,050	7,730	
7	9,520	13,600			15,470	42,050		10,880	8,240	
7.5	10,190	14,210				45,860		11,650	8,760	
8	10,860	14,810				48,400		12,460	9,230	
8.5	11,620	15,410				50,700				
9	12,380	16,040				53,100				
9.5	13,190	16,670				56,600				
10	14,000	17,340				58,500				
10.5	14,705	18,110				60,300				
11	15,410	19,030				62,100				
11.5	16,195	19,890				64,000				
12	16,980	20,700				65,900				
12.5	17,860	21,420				66,800				
13	18,740	22,090								
13.5	19,720	22,530								
14	20,700									
14.5	21,715									
15	22,730									
15.5	23,845									
16	24,960									
16.5	26,135									
17	27,310									
17.5	28,510									
18	29,710									
18.5	31,070									

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Table 3. Area according to the change in reservoir height, Estimation

h(m)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
	A(m ²)									
0	0	0	0	0	0	0	0	0	0	0
0.5	1,012	59	4,029	1,484	107	7	18	1,030	53	4,084
1	1,542	227	4,995	4,164	2,549	151	3,375	1,635	1,466	6,603
1.5	2,088	432	5,345	5,493	3,759	1,059	11,196	2,236	2,069	7,942
2	2,634	807	5,664	6,161	5,010	3,050	14,616	2,864	2,625	8,569
2.5	3,164	1,643	5,954	6,740	6,377	6,304	16,510	3,531	3,148	9,158
3	3,694	3,395	6,214	7,338	7,754	10,360	18,325	4,158	3,748	9,757
3.5	4,477	6,247	6,294	7,896	9,012	14,316	20,229	5,644	4,350	10,365
4	5,260	7,854		8,455	10,180	17,213	20,698	6,422	4,905	10,973
4.5	5,905	9,062		9,003	11,168	20,819		6,979	5,475	11,600
5	6,550	10,210		9,551	12,106	25,884		7,516	6,004	11,961
5.5	7,235	11,228		10,120	12,964	30,440		8,102	6,553	
6	7,920	12,156		10,937	13,663	34,136		8,803	7,173	
6.5	8,720	12,924			14,381	38,571		9,648	7,722	
7	9,520	13,573			15,439	42,008		10,444	8,232	
7.5	10,190	14,182				45,814		11,184	8,751	
8	10,860	14,780				48,352		11,961	9,221	
8.5	11,620	15,379				50,649				
9	12,380	16,008				53,047				
9.5	13,190	16,637				56,543				
10	14,000	17,305				58,442				
10.5	14,705	18,074				60,240				
11	15,410	18,992				62,038				
11.5	16,195	19,850				63,936				
12	16,980	20,659				65,834				
12.5	17,860	21,377				66,733				
13	18,740	22,046								
13.5	19,720	22,485								
14	20,700									
14.5	21,715									
15	22,730									
15.5	23,845									
16	24,960									
16.5	26,135									
17	27,310									
17.5	28,510									
18	29,710									
18.5	31,070									

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Table 4. Volume according to the change in reservoir height, Measurement

h(m)	R(1)	R(2)	R(3)	R(4)	R(5)	R(6)	R(7)	R(8)	R(9)	R(10)
	V(m ³)									
0	0	0	0	0	0	0	0	0	0	0
0.5	843	14	1,109	342	9	1	3	333	14	1,397
1	2,081	139	4,742	2,719	891	51	1,497	1,555	790	6,468
1.5	3,866	485	8,021	7,072	3,698	696	10,084	3,268	2,724	12,631
2	6,209	1,223	11,296	11,456	7,337	3,393	24,337	5,633	4,793	18,684
2.5	9,074	3,032	14,828	15,916	12,380	10,065	37,152	8,729	7,339	24,725
3	12,447	7,496	18,575	20,898	18,904	22,101	50,314	12,497	10,493	31,358
3.5	16,873	16,764	19,969	26,434	26,628	38,903	65,352	18,484	14,348	38,654
4	22,541	28,048		32,472	35,287	57,597	71,632	25,894	18,713	46,605
4.5	28,638	37,883		39,047	44,598	78,995		32,248	23,585	55,242
5	35,061	47,985		46,153	54,452	108,694		38,656	28,955	61,628
5.5	42,251	58,748		53,863	64,935	145,179		45,719	34,819	
6	50,239	69,939		64,733	75,638	182,608		53,887	41,495	
6.5	59,322	81,296			86,689	223,799		63,618	48,756	
7	69,586	92,527			102,040	268,195		74,511	56,214	
7.5	80,121	103,870				314,278		85,839	64,090	
8	90,831	115,645				360,545		98,851	72,050	
8.5	102,621	127,982				403,833				
9	115,560	141,053				448,935				
9.5	129,512	154,882				501,878				
10	144,515	169,540				555,358				
10.5	159,743	185,581				602,910				
11	175,119	203,713				651,780				
11.5	191,684	223,206				703,008				
12	209,500	242,931				756,668				
12.5	228,725	262,618				791,556				
13	249,429	282,162								
13.5	271,720	297,392								
14	295,672									
14.5	320,869									
15	347,338									
15.5	375,627									
16	405,814									
16.5	437,629									
17	471,118									
17.5	506,008									
18	542,319									
18.5	584,400									

307

308

309

Table 5. Volume according to the change in reservoir height, Estimation

h(m)	R(1)	R(2)	R(3)	R(4)	R(5)	R(6)	R(7)	R(8)	R(9)	R(10)
	V(m ³)									
0	0	0	0	0	0	0	0	0	0	0
0.5	252	15	1,007	371	27	2	4	258	13	1,021
1	1,273	143	4,512	2,824	1,328	79	1,696	1,333	759	5,343
1.5	2,714	494	7,755	7,243	4,731	907	10,928	2,904	2,651	10,908
2	4,708	1,240	11,009	11,655	8,769	4,109	25,812	5,101	4,694	16,511
2.5	7,226	3,063	14,523	16,126	14,234	11,692	38,908	7,996	7,217	22,159
3	10,256	7,557	18,252	21,116	21,198	24,995	52,253	11,536	10,344	28,372
3.5	14,256	16,875	21,888	26,660	29,341	43,182	67,469	17,156	14,171	35,212
4	19,416	28,203		32,702	38,383	63,057	81,854	24,134	18,509	42,674
4.5	25,046	38,061		39,279	48,031	85,572		30,154	23,354	50,787
5	31,044	48,178		46,385	58,183	116,758		36,240	28,696	58,900
5.5	37,795	58,952		54,095	68,942	154,890		42,953	34,533	
6	45,329	70,149		63,170	79,880	193,726		50,717	41,179	
6.5	53,918	81,509			91,142	236,298		59,966	48,409	
7	63,648	92,739			104,371	282,028		70,325	55,839	
7.5	73,691	104,079				329,333		81,108	63,686	
8	83,947	115,848				376,663		92,582	71,888	
8.5	95,253	128,178				420,754				
9	107,676	141,242				466,633				
9.5	121,093	155,062				520,554				
10	135,542	169,710				574,925				
10.5	150,249	185,740				623,076				
11	165,136	203,861				672,527				
11.5	181,184	223,342				724,350				
12	198,453	243,053				778,621				
12.5	217,097	262,724				828,546				
13	237,186	282,249								
13.5	258,826	300,583								
14	282,091									
14.5	306,586									
15	332,337									
15.5	359,873									
16	389,269									
16.5	420,269									
17	452,920									
17.5	486,960									
18	522,408									
18.5	560,528									

Table 6. Reservoir volume comparison and results

Classification	Measurement(m^3)	Estimation(m^3)	Error rate(%)
R1	584,400	560,528	4.26
R2	297,392	300,583	1.07
R3	19,969	21,888	9.61
R4	64,733	63,170	2.47
R5	102,040	104,371	2.28
R6	791,556	828,546	4.67
R7	71,632	81,854	14.27
R8	98,851	92,582	6.77
R9	72,050	71,888	0.23
R10	61,628	58,900	4.63

Figure. 7 A-h relationship curve

Figure. 8 V-h relationship curve

Figure. 9 Hypsometric curves at 10 locations including Ga-Gog Reservoir

Table 7. Analysis of the results of reservoir morphological characteristics

Classification	Value (Leonard, 1999)	Classification	Value (Lehner, 2004)	Classification	Value (Takeuchi, 1997)
R1	5.70	R1	1.45	R1	3.65
R2	5.38	R2	1.08	R2	3.05
R3	3.76	R3	2.09	R3	1.30
R4	2.00	R4	17.87	R4	0.86
R5	2.78	R5	4.23	R5	1.36
R6	13.18	R6	0.61	R6	11.32
R7	1.75	R7	1.85	R7	0.95
R8	2.60	R8	6.86	R8	1.17
R9	4.29	R9	1.69	R9	1.71
R10	2.19	R10	2.11	R10	0.98

4.3 Analysis of reservoir characteristics through cluster analysis

To identify the characteristics of the reservoirs with different specifications, cluster analysis was conducted using the basic specifications of each reservoir. As shown in Table 8, the specifications of the ten reservoirs, including the Ga-Gog Reservoir, were used as input data. The input data included the basin area, useful capacity, area of full water, levee height, levee length, permissible area, area irrigated, and frequency of drought.

Table 8. Basic specifications of 10 places including Ga-Gog Reservoir

Classification	Basin area (m^2)	Useful capacity ($1,000m^3$)	Area of full water (m^2)	Levee height (m)	Levee length (m)	Permissible area (ha)	Area irrigated (ha)	Frequency of drought (year)
R(1)	1,500,000	480	31,070	12.5	84	35	28	1
R(2)	530,000	280	22,530	6.2	172	8.7	8.7	10
R(3)	600,000	28.9	6,300	8.5	101	10	6	1
R(4)	1,100,000	35.4	10,970	18	170	36.6	25	1
R(5)	1,750,000	82.1	15,470	12.5	130	47	12	10
R(6)	2,250,000	349	66,800	10	207	67.9	40.6	10
R(7)	1,020,000	80	20,760	6.3	180	28.1	23.1	1
R(8)	400,000	55.4	12,460	14.1	140	14	9	10
R(9)	410,000	58.2	9,230	10.2	112	10.4	8	10
R(10)	580,000	47.3	12,590	7.6	241	42.2	15	1

As shown in Figure. 10, the cluster analysis classified the reservoirs into two groups: group (I) with reservoirs whose useful capacity and area of full water were large, including R1, R2, and R6, and group (II) with reservoirs whose useful capacity and area of full water were small, including R3, R4, R5, R7, R8, R9, and R10. The results of conducting cluster analysis using the basic specifications of the reservoirs showed that the reservoirs could be classified based on the useful capacity and area of full water, which were identified as indicators that were more influential than other basic specifications in the cluster analysis process.

Figure. 10 Cluster analysis result

4.4 Morphological analysis of the collapsed reservoirs using cluster analysis and HC

HC and the cluster analysis method were applied to reservoirs that had collapsed and caused damage in the past. The reservoirs were located near Miryang city, Gyeongsangnam province, and only the recent damage cases were applied. The Sandae Reservoir located in Gyeongju city, Gyeongsangbuk province, which collapsed in 2013, has an area of full water of $49,200 \text{ m}^2$, a useful capacity of 194.4 thousand m^3 , a levee height of 12.2 m, and a levee length of 210 m. The Goeyeon Reservoir located in Yeongcheon city, Gyeongsangbuk province, which collapsed in 2014, has an area of full water of $61,000 \text{ m}^2$, a useful capacity of 61.42 thousand m^3 , a levee height of 5.5 m, and a levee length of 160 m. In this study, HC and cluster analysis were applied to the Sandae and Goeyeon Reservoirs, which are located near the ten target reservoirs and caused damage in the past.

The morphology index was found to be 11.65 for the Sandae Reservoir and 26.68 for the Goeyeon Reservoir. These high morphology index values indicate that the reservoirs are deeper compared to other reservoirs. The results of the storage-area of full water-levee height relationship were found to be 1.13 for the Sandae Reservoir and 2.26 for the Goeyeon Reservoir, indicating that they had a larger area of full water than other reservoirs. The results of the storage-area of full water relationship were 6.15 for the Sandae Reservoir and 8.87 for the Goeyeon Reservoir, indicating that they had larger storage than other reservoirs.

Cluster analysis was conducted using the specifications of the ten target reservoirs as well as the Sandae (11) and Goeyeon (12) Reservoirs as input data. The cluster analysis classified the reservoirs into three groups: group (I) with the R3, R4, R5, R7, R8, R9, and R10 reservoirs whose area of full water and useful capacity were relatively small; group (II) with the R1, R2, and R6 reservoirs whose area of full water and useful capacity were relatively large; and group (III) with the Sandae (11) and Goeyeon Reservoirs whose area of full water and useful capacity were largest (Figure. 11).

To identify the characteristics of each group, the morphological characteristics of the reservoirs were investigated using their HCs. It was found that group (I) had the original ground surface not significantly eroded and group (II) had the original ground surface significantly eroded. Group (III) had the original ground surface further eroded (Figure. 11).

The Sandae and Goeyeon Reservoirs that collapsed had the larger storage and area than the other reservoirs, and the HC results showed that considerable erosion occurred in their watersheds. In other words, the Sandae and Goeyeon Reservoirs had insufficient allowable storage capacity compared to other reservoirs.

Figure. 11 Cluster analysis result using collapsed reservoir

Figure. 12 Altitude distribution curve result using collapsed reservoir

5. Conclusion

In this study, the geometry of unmeasured reservoirs was constructed using their topographic information, and morphological analysis was conducted for them. The hypsometric curve (HC) was created for each reservoir to understand their geometry and identify the area by elevation and storage capacity. In addition, the morphology index was quantitatively presented through the analysis of the storage-area of full water relationship for each reservoir. The topographic and morphological analysis of reservoirs that had collapsed due to aging, insufficient management, and flooding were analyzed to identify the potential causes of collapse.

- (1) The area by elevation and volume were calculated for ten reservoirs located in Miryang city, Gyeongsangnam province, including the Ga-Gog Reservoir, using digital topographic maps. When the results were compared with the volumes of the reservoirs measured by the National Disaster Management Research Institute, the error rate ranged from 0.23 to 14.27%. The error rate was excellent as its average value was approximately 5.03%. In addition, HC was created for each reservoir using the area by elevation and volume.
- (2) Cluster analysis was conducted to classify similar types of reservoirs into groups using basic specifications, such as the basin area, useful capacity, and area of full water. The cluster analysis classified the reservoirs into two groups: the R1, R2, and R6 reservoirs whose useful capacity and area of full water were large and the R3, R4, R5, R7, R8, R9, and R10 reservoirs whose useful capacity and area of full water were small. The useful capacity and area of full water were identified as indicators that had a larger impact on the cluster analysis results than the other specifications.
- (3) When the results of the morphology index, storage-area of full water-levee height relationship, and storage-area of full water

relationship were comprehensively examined, it was found that the R3, R4, R5, R7, R8, R9, and R10 reservoirs had a relatively lower depth and a relatively smaller area of full water compared to the R1, R2, and R6 reservoirs.

- (4) HC and the cluster analysis method were applied to reservoirs that had collapsed and caused damage in the past. The cluster analysis classified these reservoirs and the ten target reservoirs into three groups: group (I), group (II), and group (III). The HCs of the collapsed reservoirs exhibited the convex downward shape compared to other normal reservoirs, indicating that they were significantly aged. In other words, the collapsed reservoirs were subjected to considerable erosion.

Each reservoir has different basic specifications, such as the area of full water and storage capacity. If the geometry of reservoirs is understood and the common characteristics of similar types of reservoirs are classified and identified using morphological analysis and HC, they are expected to be used as measures to reduce the damage caused by the collapse of reservoirs. It will be possible to reduce damage through proactive disaster management if the potential causes of reservoir collapse can be identified before the occurrence of the disaster.

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