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On Hypsometric Curve and Morphological Analysis of the Collapsed Irrigation Reservoirs

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Abstract: The impact of irrigation reservoirs requires investigation through hydrological analysis to identify the flood control functions of these reservoirs. However, there is insufficient information concerning important geographical, morphological, and topographic characteristics, such as the reservoir cross-section. Therefore, this study aimed to identify the morphological and topographic characteristics of reservoirs using geographical information instead of measurement data. Ten reservoirs, including the Ga-Gog reservoir located in Miryang City, South Korea, were selected. The topographic information of the reservoirs was obtained using topographic maps and GIS techniques. Based on this information, the volume (V)-area (A)-depth (H) relationship and the hypsometric curve (HC) according to the relative area (a/A) and relative height (h/H) were created. A comparison of the reservoir volume, estimated using topographic information, with the measured volume revealed an error rate between 0.23% and 14.27%. In addition, two collapsed reservoirs located near Miryang City were investigated by creating V-A-H relationships and HCs using topographic information. The morphological characteristics of the reservoirs were identified by analyzing the (1) morphology index, (2) full water storage area-levee height relationship, and (3) full water storage area relationship. The analysis results showed that the collapsed reservoirs had high water depth and a large area relative to other reservoirs. Similar types of reservoirs were grouped by conducting a cluster analysis using basic properties such as the basin area, storage, and levee height. The cluster analysis results, based on HC analysis, grouped the reservoirs into three shapes: convex upward (youthful stage), relatively flat (mature stage), and convex downward (old stage). The HCs of the collapsed reservoirs exhibited a convex downward shape, indicating that they were subjected to considerable erosion due to aging. Moreover, this considerable erosion caused a large quantity of sediment to accumulate in the reservoirs, resulting in an insufficient allowable storage capacity of the reservoir because the flood control capacity was reduced, which may have led to their collapse during heavy rainfalls. Therefore, the identification of potential causes of reservoir collapse through the morphological characteristics and HCs of reservoirs are expected to support the operation and management of reservoirs to reduce flood damage.

Keywords: hypsometric curve; cluster analysis; volume (V)-area (A)-depth (H); morphology index

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1. Introduction

During the summer rainy season, water from precipitation in the form of heavy rainfall and typhoons is stored for use in the following year. In this way the water supply is secured, and water resources are managed through hydraulic facilities such as dam reservoirs that provide water and irrigation reservoirs for agriculture [1–5]. The influence of climate change is observed through the increased variability of precipitation and an imbalance in precipitation by region. Consequently, reservoirs in different regions are becoming more vulnerable to either droughts or floods. In particular, flood damage caused by the collapse of irrigation reservoirs occurs because rainfall is more frequent and has an increased rainfall intensity [6].

According to the National Disaster Management Research Institute, there are 16,791 reservoirs in South Korea, including 3406 reservoirs managed by the Korea Rural Community Corporation and 13,385 reservoirs managed by local governments. These reservoirs, having individual properties, vary depending on their topographic characteristics at time of completion [7].

Research on the hydraulic and hydrological analyses of reservoirs and their impact are necessary to implement drought and flood control, which is a function of reservoirs. Basic research on the topographic and morphological characteristics of reservoirs is important for accurate research [8]. While reservoir storage rates are monitored and the systematic management of reservoirs is maintained by the Korea Rural Community Corporation, there is insufficient supervision of small irrigation reservoirs that are managed by local governments. Many of the existing irrigation reservoirs in Korea are more than 50 years old [6,9], and these are small reservoirs with irrigation scales of 100 ha (0.01 km^2) or less. In addition, reservoirs have been inefficiently managed because of limited management personnel and considerable cost requirements [10]. Reservoirs, located in different parts of the country, exhibit different damage patterns during heavy rainfall events and have different shapes and characteristics. The flood damage patterns of irrigation reservoirs due to heavy rainfall are correlated to the topographic and physical factors of the reservoirs. Therefore, it is necessary to analyze the topography of the reservoirs and identify their morphological and physical characteristics [8,11,12].

Precision measuring instruments have been used in recent years to efficiently manage reservoirs by accurately quantifying properties such as area by water depth and the storage capacity. According to previous studies, manned and unmanned boats equipped with GPS and water depth sensors are used to measure the topography (area by water depth) and storage capacity of reservoirs [13–18]. However, these accurate reservoir property measurements, such as the area and storage capacity, necessitate considerable time and cost. In addition, as reservoirs are located in mountainous areas, access is a challenge for water depth-measuring equipment. Therefore, in this study, the water depth and area were obtained using topographic maps and GIS techniques. Using these data, an attempt was made to apply the hypsometric curve (HC), normally used for river basins, to quantitatively analyze the topographic and morphological characteristics of reservoirs.

Langbein et al. [19] used the HC to identify the topographic characteristics of basins in the northeastern United States. In addition, HCs were created by identifying the area by water depth, and the storage capacity using reservoir topographic information; thus, the topographic and morphological characteristics of these basins were identified and used as basic data [20–23]. The morphology index and HC are important information for researching reservoir topographic characteristics, and studies are required to quantitatively investigate topographic characteristics [24–31].

Should reservoir topographic and morphological characteristics be reliably identified through quantitative data obtained from topographic maps and GIS techniques, topographic information on reservoirs located in mountainous or remote areas with poor accessibility could be indirectly obtained. In addition, the topographic information obtained could be used for hydraulic and hydrological analyses, and for reservoir management.

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

2. Methodology and Material

2.1. Study Area

Ten reservoirs were selected for this study, including the Ga-Gog reservoir located in Miryang City, Gyeongsangnam Province. The total storage capacity was defined as the height from the bottom of the reservoir to full water level. As the dead storage levels could not be identified, the total storage volumes were compared and analyzed. The locations of the ten reservoirs, including the Ga-Gog Reservoir, are shown in Figure 1. 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.

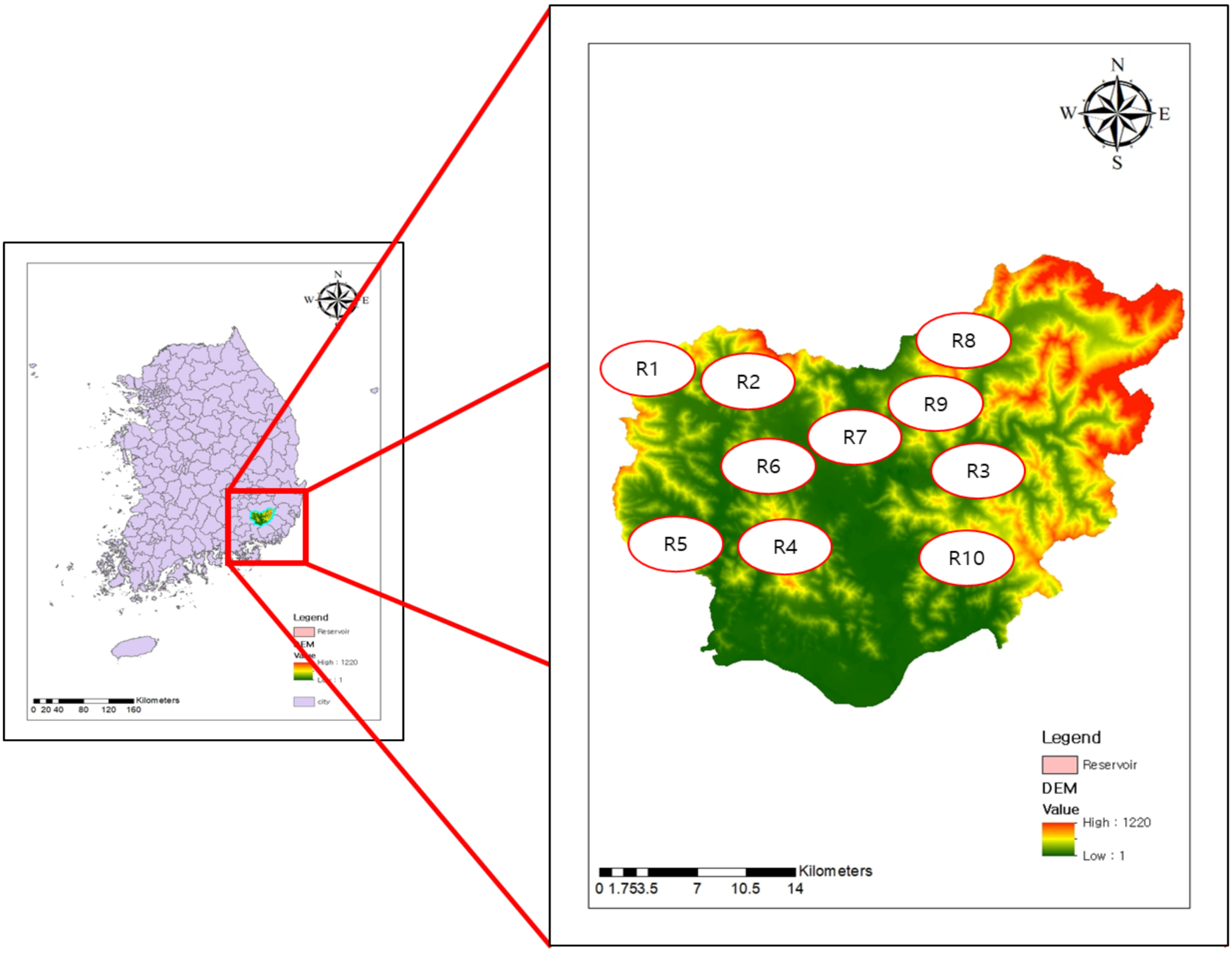

Figure 1. Study area and locations of 10 reservoirs including the Ga-Gog reservoir in Miryang city, Gyeongsangnam province.

2.2. The Area-Volume Relationship of Reservoirs According to the Depth of Water

The geometry of a reservoir (Figure 2) is very important to identify the HC of the reservoir using the volume (V)-area (A)-depth (H) relationship. However, reservoirs differ in geometry, and therefore 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 could be expressed using inverse functions. In addition, a basic mathematical theory was developed based on previous studies to derive first-order equations for these relationships. Thus, it was inferred that the A-h and V-h relationships were interdependent. Based on this, the following equations were derived [20,22].

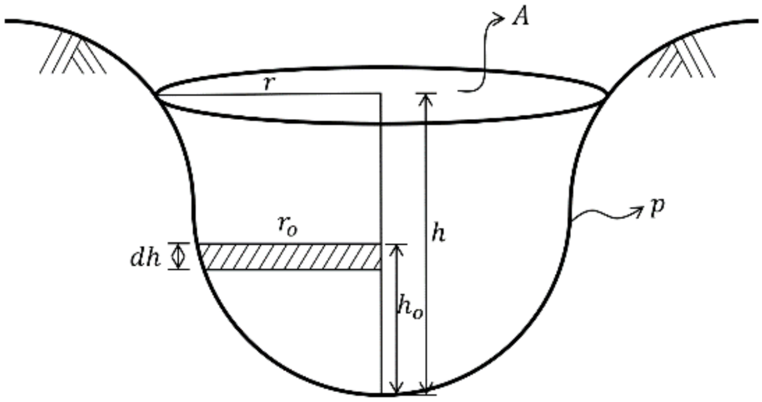

Figure 2. The Structure of a reservoir.

The reservoir volume was obtained by integrating the area along the water depth, as shown in Equation (1).

$$V = \int_0^h A(\eta)d\eta \tag{1}$$

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 wetland surface area. It was assumed that A was flat and was obtained by considering the wetland slope between dh, which is expressed as Equation (2).

$$\frac{y}{y_o} = (\frac{r}{r_0})^p \tag{2}$$

where y is the altitude of the ground surface corresponding to h, y_0 is the unit altitude of the ground surface, r is the radius of the wetland, r_0 is the radius of an arbitrary infinitesimal area of the wetland, and p is the shape factor of the side slope of the wetland. Because the area obtained using conventional methods, without considering the slope of the reservoir is $A = \pi r^2$, the change in area when factoring in water depth is $\pi r_0^2 \propto h_0$ and $\pi r^2 \propto h_0$. Therefore, Equation (3) is expressed as $h_0 \pi r^2 = h \pi r_0^2$.

$$\frac{r^2}{r_0^2} = \frac{h}{h_0} \tag{3}$$

In addition, the relationship of $\frac{y}{y_0} = (\frac{r}{r_0})^p \rightarrow (\frac{h}{h_0})^{\frac{2}{p}}$ is derived from Equations (2) and (3), and Equation (4) is inferred.

$$r^2 \sim (\frac{r}{r_0})^p \pi r_0^2 \tag{4}$$

Using Equation (4), the area is expressed as shown in Equation (5):

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

Therefore, the change in area with regards the slope is expressed by Equation (6).

$$A = \pi r_0^2 (\frac{h}{h_0})^{\frac{2}{p}} = S(\frac{h}{h_0})^{\frac{2}{p}} \tag{6}$$

The volume that factors in the shape of the sloped cross-section of the reservoir is expressed in Equation (7).

$$V = \int_0^h A(\eta)d\eta \tag{7}$$

Using $A(\eta)$, obtained from Equations (6) and (7), Equation (8) is derived.

$$V = \frac{S}{(1+2/p)} \frac{h^{1+(\frac{2}{p})}}{h_0^{2/p}} \tag{8}$$

2.3. Morphology Index and Equations for the Relationships between Basic Properties

2.3.1. Morphology Index

The morphology index of the reservoir was quantified using the average depth and full water area of the reservoir. According to Leonard and Crouzet [25], a morphology index of 10.5 or higher is considered a deep lake while a morphology index of 0.6 to 10.4 is considered a normal lake. A morphology index of 0.5 or less is classified as a shallow lake. Equation (9) shows the morphology index applied to reservoirs.

$$\text{Morphology index} = 1000 \times \text{average depth}(\text{m}) \times \text{area of full water}\left(\text{m}^2\right)^{-0.5} \tag{9}$$

2.3.2. Full Water Storage Area-Levee Height Relationship

Lehner et al. [26] estimated the storage area of the full water-levee height relationship for reservoirs and lakes worldwide, as shown in Equation (10), and showed that the storage was approximately 29% (=1/3.42) of the product of the full water area and the levee height.

$$\text{area of full water}\left(\text{m}^2\right) = 3.42 \times \frac{\text{storage}\left(\text{m}^3\right)}{\text{level height}(\text{m})} \tag{10}$$

2.3.3. Full Water Storage Area Relationship

Takeuchi [24] estimated the full water storage area relationship for reservoirs worldwide with a full water area of 36.1 km^2 or high and a storage of 0.5 km^3 or higher as shown in Equation (11).

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

2.4. Cluster Analysis

Cluster analysis is a method for classifying data with similar characteristics into groups based on the characteristics of multiple subjects. This method is divided into hierarchical and non-hierarchical cluster analysis [23,32,33]. A representative method for hierarchical cluster analysis uses the distance between data points, such as the shortest and longest connections. A representative method for nonhierarchical cluster analysis is k-means clustering. The K-means cluster analysis classifies data with similar characteristics into K groups. This method groups data that are a short distance from a central point, providing the average data in each cluster. In this study, K-means cluster analysis was conducted to determine the optimal clusters by minimizing the distances between the data in each cluster and the central point; the cluster analysis process was terminated when the arbitrarily defined central point of each cluster could no longer minimize the error. Figure 3 illustrates the concept of cluster analysis.

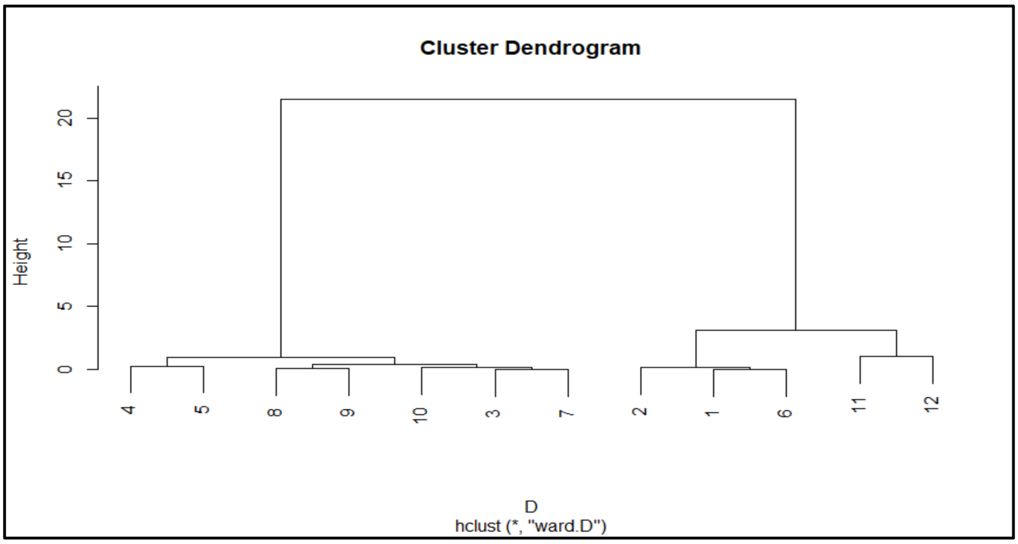

Figure 3. Concept of cluster analysis.

3. Results

3.1. Data Description

Models of the reservoirs were based on digital topographic maps (1:25,000) of Miryang City, Gyeongsangnam Province, which were provided by the National Spatial Information Portal. Procedures (1)–(6), as shown in Figure 4, were executed to quantitatively identify the altitude and topographic characteristics of the reservoirs. These procedures included: (1) contour line layer extraction, (2) the addition of watershed boundaries, (3) construction of a digital topographic map for each reservoir watershed, (4) generation of TIN data for each watershed, (5) numerical data extraction, and (6) the creation of a 5 × 5 m cell interval for each reservoir watershed. Topographic information was constructed for the ten reservoirs using topographic maps and GIS techniques, and the location and area by water depth were modeled for each reservoir (Figure 5).

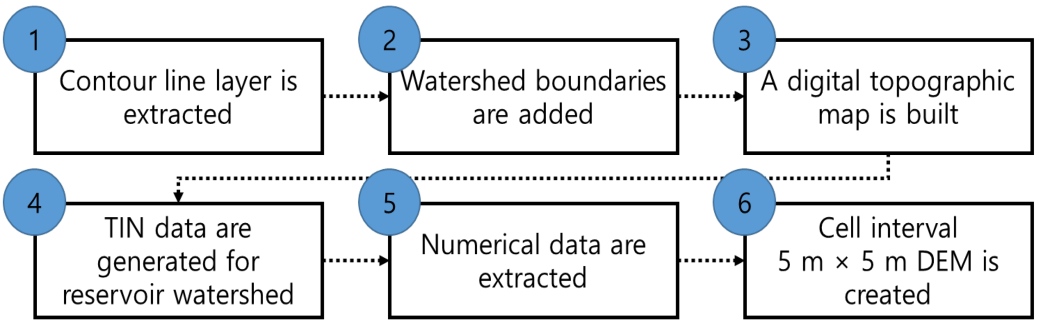

Figure 4. Reservoir modeling flow chart. To quantitatively identify the altitude and topographic characteristics of the reservoirs, procedures (1)–(6) were performed.

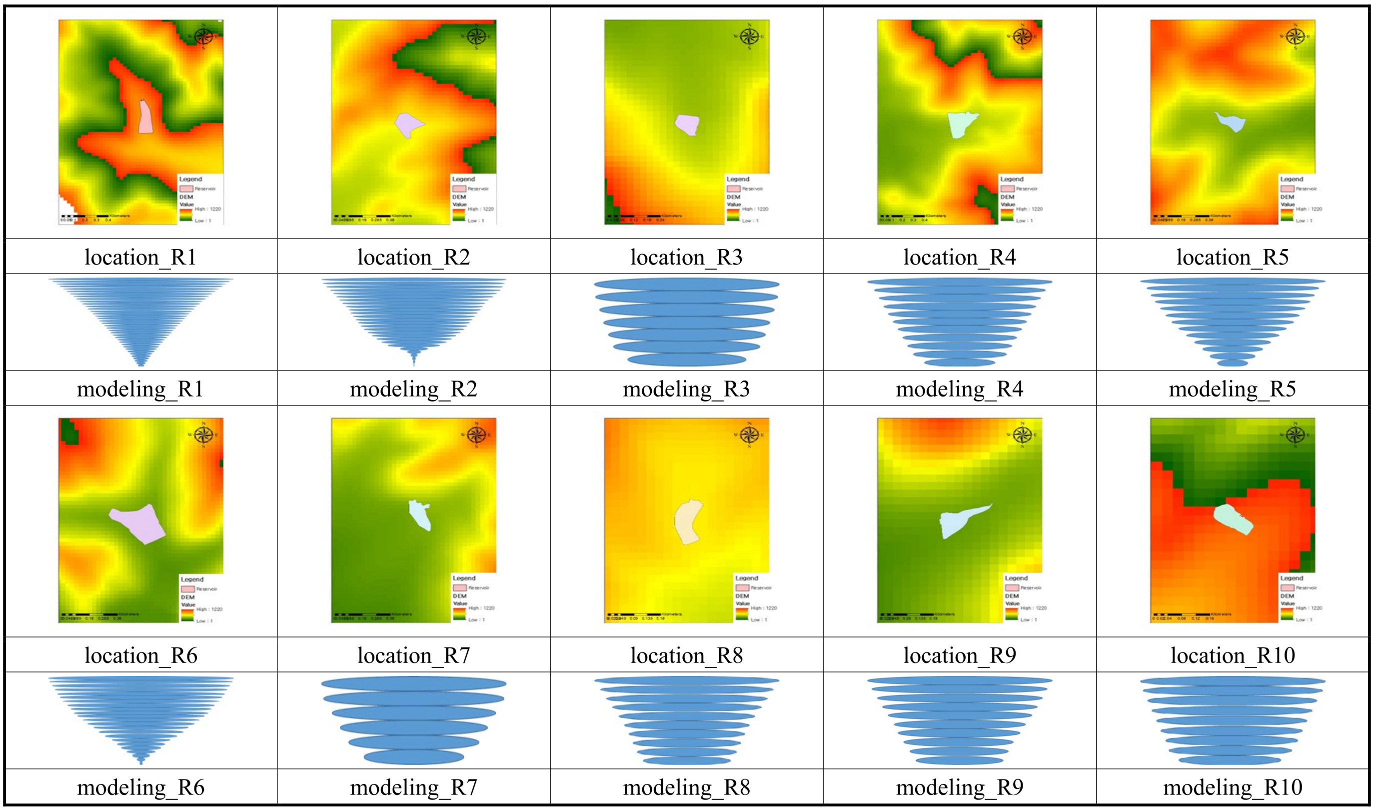

Figure 5. Locations and modelling of the reservoirs: For the ten reservoirs, including the Ga-Gog Reservoir, topographic information was constructed using topographical maps and GIS techniques. Also, the location and the area in water depth were modeled for each reservoir.

3.2. Estimation of the Area-Volume Relationship of a Reservoir According to the Water Depth

In this study, the application of HCs to reservoirs was attempted. HCs are divided into youthful, mature, and old stages (Figure 6). The youthful stage has the characteristics of a basin in which the original ground surface is not significantly eroded. The mature stage has the characteristics of a basin in which the ground surface is significantly eroded. The old stage has characteristics close to those of a peneplain because the ground surface is substantially eroded. In other words, for reservoirs, the old stage exhibits the highest level of erosion, followed by the mature and youthful stages [34]. Erosion causes reservoirs to have insufficient allowable storage capacity because the accumulated sediment in the reservoirs reduces the flood control capacity and may lead to their collapse during heavy rainfall events.

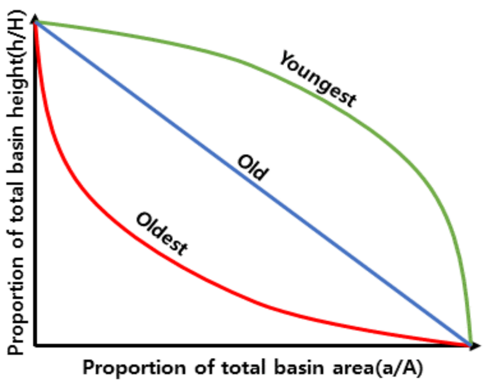

Figure 6. Interpretation of Hypsometric Curve. HC is divided into the youthful, mature, and old stages.

A HC according to the relative height (h/H) and relative area (a/A), was determined for each reservoir based on the topographic information constructed using topographic maps and GIS technique. The HC of a reservoir was 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 the X-axis as the ratio of the cumulative area (a) above a certain height (h) to the total area of the reservoir watershed (A). Thus, the relative height was reflected by h/H and the relative area by a/A. Because h/H and a/A are relative values for each reservoir watershed, the volume and area for each reservoir were calculated as h increased from zero in 0.5 m increments. Tables 1–4 show the area and volume according to the change in h for each reservoir.

Table 1. Area measurements according to the change in reservoir height.

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	1012	59	4033	1488	107	7	18	1073	53	4299
1.0	1542	227	5000	4177	2554	151	3385	1704	1467	6950
1.5	2088	433	5350	5510	3767	1060	11,230	2330	2071	8360
2.0	2634	809	5670	6180	5020	3053	14,660	2984	2628	9020
2.5	3164	1646	5960	6760	6390	6310	16,560	3679	3151	9640
3.0	3694	3402	6220	7360	7770	10,370	18,380	4332	3752	10,270
3.5	4477	6260	6300	7920	9030	14,330	20,290	5880	4354	10,910
4.0	5260	7870		8480	10,200	17,230	20,760	6690	4910	11,550
4.5	5905	9080		9030	11,190	20,840		7270	5480	12,210
5.0	6550	10,230		9580	12,130	25,910		7830	6010	12,590
5.5	7235	11,250		10,150	12,990	30,470		8440	6560	
6.0	7920	12,180		10,970	13,690	34,170		9170	7180	
6.5	8720	12,950			14,410	38,610		10,050	7730	
7.0	9520	13,600			15,470	42,050		10,880	8240	
7.5	10,190	14,210				45,860		11,650	8760	
8.0	10,860	14,810				48,400		12,460	9230	
8.5	11,620	15,410				50,700				
9.0	12,380	16,040				53,100				
9.5	13,190	16,670				56,600				
10.0	14,000	17,340				58,500				
10.5	14,705	18,110				60,300				
11.0	15,410	19,030				62,100				
11.5	16,195	19,890				64,000				
12.0	16,980	20,700				65,900				
12.5	17,860	21,420				66,800				
13.0	18,740	22,090								
13.5	19,720	22,530								

Table 1. *Cont.*

h(m)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
	A(m^2)									
14.0	20,700									
14.5	21,715									
15.0	22,730									
15.5	23,845									
16.0	24,960									
16.5	26,135									
17.0	27,310									
17.5	28,510									
18.0	29,710									
18.5	31,070									

Table 2. Area estimations according to the change in reservoir height.

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	1012	59	4029	1484	107	7	18	1030	53	4084
1.0	1542	227	4995	4164	2549	151	3375	1635	1466	6603
1.5	2088	432	5345	5493	3759	1059	11,196	2236	2069	7942
2.0	2634	807	5664	6161	5010	3050	14,616	2864	2625	8569
2.5	3164	1643	5954	6740	6377	6304	16,510	3531	3148	9158
3.0	3694	3395	6214	7338	7754	10,360	18,325	4158	3748	9757
3.5	4477	6247	6294	7896	9012	14,316	20,229	5644	4350	10,365
4.0	5260	7854		8455	10,180	17,213	20,698	6422	4905	10,973
4.5	5905	9062		9003	11,168	20,819		6979	5475	11,600
5.0	6550	10,210		9551	12,106	25,884		7516	6004	11,961
5.5	7235	11,228		10,120	12,964	30,440		8102	6553	
6.0	7920	12,156		10,937	13,663	34,136		8803	7173	
6.5	8720	12,924			14,381	38,571		9648	7722	
7.0	9520	13,573			15,439	42,008		10,444	8232	
7.5	10,190	14,182				45,814		11,184	8751	
8.0	10,860	14,780				48,352		11,961	9221	
8.5	11,620	15,379				50,649				
9.0	12,380	16,008				53,047				
9.5	13,190	16,637				56,543				
10.0	14,000	17,305				58,442				
10.5	14,705	18,074				60,240				
11.0	15,410	18,992				62,038				

Table 2. *Cont.*

h(m)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
	A(m^2)									
11.5	16,195	19,850				63,936				
12.0	16,980	20,659				65,834				
12.5	17,860	21,377				66,733				
13.0	18,740	22,046								
13.5	19,720	22,485								
14.0	20,700									
14.5	21,715									
15.0	22,730									
15.5	23,845									
16.0	24,960									
16.5	26,135									
17.0	27,310									
17.5	28,510									
18.0	29,710									
18.5	31,070									

Table 3. Volume measurements according to the change in reservoir height.

h(m)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
	V(m^3)									
0	0	0	0	0	0	0	0	0	0	0
0.5	843	14	1109	342	9	1	3	333	14	1397
1.0	2081	139	4742	2719	891	51	1497	1555	790	6468
1.5	3866	485	8021	7072	3698	696	10,084	3268	2724	12,631
2.0	6209	1223	11,296	11,456	7337	3393	24,337	5633	4793	18,684
2.5	9074	3032	14,828	15,916	12,380	10,065	37,152	8729	7339	24,725
3.0	12,447	7496	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
4.0	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
5.0	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	
6.0	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	
7.0	69,586	92,527			102,040	268,195		74,511	56,214	
7.5	80,121	103,870				314,278		85,839	64,090	
8.0	90,831	115,645				360,545		98,851	72,050	
8.5	102,621	127,982				403,833				
9.0	115,560	141,053				448,935				
9.5	129,512	154,882				501,878				

Table 3. *Cont.*

h(m)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
	V(m^3)									
10.0	144,515	169,540				555,358				
10.5	159,743	185,581				602,910				
11.0	175,119	203,713				651,780				
11.5	191,684	223,206				703,008				
12.0	209,500	242,931				756,668				
12.5	228,725	262,618				791,556				
13.0	249,429	282,162								
13.5	271,720	297,392								
14.0	295,672									
14.5	320,869									
15.0	347,338									
15.5	375,627									
16.0	405,814									
16.5	437,629									
17.0	471,118									
17.5	506,008									
18.0	542,319									
18.5	584,400									

Table 4. Volume estimations according to the change in reservoir height.

h(m)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
	V(m^3)									
0	0	0	0	0	0	0	0	0	0	0
0.5	252	15	1007	371	27	2	4	258	13	1021
1.0	1273	143	4512	2824	1328	79	1696	1333	759	5343
1.5	2714	494	7755	7243	4731	907	10,928	2904	2651	10,908
2.0	4708	1240	11,009	11,655	8769	4109	25,812	5101	4694	16,511
2.5	7226	3063	14,523	16,126	14,234	11,692	38,908	7996	7217	22,159
3.0	10,256	7557	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
4.0	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
5.0	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	
6.0	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	
7.0	63,648	92,739			104,371	282,028		70,325	55,839	

Table 4. *Cont.*

h(m)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
	V(m^3)									
7.5	73,691	104,079				329,333		81,108	63,686	
8.0	83,947	115,848				376,663		92,582	71,888	
8.5	95,253	128,178				420,754				
9.0	107,676	141,242				466,633				
9.5	121,093	155,062				520,554				
10.0	135,542	169,710				574,925				
10.5	150,249	185,740				623,076				
11.0	165,136	203,861				672,527				
11.5	181,184	223,342				724,350				
12.0	198,453	243,053				778,621				
12.5	217,097	262,724				828,546				
13.0	237,186	282,249								
13.5	258,826	300,583								
14.0	282,091									
14.5	306,586									
15.0	332,337									
15.5	359,873									
16.0	389,269									
16.5	420,269									
17.0	452,920									
17.5	486,960									
18.0	522,408									
18.5	560,528									

A comparison with the reservoir volumes 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 5). In addition, a HC was created for each reservoir using the a/A and h/H ratios (Figure 7).

Table 5. Reservoir volume comparison and results.

Classification	Measurement (m^3)	Estimation (m^3)	Error Rate (Measurement Estimation)	Error Rate (Measurement Estimation)
R1	584,400	560,528	4.08%	4.26%
R2	297,392	300,583	−1.07%	−1.06%
R3	19,969	21,888	9.61%	−8.77%
R4	64,733	63,170	2.41%	2.47%
R5	102,040	104,371	−2.28%	−2.23%
R6	791,556	828,546	−4.67%	−4.46%

Table 5. *Cont.*

Classification	Measurement (m^3)	Estimation (m^3)	Error Rate (Measurement Estimation)	Error Rate (Measurement Estimation)
R7	71,632	81,854	−14.27%	−12.49%
R8	98,851	92,582	6.34%	6.77%
R9	72,050	71,888	0.22%	0.23%
R10	61,628	58,900	4.43%	4.63%

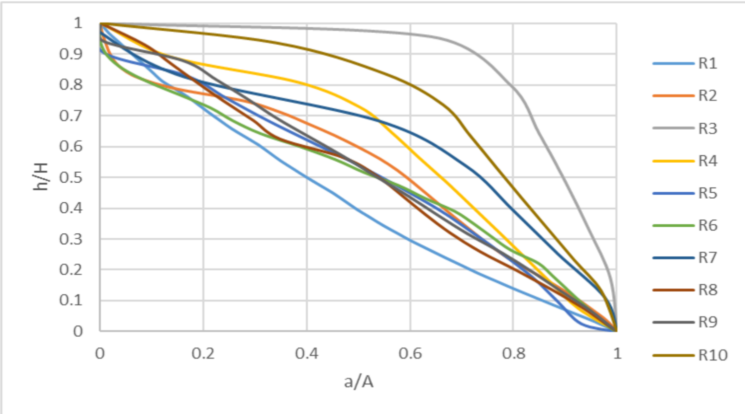

Figure 7. Hypsometric curves for ten reservoirs created using the A-h and V-h relationship curves.

3.3. Analysis of the Morphological Characteristics of the Reservoirs

To identify the characteristics of the reservoirs, the morphology index and full water storage area-levee height relationship used by Leonard and Crouzet (1999) and Lehner et al. (2004) were used. Leonard and Crouzet (1999) quantified the morphology index of a reservoir using the average depth and area of the reservoir at full water. In this study, the average morphology index of the ten reservoirs was found to be approximately 4.36; 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 than other reservoirs. In addition, the morphology index results revealed that reservoirs R1, R2, and R6 were deep lakes.

Lehner et al. (2004) proposed a relationship between reservoirs and lakes. In this study, the storage area of the full water-levee height relationship for the reservoirs was analyzed. Furthermore, the relationship between the storage, and the product of the area at full water and levee height was derived as shown in Equation (12).

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

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

Takeuchi (1997) estimated the relationship between the full water area and the reservoir storage worldwide with a full water area 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 Equation (13) was derived.

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

The results of the full water storage area relationship revealed that the R3, R4, R5, R7, R8, R9, and R10 reservoirs had a smaller storage relative to that of the R1, R2, and R6 reservoirs (Table 6).

Table 6. Analysis of the results of reservoir morphological characteristics.

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

3.4. Analysis of Reservoir Characteristics through Cluster Analysis

Cluster analysis was conducted, using the basic properties of each reservoir, to identify the reservoir characteristics with different properties. As shown in Table 7, the properties of the ten reservoirs were used as input data. The input data included the basin area, useful capacity, full water area, levee height, levee length, permissible area, irrigated area, and drought frequency.

Table 7. Basic properties of ten reservoirs.

Classification	Basin Area (km^2)	Useful Capacity (1000 m^3)	Full Water Area (m^2)	Levee Height (m)	Levee Length (m)	Permissible Area (ha)	Area Irrigated (ha)	Frequency of Drought (Year)
R1	1.5	480	31,070	12.5	84	35	28	1
R2	0.5	280	22,530	6.2	172	8.7	8.7	10
R3	0.6	28.9	6300	8.5	101	10	6	1
R4	1.1	35.4	10,970	18	170	36.6	25	1
R5	1.7	82.1	15,470	12.5	130	47	12	10
R6	2.2	349	66,800	10	207	67.9	40.6	10
R7	1.0	80	20,760	6.3	180	28.1	23.1	1
R8	0.4	55.4	12,460	14.1	140	14	9	10
R9	0.4	58.2	9230	10.2	112	10.4	8	10
R10	0.6	47.3	12,590	7.6	241	42.2	15	1

As shown in Figure 8, the cluster analysis classified the reservoirs into two groups: group (I) consisted of reservoirs R1, R2, and R6, whose useful capacity and full water area were large, and group (II) consisted of reservoirs R3, R4, R5, R7, R8, R9, and R10, whose useful capacity and full water area were small. The cluster analysis results, using the basic reservoir properties, revealed that the reservoirs could be classified based on their useful capacity and full water area; these indicators were identified as being more influential than other basic properties in the cluster analysis process.

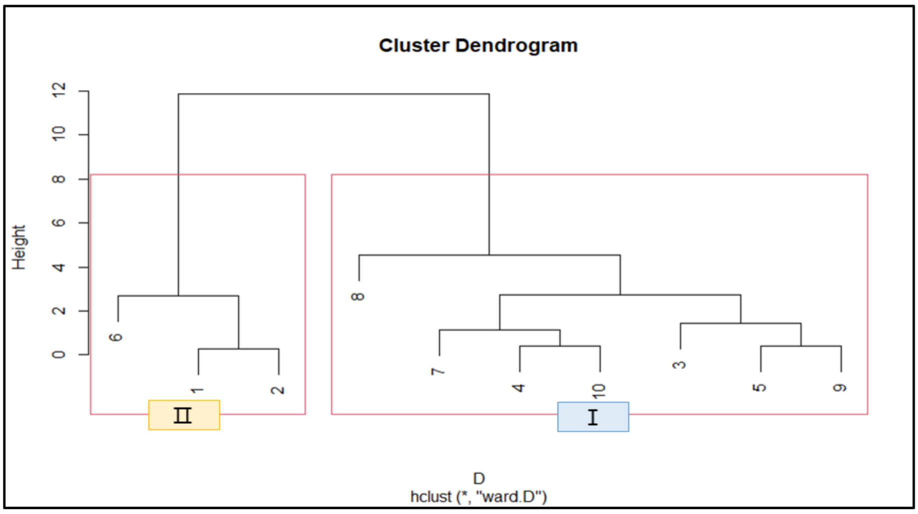

Figure 8. Result of reservoir characteristics through cluster analysis.

3.5. Morphological Analysis of the Collapsed Reservoirs Using Cluster Analysis and HC

HCs and the cluster analysis method were applied to reservoirs that had collapsed and caused damage. Only recent cases located near Miryang City, Gyeongsangnam Province were investigated. The Sandae Reservoir, located in Gyeongju City, Gyeongsangbuk Province, collapsed in 2013 and had a full water area of 49,200 m^2, a useful capacity of 194,400 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, collapsed in 2014 and had a full water area of 61,000 m^2, a useful capacity of 61,420 m^3, a levee height of 5.5 m, and a levee length of 160 m. In this study, HCs and a cluster analysis were applied to the Sandae and Goeyeon reservoirs, which are located near the ten reservoirs and had caused damage in the past.

The morphology indexes were found to be 11.65 and 26.68 for the Sandae and Goeyeon reservoirs, respectively. These high morphology index values indicated that the reservoirs were deeper than other reservoirs. The results of the full water storage area-levee height relationship were found to be 1.13 and 2.26 for the Sandae and Goeyeon reservoirs, respectively, indicating that they had larger full water areas than other reservoirs. The results of the full water storage area relationships were 6.15 and 8.87 for the Sandae and Goeyeon reservoirs, respectively, indicating that they had a larger storage capacity than other reservoirs.

Cluster analysis was conducted using the properties of the ten reservoirs, as well as the Sandae (11) and Goeyeon (12) reservoirs, as input data. Cluster analysis classified the reservoirs into three groups: Group (I) included the R3, R4, R5, R7, R8, R9, and R10 reservoirs, whose full water area and useful capacity were relatively small, Group (II) included the R1, R2, and R6 reservoirs, whose full water area and useful capacity were relatively large, and Group (III) including the Sandae (11) and Goeyeon Reservoirs, whose full water area and useful capacity were the largest (Figure 9).

To identify the characteristics of each group, the morphological characteristics of the reservoirs were investigated using the HCs. It was found that group (I) had the original ground surface that was not significantly eroded, group (II) had the original ground surface that was significantly eroded, and group (III) had the original ground surface eroded more extensively (Figure 10).

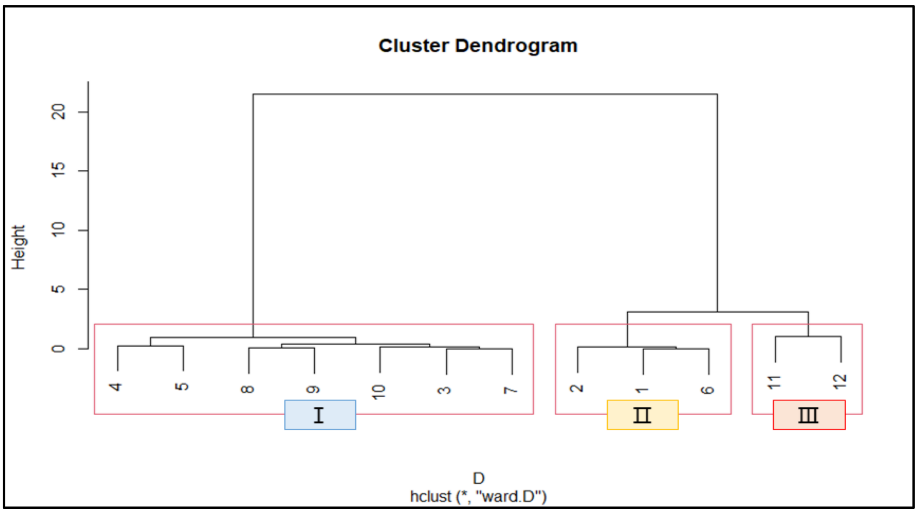

Figure 9. Result of the collapsed reservoirs using cluster analysis.

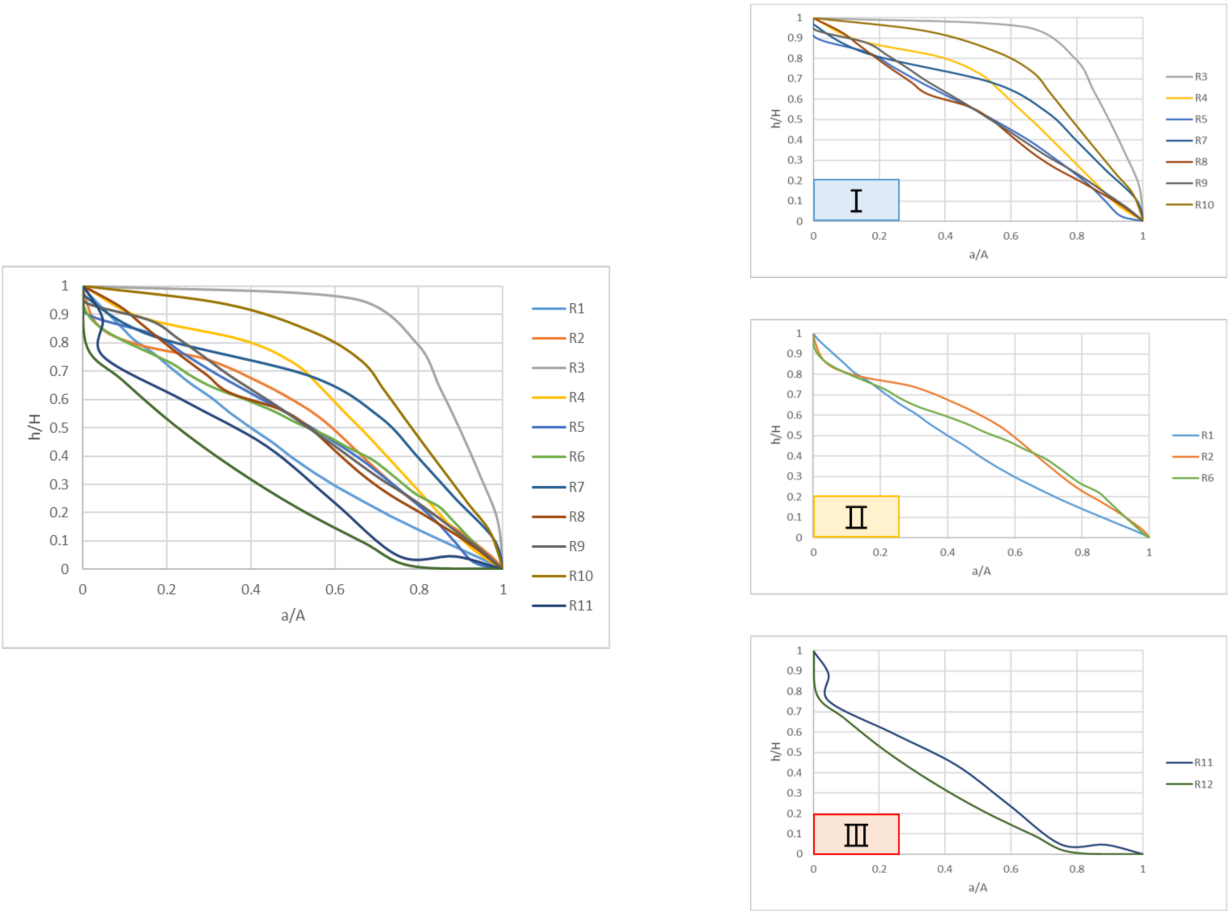

Figure 10. Morphological analysis of the collapsed reservoirs using cluster analysis and HC.

The Sandae and Goeyeon reservoirs that collapsed had larger storage areas 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 capacities compared to the other reservoirs.

4. Discussions and Conclusions

In this study, the geometry of unmeasured reservoirs was determined using topographic information, and a morphological analysis was conducted. The geometry and area by elevation and storage capacity of the reservoirs were determined by creating HCs for the reservoirs. In addition, the morphology index was quantitatively determined through an analysis of the full water storage area relationship for each reservoir. Topographic and morphological analyses of two reservoirs that had collapsed because of aging, insufficient management, and flooding were investigated to identify the potential causes of these collapses.

The area by elevation and volume for ten reservoirs located in Miryang City, Gyeongsangnam Province, including the Ga-Gog reservoir, were calculated using digital topographic maps. When the results were compared with the reservoir volumes measured by the National Disaster Management Research Institute, the error rate ranged from 0.23% to 14.27%. This error rate, with an average of approximately 5.03%, was excellent.

The full water storage area-levee height relationship and full water storage area relationship were comprehensively examined. It was found that the R3, R4, R5, R7, R8, R9, and R10 reservoirs had a lower depth and a smaller full water area relative to that of the R1, R2, and R6 reservoirs.

Cluster analysis was conducted to classify similar types of reservoirs into groups using basic properties, such as basin area, useful capacity, and full water area. The cluster analysis classified the reservoirs into two groups: the R1, R2, and R6 reservoirs, whose useful capacity and full water area were large, and the R3, R4, R5, R7, R8, R9, and R10 reservoirs, whose useful capacity and full water area were small. The useful capacity and full water area were identified as the indicators having the largest impact on the cluster analysis results.

HCs and the cluster analysis method were applied to two reservoirs that had collapsed and caused damage. The cluster analysis classified these two reservoirs and the ten reservoirs into three groups. The HCs of the collapsed reservoirs exhibited a convex downward shape compared to those of the other normal reservoirs, indicating that they were significantly aged and had been subjected to considerable erosion.

Each reservoir had different basic properties, such as a full water area and storage capacity. Should reservoir geometry be understood and the common characteristics of similar reservoir types be classified and identified using morphological analysis and HCs, these could be used to reduce the damage caused by reservoir collapse. The identification of potential causes of reservoir collapse prior to the disaster, through proactive disaster management, could possibly reduce the damage.

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