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Impacts of heavy rain and floodwater on floating debris entering an artificial lake (Daecheong Reservoir, Korea) during the summer

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ABSTRACT

Floating debris entering a reservoir is one of the major environmental issues to be dealt with in terms of water resource management in many countries of the world, as it may negatively impact ecosystems and cause economic damage. Our study examined the amount of floating debris and actual conditions experienced during the summer each year in an artificial lake located in the temperate region for 26 y. In particular, the rainfall and inflow characteristics were compared with the main influential factors for transporting floating debris to the reservoir. The maximum daily rainfall and inflow were important variables in the meteorological and hydrological characteristics of the reservoir operation during the summer. When these factors were influenced, most of the floating debris that was widely scattered in the watershed was supplied by the rapid flow of streams and rivers. The range and mean value of the floating debris weight accumulated within the reservoir were 421.0–34,137.0 $m^3 y^{-1}$ and 8,758.4 $m^3 y^{-1}$, respectively, and the difference between the years was very large. The maximum daily inflow was positively correlated with maximum daily rainfall ($r = 0.843$, $p < 0.05$). Based on linear regression, the regression between the floating debris and the maximum daily inflow ($r^2 = 0.9092$, $p < 0.001$) showed a better fit than that between the floating debris and the maximum daily rainfall ($r^2 = 0.8250$, $p < 0.001$). They showed an almost linear relationship, and the floating debris distribution above and below 20,000 $m^3 y^{-1}$ was contrasted. In addition, the frequency distribution of the event was relatively dense below 120 mm d^{-1} of rainfall and below 3,000 $m^3 d^{-1}$ of inflow, and the event was rare as the maximum daily rainfall and inflow increased. Finally, the average load of floating debris per unit area of the watershed was approximately 2.1 $m^3 km^{-2}$, and further details on the loading should be understood in terms of effective pollutant management.

Keywords: Floating debris; Floodwater; Heavy rain; Monsoon; Reservoir

1. Introduction

Floating debris problems arises in almost every type of water body including streams, rivers, reservoirs, and coasts, but the nature of these problems and their severity vary substantially [1]. Debris is mostly scattered on the watershed's land and then transported to various water bodies depending on the action of wind and water flow [2]. Therefore, it is not easy to control artificially over a wide watershed.

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Floating debris entering reservoirs is one of the major environmental issues to be dealt with in terms of water resource management, as it may negatively impact ecosystems and cause economic damages such as water quality pollution, the proliferation of harmful cyanobacterial blooms, clogging risks on hydropower generation facilities, water withdrawal and dam spillway, inhibition of leisure activities, and disturbance of the aquatic ecosystems [1,3–5]. Floating debris flowing into the reservoir in large waste quantities is distributed by natural and anthropogenic causes and is instantaneously supplied from the upstream watershed by heavy rain and floodwater [6,7]. Natural factors include debris due to forests and river vegetation occurring in the watershed, and anthropogenic factors include household items due to various human activities, such as plastic, vinyl, and bottles.

The floating debris dynamics in reservoirs differ from those in streams or rivers due to slower flow velocities, particularly in the transition zone of storage basins [2,8]. Unless there is special control within the reservoir, all floating debris is rapidly transported downstream of the dam, and various potential effects described above are directly or indirectly experienced in many areas of the reservoir. Therefore, an optimal control system for this material at a suitable location, considering the flow velocity in the reservoir, is necessary.

Floating debris problems may seem unusual for research since it has existed for a long time in a clearly identifiable form and abundant supply. Floating debris would also appear adaptable to being handled and disposed of by ordinary methods and equipment [1]. For this reason, research on this topic appears to have been neglected, and is, in fact, limited, except for the engineering approach on the control system design for efficient floating debris removal [3,6]. However, the presence of this material in a specific location and time can have an extremely harmful effect on certain structures or aquatic ecosystems. Therefore, further studies on causes, transport, control, and disposal are necessary.

The purpose of this study was to investigate the floating waste distribution occurring almost every year during the rainy season in many artificial lakes located in temperate regions, and to evaluate the impacts of hydrometeorological factors, such as rainfall and floodwater characteristics on waste distribution.

2. Materials and methods

2.1. Description of study area

The Daecheong Reservoir (36° 50 N, 127° 50 E) is the third largest in Korea and was built in December 1980 by constructing a dam in the middle and lower reaches of the Geum River for multiple uses, such as flood control, water supply, and hydropower electric generation (Fig. 1, Table 1) [9]. The watershed area is 4,134 km^2, consisting of a forest 3,076.3 km^2 (74.4%), agricultural land 695.5 km^2 (16.9%), a residential area of 42.2 km^2 (1.0%), and other areas, including roads and rivers of 320.0 km^2 (7.7%).

The reservoir area is 72.8 km^2, and the ratio of the basin area/reservoir area is 57 (Table 1). The total impoundment quantity was 1,490 × 10^6 m^3. The reservoir length was 86 km, and the mean depth was 27 m (range

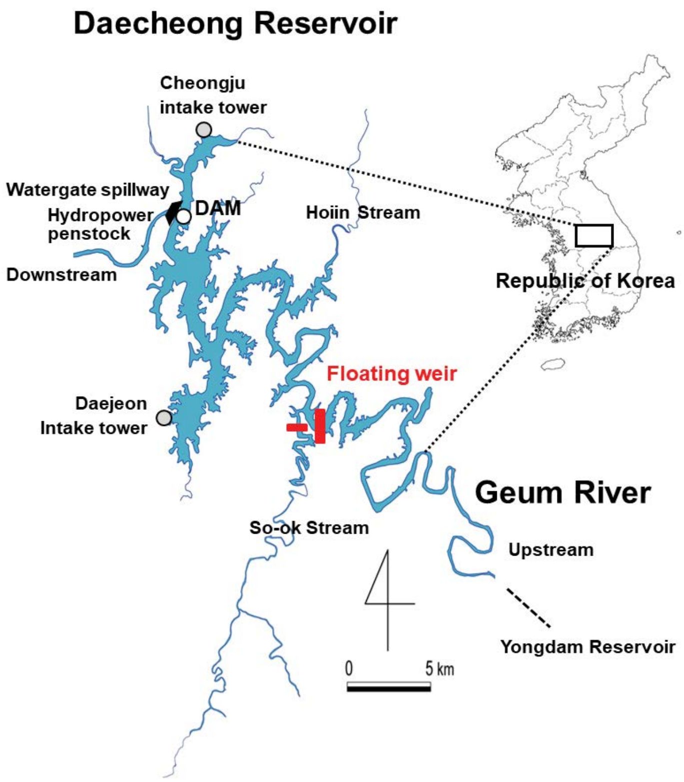

Fig. 1. Map showing location and main information related with this study on Daecheong Reservoir.

Table 1
General geographic and limnological features of Daecheong Reservoir constructed on the midstream of the Geum River in 1980. Data are used mean values from 1996 to 2019

Attribute	Daecheong Reservoir
Latitude	36° 50′ N
Longitude	127° 50′ E
Elevation (EL. m)	83.0
Functions	Flood control
	Hydropower electric generation
	Water supply
Shape type	Dendritic
Circulation type	Monomictic (in the lower part of reservoir)
Trophic state	Meso-eutrophic (upreservoir and tributary)
Yearly average precipitation (mm)	9.0
Yearly average inflow ($m^3 s^{-1}$)	114.8
Yearly average outflow ($m^3 s^{-1}$)	105.1
Watershed area (km^2)	4,134.0
Agriculture area (km^2)	684.0
Forest area (km^2)	3,047.0
Urban area (km^2)	399.0
Reservoir area (km^2)	72.8
Mean depth (m)	27.0
Maximum depth (m)	50.0
Length of longitudinal main axis (km)	86.0
Reservoir shoreline (km)	300.0
Reservoir volume (km^3)	$1,490 \times 10^6$
Hydraulic residence time (d)	51.0~231.0 (average 144.9)
Population density (km^{-2})	78.6
Dam height (m)	72.0
Dam length (m)	495.0
Dam width (m)	16 (upper), 35 (bottom)
Penstock position from bottom (m)	29.0

7–50 m). Rainfall and flow during the year are concentrated in the summer season (June to September). The shape of the reservoir is dendritic around the main river, and the hydraulic residence time is approximately 145 d, which is close to that of a typical river-type reservoir.

The floating weir was installed in December 1998 at a distance of 35 km upstream from the dam to prevent floating debris from being carried downstream [10]. Before this was installed, all the waste was scattered or accumulated over the middle and lower reaches of the reservoir. In rare cases, when the waste was discharged through the sluice and spillway, its influence spread downstream of the dam. The extent of the diffusion effect depended on the discharge amount and duration.

2.2. Data collection

The data used in this study were produced in the Daecheong Reservoir from January 1996 to August 2020. The daily rainfall and inflow data on the Daecheong Reservoir were downloaded from the National Water Resources Management Information System (WAMIS), which is operated by the Ministry of Land, Infrastructure, and Transport (MOLIT) in real-time. Daily rainfall data were limited during the summer period from June to September, and the total rainfall within this period was treated as "summer rainfall". The maximum daily rainfall and inflow were selected as the highest values within this period. The total amount of floating debris per year was obtained from the Ministry of Environment (MOE) and the Korea Water Resources Corporation (K-water). The main specifications and information on the Daecheong Reservoir were obtained from the Dam Management Office of K-water.

2.3. Data analysis

The descriptive statistics of each data and the Pearson correlation, Levene's test, and regression analyses between factors were conducted using the SPSS version 18 statistical program (IBM-SPSS Inc., Armonk, New York, US). The significance level was set at $p < 0.05$.

3. Results

3.1. Yearly rainfall and inflow variation

Fig. 2a shows the summer rainfall (June–September) for each year from 1996 to 2020. During the 26 y, the summer rainfall with monsoon and typhoon events ranged from 343.5 to 1,287.0 mm (mean 816.1 mm) (Table 2). Above all, the difference in summer rainfall between each year was very remarkable. In 1998, 2000, 2003, 2004, 2007, 2011, and 2012, summer rainfall exceeded 1,000 mm, but it was extremely low between 2013 and 2015 compared to other years (Fig. 2a). As a result, the water shortage was prolonged.

Fig. 2b shows the distribution of the maximum daily rainfall per year. The maximum daily rainfall range was 52.9–187.7 mm d^{-1}, and the mean value was 99.7 mm d^{-1}. Based on the average value of the maximum daily rainfall, the frequencies above and below that value were 50% (n = 13). The maximum daily rainfall in 2014 and 2015 was 55.1 and 52.9 mm d^{-1}, respectively, and the mean value was 54.0 mm d^{-1}, which was the lowest.

Fig. 2c shows the distribution of maximum daily inflow throughout the year. The maximum daily inflow ranged from 377.5 to 5,321.2 m^3 s^{-1}, and the mean value was 2,173.6 m^3 s^{-1} (Table 3). A sharp inflow difference was observed during the transition between 2001 and 2002. Years below 500 m^3 s^{-1} in maximum daily inflow were in 2001 and 2015, and those in the range between 500 and 1,000 m^3 s^{-1} were 2008, 2013, 2014, and 2017. In addition, all the other years were above 1,000 m^3 s^{-1}. The frequency exceeding the mean value was 48%. Based on the Pearson correlation analysis, the maximum daily inflow was correlated with summer rainfall (r = 0.584, p < 0.05) and maximum daily rainfall (r = 0.843, p < 0.05) (Fig. 3) and showed a higher correlation with the maximum daily rainfall than the summer rainfall.

3.2. Yearly floating debris variation

Fig. 4 shows the distribution by measuring the wet weight of floating debris entering the reservoir each year. The range and mean value of the floating debris weight accumulated within the reservoir were 421.0–34,137.0 m^3 y^{-1} and 8,758.4 m^3 y^{-1}, respectively, and the difference between the years was very large. Before the floating weir was installed, between 1996 and 1998, the floating debris was minimal, with an average of 532.7 m^3 y^{-1}. On the other hand, the floating debris increased significantly with an average

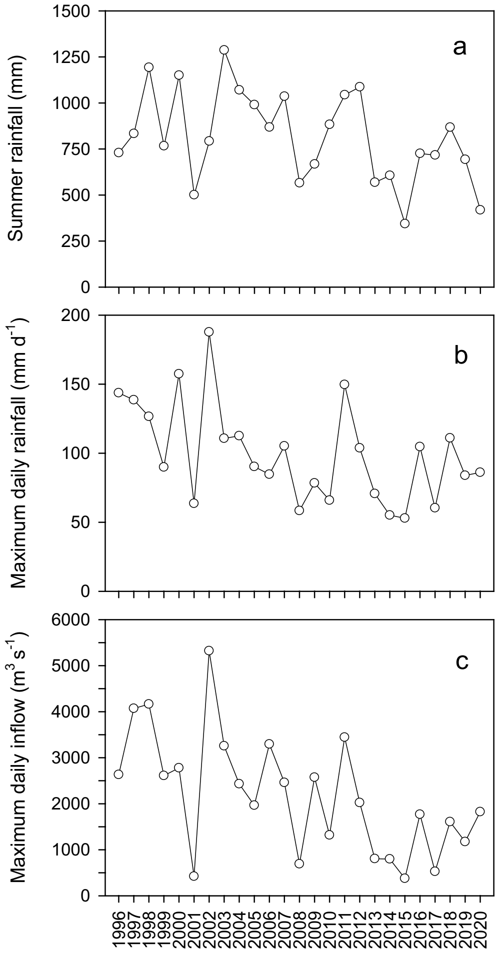

Fig. 2. Yearly distribution of summer rainfall, maximum daily rainfall, and maximum daily inflow in Daecheong Reservoir from 1996 to 2020.

Table 2
Descriptive statistics of main factors before and after floating weir installation in Daecheong Reservoir from 1996 to 2020. The values indicate mean, standard deviation, and range (maximum and minimum)

Factors	Total (1996~2020)	Installation of floating weir	
		Before (1996~1998)	After (1999~2020)
Summer rainfall (mm)	816.1 ± 247.4 (1,287.0/343.7)	918.5 ± 243.2 (1,192.8/729.1)	802.1 ± 250.2 (1,287.0/343.7)
Maximum daily rainfall (mm d^{-1})	99.7 ± 35.5 (187.7/52.9)	136.3 ± 8.8 (143.7/126.6)	94.7 ± 34.9 (187.7/52.9)
Maximum daily inflow (m^3 s^{-1})	2,173.6 ± 1,290.0 (5,321.2/377.5)	3,622.2 ± 858.0 (4,163.5/2,633.0)	1,976.0 ± 1,221.1 (5,321.2/377.5)
Floating debris (m^3 y^{-1})	8,758.4 ± 9,772.7 (34,137.0/421.0)	531.7 ± 82.5 (600.0/440.0)	9,880.2 ± 9,907.7 (34,137.0/421.0)

Table 3
Descriptive statistics of main factors according to the degree of maximum floodwater in Daecheong Reservoir from 1996 to 2020. The values indicate mean, standard deviation, and range (maximum and minimum)

Factors	Total	Maximum floodwater ($m^3\ s^{-1}$)		
		Below 500	500~1,000	Above 1,000
Summer rainfall (mm)	816.1 ± 247.4 (1,287.0/343.7)	422.2 ± 110.9 (500.6/343.7)	614.1 ± 70.8 (716.7/565.5)	900.1 ± 215.2 (1,287.0/418.5)
Maximum daily rainfall ($mm\ d^{-1}$)	99.7 ± 35.5 (187.7/52.9)	58.3 ± 7.6 (63.6/52.9)	61.2 ± 6.7 (70.7/55.1)	112.2 ± 38.4 (187.7/65.9)
Maximum daily inflow ($m^3\ s^{-1}$)	2,173.6 ± 1,290.0 (5,321.2/377.5)	400.0 ± 31.8 (422.5/377.5)	706.2 ± 129.7 (805.2/527.8)	2,669.2 ± 1,062.4 (5,321.2/1,173.8)
Floating debris ($m^3\ y^{-1}$)	8,758.4 ± 9,772.7 (34,137.0/421.0)	485.5 ± 91.2 (550.0/421.0)	2,140.3 ± 737.3 (2,898.0/1,390.0)	11,022.5 ± 10,222.6 (34,137.0/440.0)

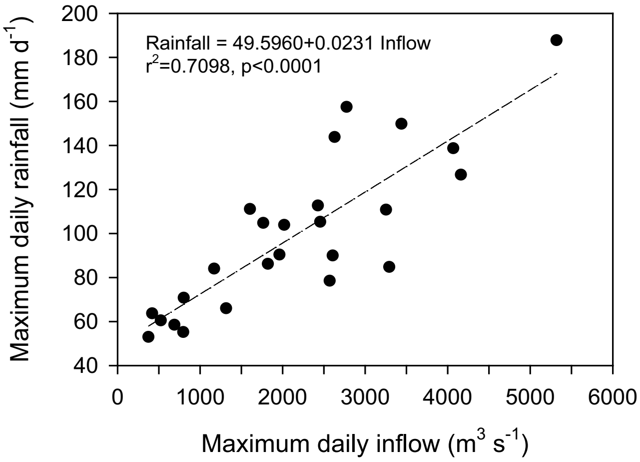

Fig. 3. Scatter plot showed a simple linear regression between maximum daily inflow and rainfall in Daecheong Reservoir (number of data = 26).

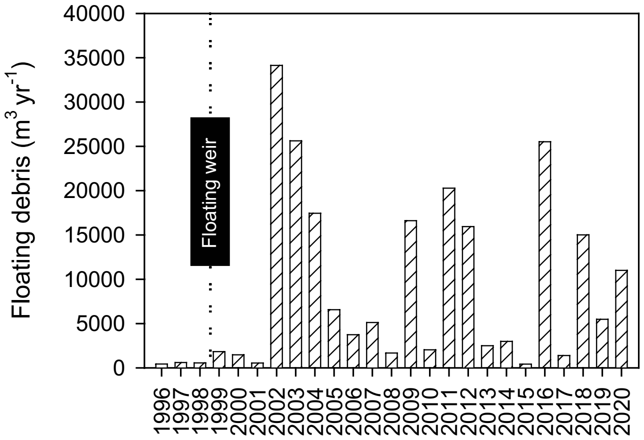

Fig. 4. Yearly distribution of floating debris in Daecheong Reservoir from 1996 to 2020.

of 9,880.2 $m^3\ y^{-1}$ after installing the floating weir during the period from the 1999 to 2020 period (F = 8.485 and p = 0.008 obtained from Levene' test). The largest and smallest floating debris amounts occurred in 2002 (34,137.0 $m^3\ y^{-1}$) and 2015 (421.0 $m^3\ y^{-1}$). The year exceeding the average value included 9 out of 26 y, such as 2002–2004, 2009, 2011–2012, 2016, 2018, and 2020. Although the amount of rainfall and inflow was large between 1996 and 1998, when no floating debris barrier was placed within the reservoir, the amount of floating debris was very low.

3.3. Hydro-meteorological impacts on floating debris entering into the reservoir

Fig. 5 shows simple linear regressions of floating debris on maximum daily rainfall and maximum daily inflow. The maximum daily inflow (r^2 = 0.9092) was more linearly related to the floating debris than the maximum daily rainfall (r^2 = 0.8250). They showed an almost linear relationship, and the floating debris distribution of above and below 20,000 $m^3\ y^{-1}$ was contrasted. In addition, the frequency distribution was relatively dense below 120 mm d^{-1} of rainfall and below 3,000 $m^3\ d^{-1}$ of inflow; the event was rare as the rainfall and inflow increased.

4. Discussion

Floating debris in the reservoir is a pollutant that should be considered important in terms of water quality management. However, in most cases, there were very few direct research studies on this topic because of the characteristics of a high flow rate, due to heavy rain, over a short time period. Until recently, in many countries around the world, there have been many studies on blocking facilities, such as floating dams or weirs and barriers, to reduce the damage to the dam and water intake structures, but the water quality in the reservoir was not considered. In particular, when the amount of floating debris and the area covering the water surface are large, the fluidity of the water body decreases, which may deteriorate the water quality and aquatic ecosystems in terms of chemistry (e.g., hypoxia and nutrient release from sediment) and biology (e.g., harmful cyanobacterial water-bloom and fish-kill). Understanding the spatiotemporal distribution

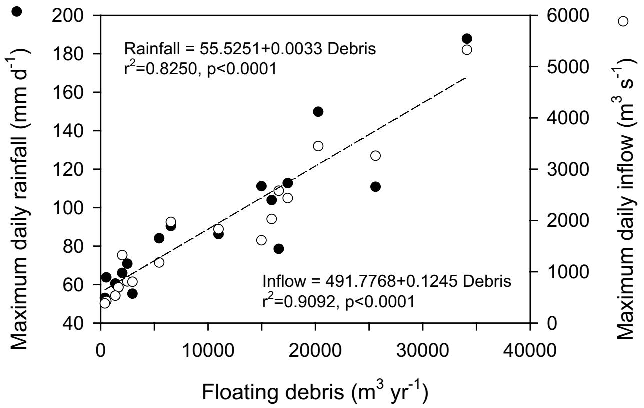

Fig. 5. Scatter plot showed a simple linear regression between floating debris and maximum daily rainfall and the debris and maximum inflow in Daecheong Reservoir (number of data = 26).

and dynamics of floating debris can therefore be important to prevent or mitigate these environmental problems. In addition, since floating debris trapped in the reservoir is composed of a large amount of plastic and wood (~20%), it can be useful information to improve the understanding of plastic pollution, which has emerged as a recent issue.

Summer rainfall was different depending on the year and showed irregular variability. High rainfall years could be attributed to the long or frequent rainy seasons and heavy rains caused by typhoons, and the few years came every 4–7 y and lasted for 1–3 y after the year of relatively large rainfall. The maximum daily rainfall was influenced by strong heavy rains during the rainy season and the typhoon, and also affected the low summer rainfall. The maximum daily inflow was also related to the rainfall duration and frequency but seemed to be more closely related to rainfall intensity [11]. Therefore, the maximum daily rainfall and inflow can be considered important physical factors, such as the power to float and transport the waste scattered in the watershed and upstream of rivers into the reservoir. It can be observed that, as the water level increases based on the bank of the river, the hydraulic potential to move floating debris increases as well.

The amount of floating debris in the reservoir highly fluctuates from year to year. Between 1996 and 1998, before installing the floating weir to artificially block the movement of floating debris downstream of the reservoir, floating debris was introduced into the reservoir and then dispersed in various places depending on the water mobility. Floating debris was concentrated in the area where the surface flow rate almost disappeared. However, when discharged through a spillway, the travel distance was longer compared to the case where it was not. On the other hand, after installing floating beams from 1999 to 2020, the effect of trapping floating debris was remarkable, and the result could be clearly observed after 2002 [12,13].

The increase in the amount of floating debris entering the reservoir occurred when the maximum daily rainfall and inflow in the preceding year were not high. Hence, when the amount of floating debris was minimal, heavy rains, and floods were caused by rainy seasons and typhoons in the subsequent year. In addition, the decrease in the floating debris amount entering the reservoir may be attributed to the effects of meteorological and hydrological factors and the decrease in the accumulation amount in the watershed over a short time period due to the mass transfer effect of the preceding year. Finally, the research presented in this paper deals with the effects of heavy rains and floods on the total amount to understand the current status and dynamics of floating debris, but it is considered that detailed studies on the composition of floating debris should be followed in the future.

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