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Determination of Clark unit hydrograph parameters for estimating probable maximum flood

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ABSTRACT

The probable maximum flood (PMF) is the flood caused by the probable maximum precipitation (PMP). A unit hydrograph (UH) is generally used to derive the PMF for the given PMP, but a method is needed to modify the UH parameters to reflect the PMP condition. This study presents a new method using the estimated channel velocity to modify the Clark UH parameters under the ordinary condition into those under the PMP condition. This study considers major dam basins in Korea and evaluates the application results in comparison to several previous studies. As application results of the proposed method, the Clark UH parameters under the PMP condition are found to be within the range 39–53% of those under the ordinary condition, with their mean of about 44%. The UH derived by applying this mean ratio shows that its peak time and the peak flow are just 44 and 227% of the UH under the ordinary condition, respectively. This change from the ordinary condition to the PMP condition is more extreme in Korea than that in Australia and the United Kingdom. This extreme change seems to be due to the climate in Korea, located in the Asian Monsoon region.

Key words: channel velocity, Clark unit hydrograph, concentration time, probable maximum flood, probable maximum precipitation, storage coefficient

HIGHLIGHTS

- The probable maximum flood (PMF) varies according to the unit hydrograph (UH) parameters.
- It is necessary to modify the UH parameters to express under the extreme condition.
- A method to determine the UH parameters for estimating the PMF is suggested.
- The method is more flexible and easier to use than those in several previous studies.
- The ratio to modify the Clark UH parameters is extreme in Korea.

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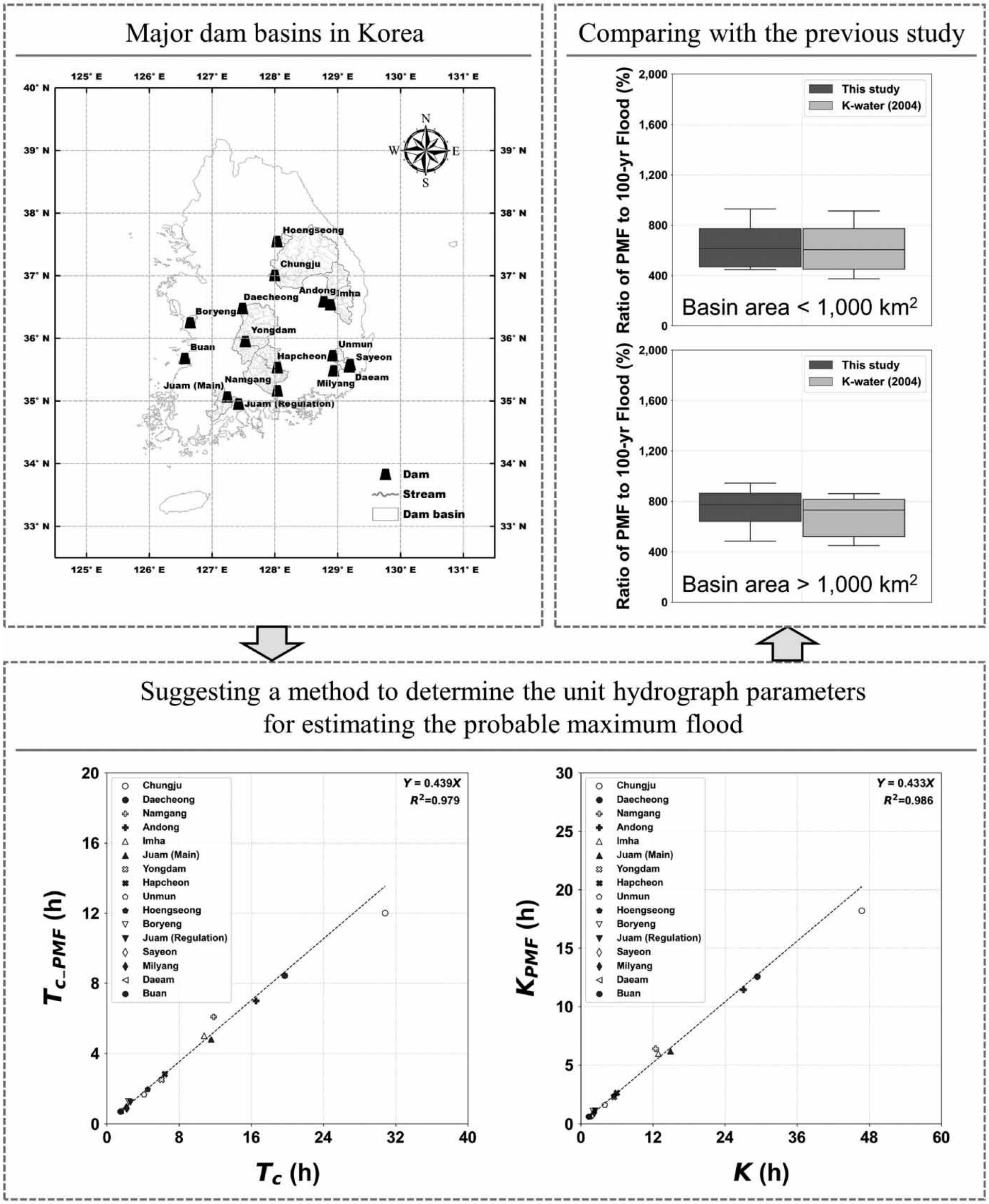
GRAPHICAL ABSTRACT



INTRODUCTION

When designing a dam, the probable maximum flood (PMF) is considered. The PMF is the flood caused by the probable maximum precipitation (PMP), and rainfall–runoff analysis is needed to estimate the PMF for the given PMP. That is, the PMF is

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obtained through rainfall–runoff analysis using a hydrological model with the PMP as an input. There have been studies using complex hydrological models to estimate the PMF (Beauchamp *et al.* 2013; Jothityangkoon *et al.* 2013; Chen & Bradley 2016; Yigzaw & Hossain 2016). However, due to limitations such as calibration and validation of numerous input data, the use of a unit hydrograph (UH) is set as a design standard in most countries. Among several UHs, the superiority of the Clark UH for natural basins has been confirmed by many studies (Ghumman *et al.* 2014; Adib *et al.* 2019).

For this reason, the Clark UH is mostly used in Korea. Therefore, even if the same PMP is considered, the estimated PMF varies according to the applied Clark UH. Additionally, under the condition that the PMP occurs, the response from the basin becomes much faster and stronger than that under the ordinary condition (KDI 2007; K-water 2008; Kjeldsen *et al.* 2016). Simply put, it is necessary to properly modify the shape of the Clark UH to express the basin response under this extreme condition. Therefore, the two parameters (i.e., the concentration time and storage coefficient), which determine the shape of the Clark UH, play a decisive role in the estimation process of the PMF.

There are several methods available for modifying the shape of the ordinary-UH to be applied to the derivation of the PMF. All of these methods begin from the UH under the ordinary condition. For example, in the United Kingdom, it begins with the empirically determined triangular-shaped UH under the ordinary condition. Then, the peak flow of the UH is increased by 1/2, and the peak time and base time are decreased by 1/3, to make the volume of the modified UH identical to the volume of the original UH (NERC 1975). A similar approach can be found in Australia, where the Clark UH is modified under the ordinary condition to consider the extreme condition of the PMP occurring. The rising limb of the Clark UH is simply increased by 15–20% depending on the local basin conditions, while the falling limb is modified to make the volume of the modified UH identical to the volume of the original UH (IEA 1987). The United States also uses the Clark UH, but the UH is modified by selecting the model parameters from the most extreme event recorded. The Clark UH representing the biggest rainfall event in the past is simply assumed to be similar to that under the PMP condition (FERC 2001). When a long record is available, this method could be reasonable.

In Korea, the Commentary of Dam Design Criteria (MOCT 2001) warned that the use of the ordinary-UH based on the average concept might underestimate the PMF. Since then, several studies have been conducted on the modification of the Clark UH to estimate the PMF. First, K-water (2004) suggested following the United States method to select the parameters derived from the most extreme rainfall event recorded. This suggestion was then modified by KDI (2007), so that each parameter could be selected independently among the parameters from several major rainfall events. This method was found to make the Clark UH more extreme, as much shorter concentration time and storage coefficient could be selected. However, these two suggestions still showed the problem of data dependency. That is, these suggestions could not solve the problem that the length of the rainfall–runoff data in Korea is limited to a maximum 50 years, and that the data length varies greatly, depending on the river basin of interest.

To overcome this problem, K-water (2008) suggested finding the asymptotic values. That is, by analyzing the behavior of the parameters with respect to the peak flow, it was expected to select the asymptotic values of the two parameters. As a result, a more extreme Clark UH could be derived. However, the result still showed the consistency problem. The results simply showed a strong dependency on the data length, and also showed some significant amount of randomness, due to the fluctuation of the observed parameters, and the resulting subjective judgment on the asymptotic values. An even worse problem is that the runoff measurement in Korea is not as intensive as the rainfall measurement. That is, if the hydraulic structure is planned in a remote place or in an ungauged basin, it is always possible that no runoff data is available.

As a solution to the above-mentioned problems when selecting the two parameters of the Clark UH for the estimation of the PMF, this study proposes use of the channel velocity. This channel velocity can be directly used to estimate the concentration time, and the concentration time is then used to determine the storage coefficient based on their significant relation. The channel velocity should be the parameter to represent the PMP condition. Also, it should be estimated in an ungauged basin. These conditions are to be overcome one-by-one, using many theories in open channel hydraulics and geomorphology. Ultimately, this study is to propose a method to modify the Clark UH under the ordinary condition, into that under the PMP condition. This study considers major dam basins in Korea, as it is easy to find the PMP and PMF information. The PMP and PMF are generally applied for the design of a dam in Korea. The available PMF information about those dams is the result derived by applying the previous suggestions to modify the Clark UH. The results in this study, including the new parameters of the Clark UH and the new PMF for each dam basin, are compared with those previous ones. The comparison is also made with several measures of consistency, like the ratio of the PMF to the 100-year design flood.

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METHODOLOGY

The proposed method to determine the parameters of the Clark UH is based on the assumption that the peak flow velocity in a channel remains unchanged from upstream to downstream. This assumption is definitely valid for the given rainfall event only. The peak flow velocity can be different for another rainfall event. This assumption has been supported by many studies (Rodríguez-Iturbe & Valdés 1979; Molnár & Ramírez 1998; Giannoni *et al.* 2000; Kampel *et al.* 2009).

The first step of the proposed method is to apply the rational formula to estimate the peak flow. The basin area should be small enough to make the application of the rational formula valid. There are many different suggestions on the maximum basin area for the application of the rational formula (Jeong & Yoon 2007; Yoon 2007; Dhakal *et al.* 2012; ASCE 2017; Kim *et al.* 2017), which range 0.8–440 km^2. If the basin of interest is larger than this limit, some location at the upstream part of the basin should be selected to guarantee that its sub-basin area is smaller than this limit. The peak flow is used for the estimation of the peak flow velocity at the exit of this sub-basin.

The rational formula is expressed as follows:

$$Q_p = mCIA \tag{1}$$

where Q_p is the peak flow (m^3/s), C is the runoff coefficient, I is the rainfall intensity (mm/h), A is the basin area (km^2), and m is the conversion factor (0.2778 in the SI unit system). For a non-uniform rainfall event, the rainfall intensity should be determined as the mean rainfall intensity during the concentration time around the rainfall peak. The runoff coefficient can also be estimated using the SCS–CN method (McCuen & Bondelid 1981).

$$C = \frac{(P - 0.2S)^2}{P(P + 0.8S)} \tag{2}$$

$$S = \frac{25,400}{CN} - 254 \tag{3}$$

where P is the total rainfall (mm), S is the potential maximum retention (mm), and CN is the curve number. The CN value can be estimated using the soil and land use information.

Once the peak flow is estimated, the peak flow velocity is determined by Manning's equation with the information of the channel cross-section and bed materials. Manning's equation is expressed as follows:

$$V = \frac{1}{n} R^{2/3} S_0^{1/2} \tag{4}$$

where V is the flow velocity (m/s), R is the hydraulic radius (m), S_0 is the channel slope (m/m), and n is the roughness coefficient ($s/m^{1/3}$). The roughness coefficient could be determined using the information of the channel bed materials. Aggregate and cobble are common bed materials for most upstream channels in Korea. Thus, the value ranging 0.030–0.050 is recommended as a roughness coefficient for these upstream channels (Chow 1959; KWRA 2019).

The velocity determined in the previous step is used as an initial value to determine the final peak flow velocity. The velocity is used to determine the concentration time and the storage coefficient. The Clark UH can now be determined for the uppermost sub-basin, which can also be used to estimate the peak flow. Basically, this peak flow could be a bit different from that derived by applying the rational formula, mainly due to the consideration of the storage effect. Simply put, the rational formula does not consider the storage effect. The new peak flow is then used to derive the peak flow velocity again, and the concentration time and storage coefficient. The new Clark UH is also used to estimate the peak flow, which must then be closer to the previous estimate. Only two or three repetitions are sufficient to see the convergence. The asymptotic peak velocity is that making the peak discharge estimated by applying the rational formula be identical to that by the Clark UH.

This peak flow velocity estimated at the exit of the uppermost sub-basin is assumed to be the same as that at the exit of the entire basin of interest. As a result, the concentration time can be determined as follows:

$$T_{c\_PMF} = 0.2778 \frac{L}{V_{PMF}} \tag{5}$$

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where L is the channel length (km), while V_{PMF} and T_{c_PMF} indicate the peak flow velocity (m/s) and the concentration time (h) under the PMP condition. The storage coefficient can also be estimated using the relation between the storage coefficient and the concentration time in a basin:

$$K_{PMF} = \alpha T_{c\_PMF} \tag{6}$$

where K_{PMF} indicates the storage coefficient (h) under the PMP condition. The constant α represents the ratio between the storage coefficient and the concentration time. This constant has been proven to be unchanged in a basin, regardless of the channel flow velocity under different rainfall events (Yoo *et al.* 2014; Yoo *et al.* 2019; Lee 2021; Lee & Yoo 2022).

The constant α in Equation (6) can be estimated using the empirical equation for the concentration time and the storage coefficient. In Korea, the Kraven (II) formula (JSCE 1999) is generally used to estimate the concentration time. The formula is expressed as follows:

$$T_c = 0.2778 \frac{L}{V_o} \tag{7}$$

where T_c is the concentration time (h), L is the channel length (km), and V_o is the flow velocity (m/s) under the ordinary condition. V_o is allocated differently, according to the channel slope (S_0). Jeong *et al.* (2002) analyzed the channel flow velocities under the rainfall event having an approximate 50-year return period at 13 national rivers, 26 local rivers, and 30 minor rivers. Their analysis was summarized by the following empirical formula:

$$V_o = -\frac{0.0057}{S_0 + 0.0030} + 3.45 \tag{8}$$

This formula is generally applied to hydrologic design in Korea and covers the return period of up to 100 or 200 years (KISTEC 2013).

The Sabol formula (Sabol 1988) is generally used to determine the storage coefficient in Korea. This formula links the concentration time to the storage coefficient by additionally considering the shape factor of the basin. However, as this formula is not applicable to the basin with very small shape factor, its modified version, the Modified Sabol formula, is more frequently used (MLTM 2012b). The Modified Sabol formula is as follows:

$$K = \frac{T_c}{\left(\frac{97.28}{SF^{-2.88} + 128.19}\right) + 0.59} \tag{9}$$

where K is the storage coefficient (h), and SF is the shape factor of the basin, i.e., A/L^2. The constant α is then derived as the ratio of the storage coefficient to the concentration time, i.e.,

$$\alpha = \frac{K}{T_c} = \frac{1}{\left(\frac{97.28}{SF^{-2.88} + 128.19}\right) + 0.59} \tag{10}$$

In fact, the above relation is a kind of Russel coefficient to link the storage coefficient to the concentration time (Russell *et al.* 1979). The range of the constant is 0.8–1.2 for natural basins in Korea (Yoo 2009; MLTM 2012b). Additionally, it should be confirmed that the constant remains unchanged, regardless of the size of a rainfall event (Yoo *et al.* 2014, 2019). Lee & Yoo (2022) reviewed various rainfall events of the 21 basins in the Chungju Dam basin in Korea, and found the ratio between the storage coefficient and concentration time of a basin remains unchanged. Based on this result, the constant α could be assumed to be used for the condition of PMP occurrence. The PMP is a kind of hypothetical design rainfall that exceeds the scale of actual rainfall events, but it can be expected that the ratio of the concentration time to the storage coefficient (α) is not significantly different from that obtained by analyzing the observed rainfall events. That is, this constant α can be utilized for parameter estimation under PMP condition.

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STUDY AREA AND DATA

Study basins and their characteristics

This study considered 16 major dam basins in Korea. Additionally, the uppermost sub-basin within each dam basin was considered as the application of the rational formula. These uppermost sub-basins were selected by considering the available information of the cross-section and channel bed materials at the exit of the sub-basin. All of these 16 dam reservoirs were also considered in the report of K-water (2004), while only three dams were considered in the reports of KDI (2007) and K-water (2008). Figure 1 shows the locations of the dam basins and outlet points of the uppermost sub-basins considered in this study.

Table 1 summarizes the basic characteristics of each dam, such as the basin area, channel length, channel slope, basin shape factor, mean annual precipitation and temperature, and average elevation. Also, the *CN* values were borrowed from

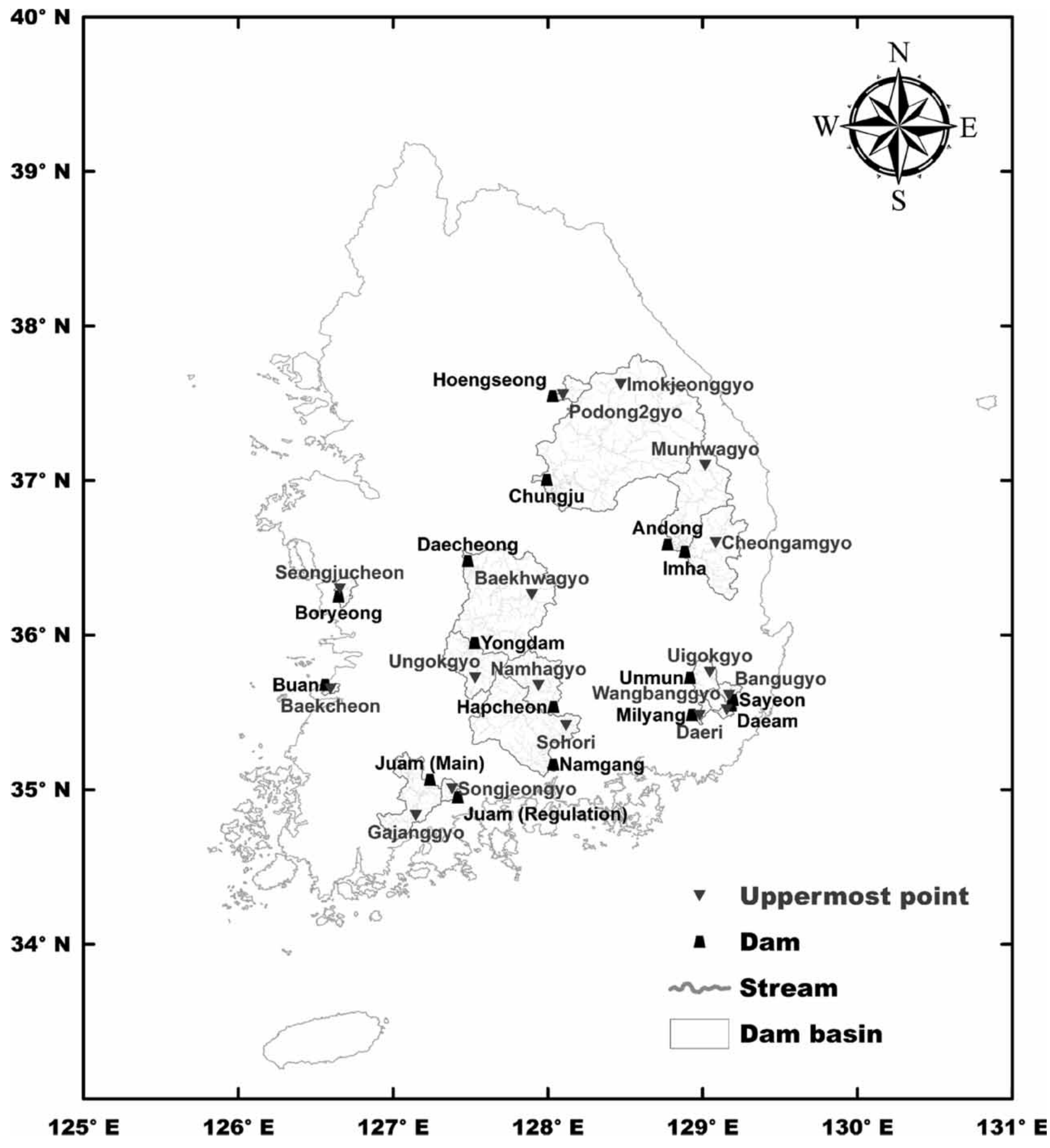

Figure 1 | Location of study basins, dams, and outlets of uppermost sub-basins.

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Table 1 | Basic information of the study dam basins

#	Dam	Area (km²)	Length (km)	Slope (m/m)	Shape factor	Average elevation (m)	CN	Mean annual precipitation (mm)
1	Chungju	6,648.0	282.2	0.0032	0.0473	546.0	85.7	1,197.6
2	Daecheong	3,204.0	190.0	0.0043	0.0888	362.6	93.6	1,230.0
3	Namgang	2,293.4	113.2	0.0041	0.1790	427.6	87.0	1,514.3
4	Andong	1,589.2	171.6	0.0069	0.0540	556.1	88.5	950.0
5	Imha	1,365.5	97.5	0.0030	0.1436	393.1	87.3	1,055.1
6	Juam (M)	1,026.1	90.5	0.0014	0.1253	269.8	82.0	1,530.0
7	Yongdam	929.9	62.7	0.0067	0.2365	510.3	83.9	1,259.7
8	Hapcheon	928.9	64.2	0.0054	0.2254	503.9	82.4	1,370.4
9	Unmun	301.3	38.0	0.0033	0.2087	416.3	92.0	1,139.4
10	Hoengseong	209.0	38.9	0.0023	0.1381	439.5	79.4	1,320.0
11	Boryeong	163.6	23.9	0.0052	0.2864	232.3	93.0	1,245.0
12	Juam (R)	134.6	23.7	0.0030	0.2396	288.6	70.0	1,620.0
13	Sayeon	124.1	22.5	0.0057	0.2452	241.0	90.0	1,153.0
14	Milyang	95.4	22.9	0.0085	0.1819	548.3	82.3	1,269.5
15	Daeam	77.0	16.6	0.0101	0.2794	179.9	85.0	1,203.2
16	Buan	59.0	15.4	0.0060	0.2488	176.3	91.7	1,271.9

K-water (2004). In fact, this *CN* value was derived by analyzing the most severe rainfall–runoff event with the smallest loss amount among the rainfall events in the past. As two dam basins share the same name 'Juam', Juam (M) represents the Juam Main Dam basin, while Juam (R) represents the Juam Regulation Dam basin.

This study investigated all the water stage monitoring stations within the dam basins operated by the Ministry of Environment and K-water. For each dam basin, the uppermost station was selected to derive a sub-basin. As there was no water stage monitoring station available within the relatively small Boryeong Dam and Buan Dam, the river mouths of their tributaries, Seongjucheon and Baekcheon, were selected as the exits of the sub-basins. The characteristics of these uppermost sub-basins were also derived through GIS analysis, which Table 2 summarizes.

Data for analysis

To apply the rational formula to the uppermost sub-basin, the rainfall duration should be considered. In the case of using evenly distributed rainfall, the concentration time is generally applied to maximize the peak flow. However, in the case of time-distributed rainfall, the same approach may not be applied. In this study, PMPs of various durations of 1–72 h were considered, as shown in Table 3, and the duration to produce the maximum peak flow was selected. These PMPs are available in the Korean PMP map (MOCT 2004).

The PMPs in Table 3 were time-distributed by the Huff method for application to the rainfall–runoff analysis. The Huff method is the most popular one for rainfall temporal distribution in Korea (ME 2019). The Ministry of Environment revises the rainfall temporal distribution every 10 years at major rain gauge stations over the Korean Peninsula. In K-water (2004), the nearest rain gauge stations to the dams of interest were selected to borrow the rainfall temporal distribution. These rain gauge stations were all from those operated by the Korea Meteorological Administration, which were assumed to have good quality control.

The PMPs for the dam basins were also estimated by the most recent PMP map (MOCT 2004). In the rainfall–runoff analysis of a dam basin, the rainfall duration is generally determined based on the concept of critical duration. The critical duration simply means the rainfall duration to maximize the dam water level. However, in this study, only the PMP for 24 h was considered. This was simply because the relative comparison of current and previous methodologies was available.

Additionally, the probable rainfall of 100 years and the resulting runoff peak were considered to evaluate the derived PMF. The reason for considering the 100-year frequency is that it is generally regarded as the representative of extreme rainfall or flood (Angel & Huff 1997; Douglas & Fairbank 2011; Gori *et al.* 2020). The probable rainfall data could be obtained from the

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Table 2 | Basic characteristics of the uppermost sub-basin selected for each dam basin

Dam basin	Uppermost sub-basin	Sub-basin area (km^2)	Channel length (km)	Channel slope (m/m)
Chungju	Imokjeonggyo	55.9	16.6	0.0079
Daecheong	Baekhwagyo	215.8	32.3	0.0055
Namgang	Sohori	102.5	12.6	0.0050
Andong	Munhwagyo	126.3	21.1	0.0072
Imha	Cheongamgyo	475.5	44.8	0.0033
Juam (M)	Gajanggyo	298.1	45.7	0.0016
Yongdam	Ungokgyo	102.2	16.1	0.0086
Hapcheon	Namhagyo	459.6	33.7	0.0077
Unmun	Uigokgyo	63.3	15.8	0.0110
Hoengseong	Podong2gyo	182.9	20.2	0.0024
Boryeong	Seongjucheon	34.3	10.7	0.0120
Juam (R)	Songjeongyo	59.7	10.1	0.0044
Sayeon	Bangugyo	90.8	14.9	0.0082
Milyang	Daeri	58.8	11.1	0.0087
Daeam	Wangbanggyo	29.2	9.3	0.0131
Buan	Baekcheon	26.2	7.0	0.0070

Table 3 | PMPs (mm) derived for the uppermost sub-basins

	Rainfall duration (h)					
Sub-basin	1	6	12	24	48	72
Imokjeonggyo	134.7	206.1	406.3	565.2	828.1	893.6
Baekhwagyo	108.6	172.1	365.5	487.4	714.6	758.1
Sohori	139.6	209.9	426.2	598.9	917.9	957.9
Munhwagyo	119.0	177.0	369.9	506.6	761.5	806.5
Cheongamgyo	92.5	158.3	343.9	443.1	630.8	708.5
Gajanggyo	129.1	220.6	453.8	635.2	960.3	1,025.1
Ungokgyo	123.7	183.0	374.5	524.2	798.1	838.4
Namhagyo	101.5	173.6	356.9	483.8	710.2	796.7
Uigokgyo	136.0	211.9	439.7	589.8	906.6	906.4
Podong2gyo	123.4	194.3	392.8	539.1	806.4	881.7
Seongjucheon	159.7	502.8	709.3	828.8	885.5	982.4
Songjeongyo	157.5	240.3	497.3	702.3	1,069.8	1,106.0
Bangugyo	140.9	212.8	439.5	624.2	954.9	982.8
Daeri	145.0	225.3	459.9	643.0	976.8	995.3
Wangbanggyo	151.5	245.5	492.7	673.3	1,012.2	1,015.5
Baekcheon	149.6	251.2	499.8	657.6	958.0	978.0

Water Resources Management Information System (WAMIS). Table 4 compares the 24-hour PMP and 100-year probable rainfall for each dam basin. For reference, it was necessary to apply the areal reduction factor (ARF) to convert the probable rainfall into the areal average one. This study used the regression equation provided by the Standard Guidelines for Flood Estimation (ME 2019). The same temporal distribution model was applied to the 24-hour PMP and 100-year probable rainfall.

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Table 4 | 24-hour PMP and 100-year probability rainfall for each dam basin

Dam basin	PMP (mm)	100-year rainfall (mm)
Chungju	492.4	148.3
Daecheong	506.3	137.8
Namgang	638.9	199.2
Andong	564.9	117.4
Imha	553.0	117.9
Juam (M)	836.3	174.2
Yongdam	635.0	153.1
Hapcheon	651.2	155.0
Unmun	775.8	160.4
Hoengseong	796.6	170.6
Boryeong	834.5	205.1
Juam (R)	1,014.3	191.7
Sayeon	963.2	228.1
Milyang	934.4	228.8
Daeam	952.4	166.5
Buan	922.8	214.9

EVALUATION OF THE PROPOSED METHOD

Application result to the Chungju Dam basin

As explained earlier, the uppermost sub-basin of the given basin was selected as the target sub-basin to estimate the channel velocity under the PMP condition. The size of the sub-basin should be small enough to satisfy the application of the rational formula. The *CN* value should then be estimated to apply the rational formula; also, the roughness coefficient and the shape of the channel cross-section at the exit of the sub-basin are required to estimate the flow velocity by applying Manning's equation.

The *CN* value (85.7) in Table 1 was used in this analysis to consider the most severe rainfall–runoff event with the smallest loss amount, among the rainfall events in the past. Most of the cross-sectional data could be obtained from the Hydrological Annual Report in Korea published by the Ministry of Environment, and other annual report from the K-water. They annually monitor the change of the channel cross-sectional area at most water stage monitoring stations by surveying the channel cross-section. This information is collected to develop the rating curve.

The roughness coefficient of the channel was also determined using the information of streambed material at the exit of the sub-basin. The information for the Imokjeonggyo sub-basin could be found in the Hydrological Survey Report (MLTM 2012a). In the case of no information being available, the information from nearby channels could be borrowed. Then, the roughness coefficient was assigned according to the composition of the bed materials, such as sand, gravel, and cobble. Their representative roughness coefficient values were assumed to be 0.03, 0.04, and 0.05, respectively, referring to Chow (1959). As an example, the channel bed at the exit of Imokjeonggyo sub-basin was found to be composed of sand and gravel, and the roughness coefficient was determined as their average to be 0.045.

The peak flow at the exit of the uppermost sub-basin could now be estimated by applying the rational formula. The concentration time was assumed to follow Equation (7), which value was used as an initial guess. The runoff coefficient C of the rational formula could be estimated by applying the SCS–CN method, such as in Equations (2) and (3). The total rainfall P and mean rainfall intensity could also be derived from the time-distributed PMP. Since the total rainfall P applied to the SCS–CN method varies depending on the rainfall duration, the runoff coefficient can thus be estimated differently. For example, the runoff coefficient C for the Imokjeonggyo sub-basin of the Chungju Dam Basin for the rainfall duration of 6 h was estimated to be 0.885, but for the rainfall duration of 12 h, became 0.915. Finally, the peak flow could be estimated for the rainfall duration of 6 h to be 1,818.9 m^3/s, and for the rainfall duration of 12 h, 1,404.4 m^3/s. Figure 2 summarizes the

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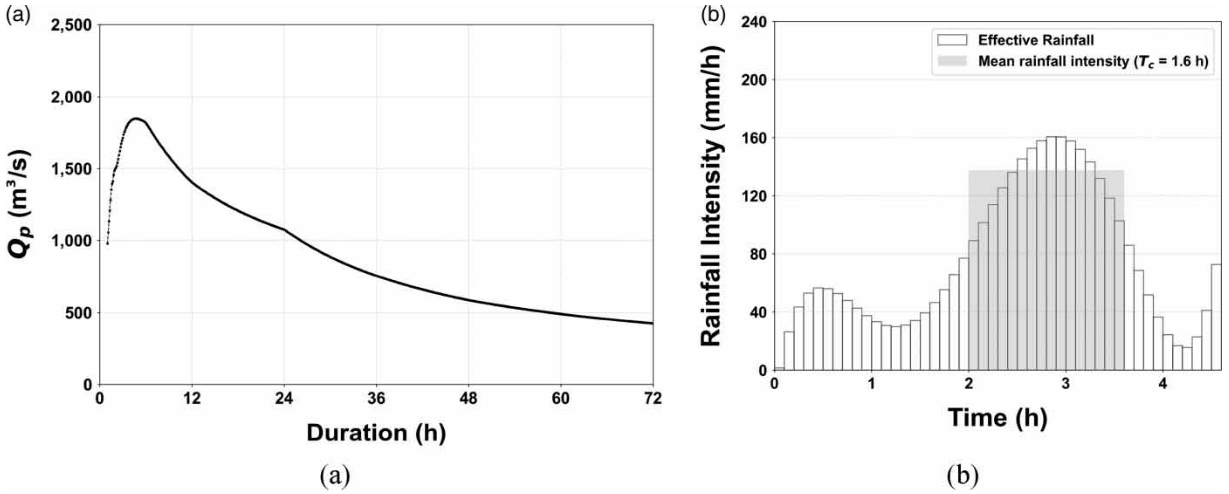

Figure 2 | Peak discharge estimation by the rational formula (Imokjeonggyo sub-basin): (a) Change of peak discharge with respect to the rainfall duration; (b) Mean rainfall intensity applied to the rational formula.

behavior of peak flow according to the rainfall duration and rainfall intensity for applying rational formula. This figure shows that the maximum peak flow was 1,848.0 m^3/s for the rainfall duration of 4.6 h. For this rainfall duration, the mean rainfall intensity was 137.7 mm/h.

The flow velocity corresponding to the PMF at the exit of the sub-basin could be estimated by applying Manning's equation. With the given roughness coefficient and the channel slope, the flow velocity could be estimated based on the trial-and-error approach. It was also possible to use the pre-determined flow rate (or flow)-velocity relation for the given location of interest. The flow velocity corresponding to the peak flow of the rational formula was determined to be approximately 6.48 m/s.

However, the estimated peak flow velocity was not the final value, but was merely used as an initial guess to find the final value. The reason for this was that the concentration time corresponding to the peak flow velocity, and the storage coefficient corresponding to the concentration time, i.e., the new Clark UH corresponding to the peak flow velocity, did not produce the same peak flow. As a second step, this new peak flow was used to derive the peak flow velocity, concentration time, and storage coefficient. A much closer peak flow could be derived at this step. After repeating this procedure, asymptotic values of the peak flow, flow velocity, concentration time, and storage coefficient could be derived. In fact, this procedure was necessary to fill the gap between the rational formula and the Clark UH. However, as a small sub-basin was considered in this step, the difference between the two was rather small. Just a few repetitions were enough to obtain the asymptotic values.

At the exit of the Imokjeonggyo sub-basin, the concentration time was estimated to be just 0.7 h. The storage coefficient was also similar to the concentration time, as the parameter α of Equation (10) was determined to be 0.982. Then, the Clark UH was applied to derive the peak flow, which was 1,887.6 m^3/s. In fact, this peak flow was slightly larger, by about 2%, than that estimated by applying the rational formula. The corresponding flow velocity was also slightly higher (6.53 m/s) than the original value (6.48 m/s). However, the next repetition derived very similar values to those in the previous step. The difference was far smaller than 1%. As a result, the flow velocity corresponding to the PMF at the exit of the Imokjeonggyo sub-basin could be determined.

The parameters of the Clark UH for the entire basin could be determined using the velocity information derived in the previous step. That is, the channel velocity under the same PMP condition was assumed to be the same. As explained in the previous section, this assumption was based on many studies (Rodríguez-Iturbe & Valdés 1979; Molnár & Ramírez 1998; Giannoni *et al.* 2000; Kampel *et al.* 2009), and also based on the data analysis by Yoo (2011) and Lee (2021). As a result, the concentration time could be determined by dividing the channel length by the channel flow velocity, and the storage coefficient as that corresponding to the concentration time. For example, the channel velocity of the Chungju Dam basin under

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the PMP condition was determined to be 6.5 m/s, and, therefore by considering the channel length of 282.2 km, the concentration time was calculated to be 12.1 h. Also, as α was estimated to be 1.517 based on Equation (10), the storage coefficient could be determined to be 18.3 h.

Validation by observed extreme events

Since the PMP is a kind of hypothetical design rainfall that significantly exceeds the scale of actual rainfall events, its verification is practically impossible. As a substitute, this study applied the proposed method to the observed extreme rainfall events.

The rainfall events considered in this part of the study were those extreme ones that occurred in the dam basins. The rainfall and runoff data, as well as the dam inflow data, could be found in WAMIS (www.wamis.go.kr). The areal average rainfall data for rainfall–runoff analysis were derived by applying the arithmetic average method using the rainfall data from the rain gauges within the dam basin. Table 5 summarizes basic information about those rainfall events. In this table, the peak flow is for the direct runoff, and the direct runoff was derived by applying the simple straight-line method.

It was also necessary to secure the rainfall information for the uppermost sub-basins of the dam basins. This information was used for the rational formula, and ultimately to derive the peak flow and peak flow velocity at the exit of the sub-basin. Table 6 summarizes the basic information for these rainfall events. Most sub-basins show different areal average rainfall from the dam basins. On the other hand, the Backcheon basin shows the same rainfall event as the Buandam basin. It is because there is only one available rain gauge in both basins.

The rainfall–runoff analyses for these three rainfall events were performed by applying the methodology explained in 'METHODOLOGY' section. The *CN* value for these cases was estimated using the information of soil and land cover. The estimated *CN* value was then modified by considering the antecedent 5-day rainfall amount as explained in Chow *et al.* (1988). Table 7 summarizes the derived results and shows the converged value of peak flow and velocity for the rainfall events, and the calculated peak dam inflow. These estimates were quite similar to those observed as shown in Figure 3. In each case, the difference between the observed and estimated peak dam inflow was found to be very small, at less than 9%. Even though only one rainfall event was considered for the dam basins, the derived result was assumed to strongly support the methodology in this study.

Table 5 | Basic characteristics of the major rainfall event for each dam basin

Dam basin	Starting time	Ending time	Rainfall duration (h)	Total rainfall (mm)	Antecedent 5-day rainfall (mm)	Peak dam inflow (m^3/s)
Chungju	Jul 14, 2006, 15:00	Jul 19, 2006, 03:00	109	631.5	292.7	21,968.5
Daecheong	Aug 30, 2002, 21:00	Sep 1, 2002, 3:00	31	478.1	14.2	10,056.3
Namgang	Jul 8, 2006, 17:00	Jul 10, 2006, 21:00	53	394.5	86.0	12,213.7
Andong	Jul 24, 2008, 20:00	Jul 26, 2008, 1:00	30	404.0	28.7	3,378.9
Imha	Sep 12, 2003, 0:00	Sep 13, 2003, 2:00	27	244.6	56.4	6,664.5
Juam (M)	Sep 14, 2007, 6:00	Sep 15, 2007, 12:00	31	267.0	54.3	3,361.8
Yongdam	Aug 7, 2020, 4:00	Aug 9, 2020, 3:00	48	392.3	84.0	4,394.9
Hapcheon	Jul 10, 2006, 5:00	Jul 10, 2006, 16:00	12	161.6	94.9	3,202.5
Unmun	Sep 6, 2020, 19:00	Sep 7, 2020, 15:00	21	277.3	223.0	2,835.6
Hoengseong	Jul 14, 2006, 10:00	Jul 19, 2006, 2:00	113	627.4	257.4	1,107.5
Boryeong	Jul 23, 2010, 14:00	Jul 24, 2010, 7:00	18	228.7	0.9	1,184.6
Juam (R)	Jul 15, 2009, 23:00	Jul 16, 2009, 12:00	14	191.6	183.2	979.2
Sayeon	Oct 2, 2019, 6:00	Oct 3, 2019, 8:00	27	229.4	9.1	633.8
Milyang	Sep 6, 2020, 17:00	Sep 7, 2020, 14:00	22	295.3	275.5	1,035.9
Daeam	Oct 5, 2016, 1:00	Oct 5, 2016, 13:00	13	282.8	14.5	1,424.7
Buan	Aug 9, 2011, 6:00	Aug 10, 2011, 6:00	25	305.0	35.8	639.7

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Table 6 | Basic characteristics of the same rainfall event for the uppermost sub-basins

Sub-basin	Starting time	Ending time	Rainfall duration (h)	Total rainfall (mm)	Antecedent 5-day rainfall (mm)
Imokjeonggyo	Jul 11, 2006, 23:00	Jul 19, 2006, 02:00	172	795.4	81.4
Baekhwagyo	Aug 30, 2002, 22:00	Sep 1, 2002, 3:00	30	356.0	13.7
Sohori	Jul 10, 2006, 5:00	Jul 10, 2006, 17:00	13	223.8	145.2
Munhwagyo	Jul 24, 2008, 20:00	Jul 26, 2008, 1:00	30	341.2	29.5
Cheongamgyo	Sep 12, 2003, 1:00	Sep 13, 2003, 2:00	26	205.6	43.2
Gajanggyo	Sep 14, 2007, 14:00	Sep 15, 2007, 12:00	23	245.5	59.2
Ungokgyo	Aug 5, 2020, 14:00	Aug 9, 2020, 3:00	86	406.7	9.0
Namhagyo	Jul 10, 2006, 5:00	Jul 10, 2006, 16:00	12	93.5	72.8
Uigokgyo	Sep 6, 2020, 21:00	Sep 7, 2020, 11:00	15	194.6	204.5
Podong2gyo	Jul 14, 2006, 15:00	Jul 19, 2006, 0:00	106	397.2	195.5
Seongjucheon	Jul 23, 2010, 14:00	Jul 24, 2010, 7:00	18	248.6	0.6
Songjeongyo	Jul 11, 2009, 12:00	Jul 16, 2009, 12:00	121	376.0	235.5
Bangugyo	Oct 2, 2019, 6:00	Oct 3, 2019, 8:00	27	229.9	8.9
Daeri	Sep 5, 2020, 12:00	Sep 7, 2020, 14:00	51	155.3	136.7
Wangbanggyo	Oct 5, 2016, 1:00	Oct 5, 2016, 12:00	12	246.3	17.2
Baekcheon	Aug 9, 2011, 6:00	Aug 10, 2011, 6:00	25	305.0	35.8

Table 7 | Comparison of peak flows and peak flow velocities derived for the sub-basins and the dam basins

	Sub-basin					Dam basin		
	Rational formula		Converged value					
Dam basin	Peak flow (m^3/s)	Peak velocity (m/s)	Peak flow (m^3/s)	Peak velocity (m/s)	Sub-basin	T_c (h)	K (h)	Peak dam inflow (m^3/s)
Chungju	1,151.6	5.5	985.6	5.2	Imokjeonggyo	15.1	18.1	19,838.1
Daecheong	894.6	5.6	1,068.6	6.0	Baekhwagyo	8.8	10.6	9,548.6
Namgang	1,042.5	4.2	1,081.9	4.2	Sohori	7.5	7.9	11,232.0
Andong	579.8	3.8	506.6	3.7	Munhwagyo	13.0	21.2	3,432.9
Imha	2,177.1	4.8	2,615.8	5.1	Cheongamgyo	5.3	6.3	5,879.9
Juam (M)	1,402.8	3.1	1,301.4	3.0	Gajanggyo	8.5	10.9	3,050.4
Yongdam	412.4	4.0	422.7	4.0	Ungokgyo	4.3	3.9	3,670.4
Hapcheon	911.8	3.7	914.2	3.7	Namhagyo	4.8	4.5	2,974.6
Unmun	499.2	4.1	541.0	4.2	Uigokgyo	2.5	2.5	2,810.9
Hoengseong	944.0	3.1	848.5	3.0	Podong2gyo	3.6	4.4	1,073.4
Boryeong	275.7	3.8	361.1	4.2	Seongjucheon	1.6	1.3	994.4
Juam (R)	613.7	3.3	543.7	3.2	Songjeongyo	2.1	1.9	896.8
Sayeon	412.8	3.8	554.7	4.2	Bangugyo	1.5	1.3	658.1
Milyang	303.9	3.3	341.6	3.4	Daeri	1.9	1.9	987.8
Daeam	345.9	4.0	450.7	4.3	Wangbanggyo	1.1	0.9	1,107.2
Buan	336.9	3.8	305.1	3.7	Baekcheon	1.2	1.0	550.2

RESULTS AND DISCUSSION

Parameters of the Clark UH for PMF

The basic parameters required for the estimation of peak flow velocity at the exit of the uppermost sub-basin were obtained one-by-one. First, based on the bed material composition, the roughness coefficient could be assigned (MLTM 2012a; MOLIT

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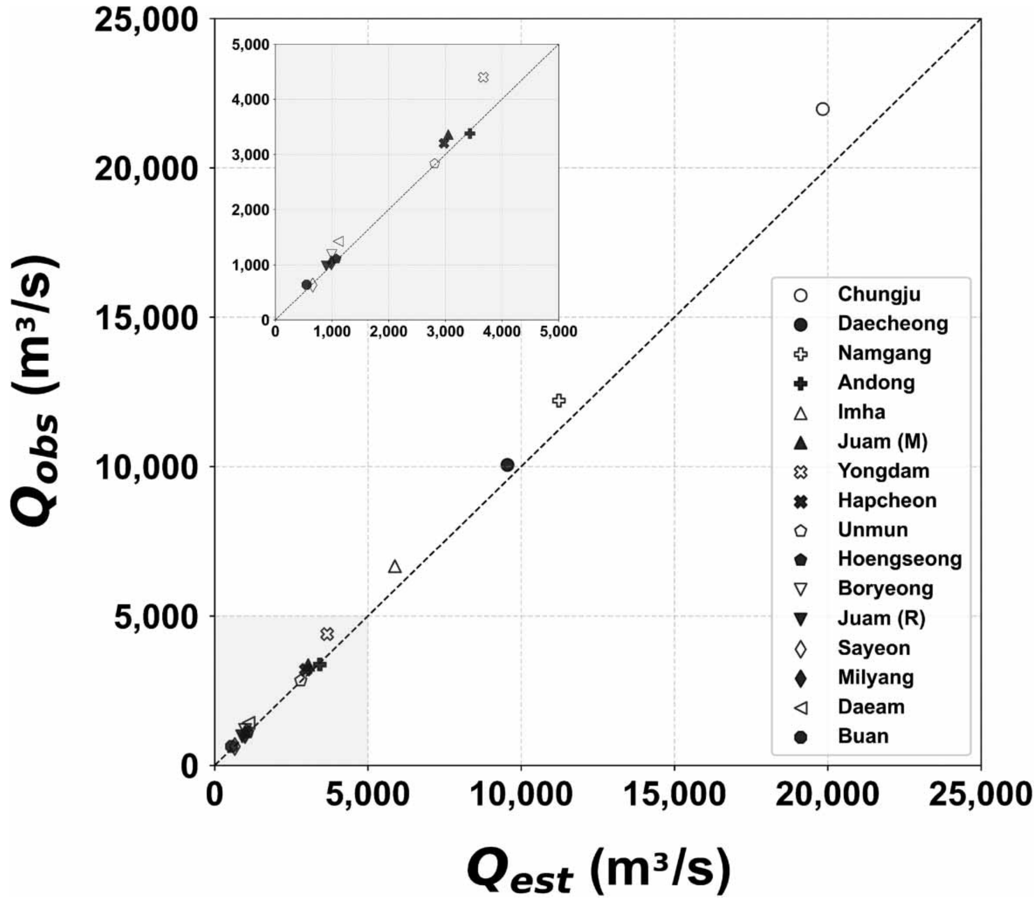

Figure 3 | Comparison of observed and simulated peak discharges at the exit of dam basins.

2016, 2017; ME 2020). The range of the assigned roughness coefficients was 0.03–0.05, with their mean of 0.041. The *CN* values in Table 1 were also used in this analysis.

In most cases, the asymptotic values could be determined after repeating the procedure just two or three times by following the same procedure. The smallest value of flow velocity was determined to be 5.1 m/s for the Sohori sub-basin, and the largest one to be 7.1 m/s for the Bangugyo sub-basin. On average, the flow velocity was about 6.1 m/s.

Additionally, it is also worth mentioning that the peak flow determined simply by applying the rational formula was very similar to that by applying the Clark UH. In fact, all of their differences were insignificant (see Figure 4). This result confirms the applicability of the rational formula to a small sub-basin, where the storage effect is not that significant. The authors of this study assume that the peak flow determined by applying the rational formula is adequate for determining the corresponding peak flow velocity in a basin.

Using the peak flow velocity determined under the PMP condition, it was possible to estimate the other parameters for the Clark UH. The parameters determined under the PMP condition are less than one half of those under the ordinary condition. This is straightforward, because the peak flow velocity under the PMP condition was estimated to be twice or more than that under the ordinary condition. The minimum ratio between the two was found at the Chungju Dam basin (0.39), while the maximum one at the Boryeong Dam basin (0.53). The mean value was about 0.44. Also, the median value was similar at 0.43. In the Box-plot analysis of those ratios, no outlier was found. As the Russel coefficient α was assumed unchanged under the PMP condition, both the concentration time and storage coefficient showed the same trend of change.

Figure 5 confirms the hypothesis that the two parameter sets determined for each basin under the ordinary and PMP conditions are consistently related. Basically, their relation is found to be linear, and the linear regression line passes the origin. The coefficient of determination is also estimated to be very high, at 0.98 for the concentration time, and 0.99 for the storage

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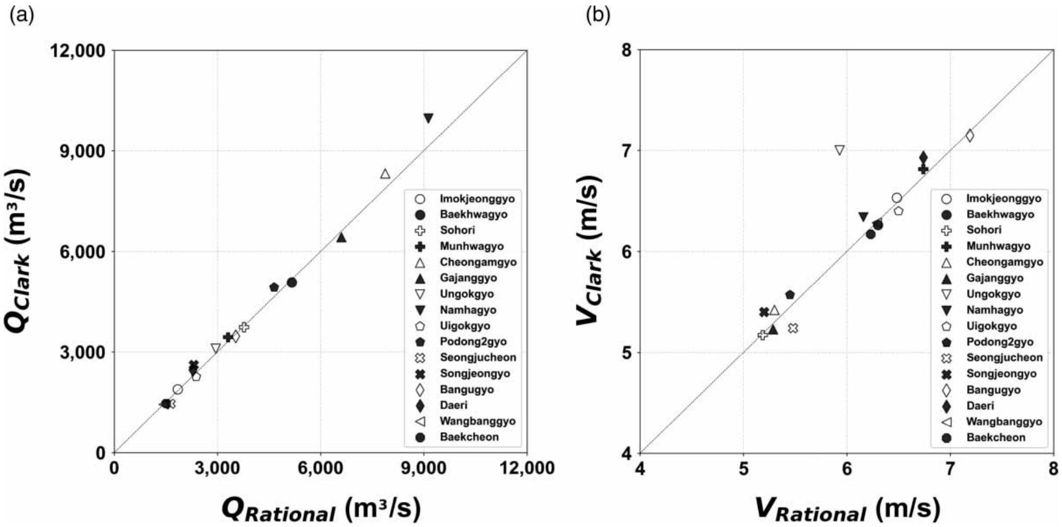

Figure 4 | Comparison of peak flow and peak flow velocity estimated by the rational formula and those converged values: (a) Peak flow and (b) Peak flow velocity.

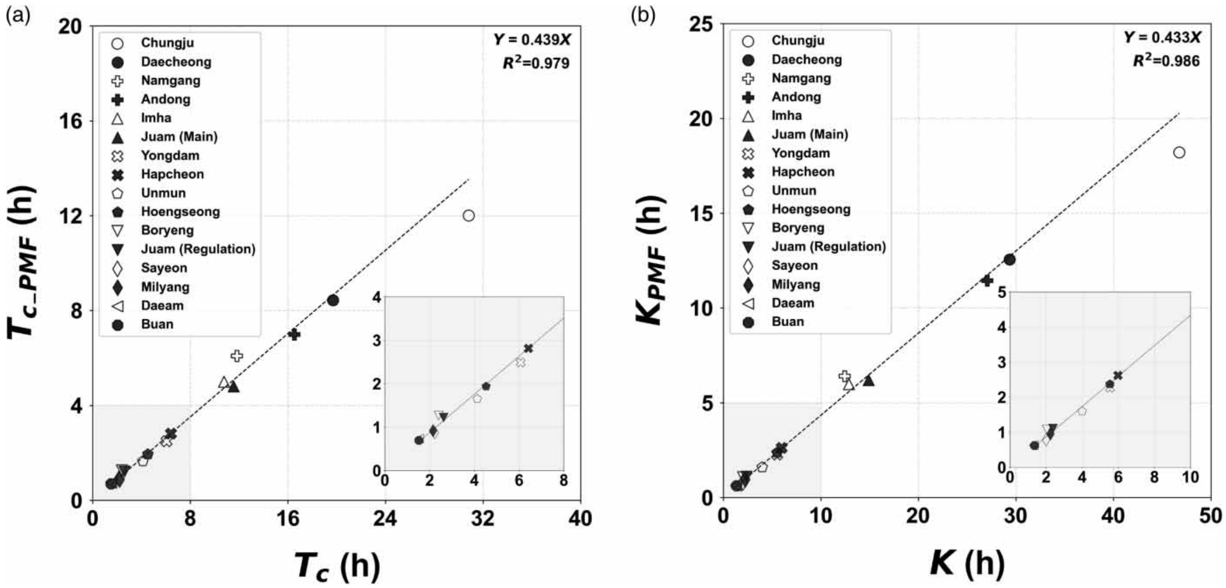

Figure 5 | Comparison of PMP-UH parameters and Ordinary-UH parameters: (a) Concentration time and (b) Storage coefficient.

coefficient. Finally, the slope was estimated to be just 0.44 for both the concentration time and storage coefficient. As a result, the authors assumed that it is possible to apply the ratio 0.44 to determining the parameters of the PMP-UH.

PMFs for major dam basins in Korea

The parameters of the Clark UH under the PMP condition were determined by multiplying those values determined under the ordinary condition by the constant 0.44. The parameter α was borrowed from previous reports. In the case of using different values, the mean value was adopted. Table 8 compares these parameters determined for each dam basin. Additionally, this table provides the parameters adopted in the previous studies (K-water 2004, 2008; KDI 2007). In K-water (2004), the parameters for all dam basins could be found; but, in KDI (2007), only three dam basins were considered, namely the Hapcheon Dam, Unmun Dam, and Buan Dam. Also, just three dam basins, namely the Namgang Dam, Hapcheon Dam, and

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Table 8 | Comparison of Clark UH parameters under the PMP condition

			PMF-UH							
	Ordinary-UH		This study		K-water (2004)		KDI (2007)		K-water (2008)	
Dam basin	T_c (h)	K (h)	T_c (h)	K (h)	T_c (h)	K (h)	T_c (h)	K (h)	T_c (h)	K (h)
Chungju	30.8	17.6	13.6	7.8	14.0	8.0				
Daecheong	19.7	4.8	8.7	2.1	16.0	3.9				
Namgang	11.8	5.5	5.2	2.4	7.1	3.1			5.2	2.5
Andong	16.6	9.3	7.3	4.1	8.0	4.5				
Imha	10.8	5.4	4.7	2.4	6.6	3.3				
Juam (M)	11.6	10.5	5.1	4.6	6.7	6.1				
Yongdam	6.1	5.3	2.7	2.3	3.0	2.6				
Hapcheon	6.4	10.7	2.8	4.7	1.8	3.7	1.0	2.0	2.2	2.4
Unmun	4.1	2.2	1.8	1.0	1.8	0.9	1.9	1.1		
Hoengseong	4.5	5.3	2.0	2.3	1.8	2.1				
Boryeong	2.4	1.6	1.1	0.7	2.6	1.2			1.7	1.5
Juam (R)	2.6	4.5	1.2	2.0	2.0	3.4				
Sayeon	2.2	2.0	1.0	0.9	4.2	3.8				
Milyang	2.1	2.7	0.9	1.2	1.5	1.9				
Daeam	1.5	1.3	0.7	0.6	1.3	1.1				
Buan	1.5	0.5	0.7	0.2	2.9	0.4	1.0	0.5		

Boryeong Dam, were considered in K-water (2008). Figure 6 compares all the Clark UHs available in Table 8 for the Hapcheon Dam basin as an example:

It is obvious that the peak time and peak flow are highly dependent upon the parameters of the Clark UH. It is thus interesting to compare the ratios of peak time and peak flow of the Clark UH under the PMP condition to those under the ordinary condition, as in Figure 6. As the Clark UH under the ordinary condition is assumed to be rather consistent, the simple comparison of the Clark UH under the PMP condition to that under the ordinary condition might be useful to evaluate the consistency of the Clark UH under the PMP condition.

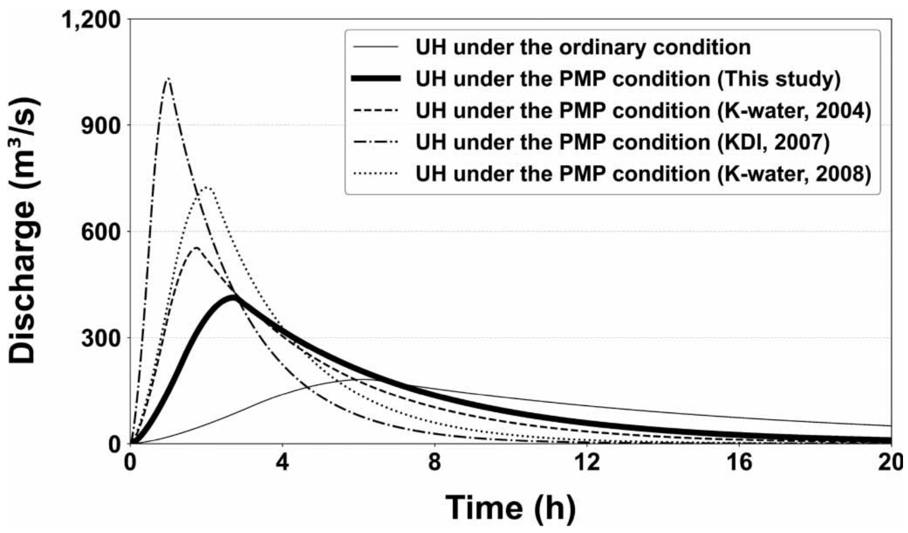

Figure 6 | Comparison of the PMP-UHs and Ordinary-UH for the Hapcheon Dam basin.

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First, the peak time of the proposed PMP-UH in this study is just 44% of the Ordinary-UH, and the peak flow is 227% of the Ordinary-UH. This relation is the same for all dam basins, as the same ratio was applied to the parameters under the ordinary condition for their application to the PMP condition. As a result, the peak time of the Ordinary-UH was reduced by 56%, but the peak flow was increased by 127%. In fact, this change was greater than that of the other methods reviewed in the introduction section. For example, the peak time of the PMP-UH in the United Kingdom was reduced by 33%, while the peak flow was increased by 50% from the ordinary-UH.

However, in the previous reports, these change ratios from the ordinary-UH to the PMP-UH were inconsistent. For example, the ratios of peak time in K-water (2004) were found to be within the large range of 29–189%. The ratios of peak flow were also similar, having the large range of 53–305%. On average, the ratios of peak time and peak flow were about 74 and 167%, respectively; i.e., in most cases, the PMF was underestimated. This underestimation problem was slightly alleviated, but the inconsistency was the same in KDI (2007). That is, the ratio of peak time ranged about 16–74% (46% on average), and that of peak flow by about 125–567% (301% on average). It was also the same in K-water (2008). That is, the ratio of peak time ranged about 33–73% (50% on average), and that of peak flow by about 123–398% (248% on average).

The runoff hydrograph was derived by applying the Clark UH to the rainfall histogram. This temporally-distributed rainfall histogram in this study was derived by applying the Huff method, which is the one officially accepted in Korea. Figure 7 provides two panels; one is of the 100-year runoff hydrograph, while the other is of the PMF hydrographs derived by applying several parameter sets of those considered in this study. These hydrographs are all for the Hapcheon Dam basin, which was selected as it had been handled in more reports. This figure shows that the PMF was estimated far greater than the 100-year peak flow, even though it was also dependent upon the parameter sets in those previous reports. For example, the PMF estimated by applying the parameters proposed in this study was about 8.4 times greater than the 100-year peak flow. On the other hand, the application results of K-water (2004), KDI (2007), and K-water (2008) showed that the PMF could be greater than the 100-year peak flow by about 9.1, 10.6, and 10.2 times, respectively.

Table 9 summarizes the PMFs derived for the dam basins considered in this study. The ratios of PMF to the 100-year peak flow are also provided for easier comparison. Interestingly, the overall results were found to be similar to each other. For example, the application of the proposed method in this study provided the ratio of PMF to the 100-year peak flow of from 4.48 to 9.44. On average, it was 6.77. The application of the parameter sets in K-water (2004) provided the ratios from 3.75 to 9.13 with their average of 6.41. The average ratios in the application of the parameter sets in KDI (2007) and K-water (2008) were also similar at 6.85 and 6.42, respectively. As KDI (2007) and K-water (2008) considered just three dam basins, it might not be meaningful to mention the minimum and maximum ratios. Overall, the PMFs were all estimated to be about six to seven times greater than the 100-year peak flow. However, the problem lies in the inconsistency and uncertainty in their application.

Finally, this study investigated the possible effect from the size of the dam basin area, with the results in this study, and those in K-water (2004). This study set the threshold basin area to be 1,000 km^2 by following the previous studies (Uhlenbrook *et al.* 2004; Zhang *et al.* 2017; Yoo *et al.* 2020) that classified basins over 1,000 km^2 as macro or large basins and divided the dam basins into two groups. The threshold dam basin area was an arbitrary one, to simply divide the dam basins into two groups. As a result, it was found that just six dam reservoirs were included in the large area group, while the remaining 10 dam basins were included in the small area group. The comparisons were made using boxplots, which Figure 8 shows:

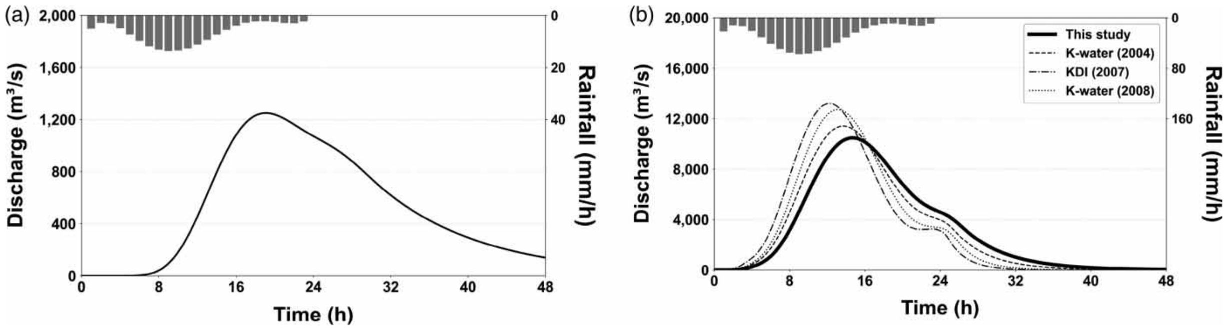

Figure 7 | Comparison of runoff hydrographs at the exit of the Hapcheon Dam basin: (a) 100-year flood and (b) PMF.

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Table 9 | Comparison of the 100-year flood and estimated PMFs

			PMF							
	100-year flood		This study		K-water (2004)		KDI (2007)		K-water (2008)	
Dam basin	T_p (h)	Q_p (m^3/s)	T_p (h)	Q_p (m^3/s)	T_p (h)	Q_p (m^3/s)	T_p (h)	Q_p (m^3/s)	T_p (h)	Q_p (m^3/s)
Chungju	41.6	5,363.7	27.2	41,140.4	27.5	40,318.7				
Daecheong	25.3	5,313.9	16.5	31,840.1	21.9	24,205.3				
Namgang	25.6	6,217.4	20.6	30,079.6	21.8	27,897.2			20.6	29,851.4
Andong	29.8	1,705.4	22.0	15,207.9	22.5	14,697.5				
Imha	25.3	2,054.7	20.4	16,030.3	21.7	14,616.0				
Juam (M)	26.9	1,670.1	21.2	15,774.3	22.4	13,968.0				
Yongdam	17.8	1,806.1	13.7	1,2137.3	14.1	11,851.6				
Hapcheon	19.1	1,249.6	14.7	10,474.0	13.7	11,414.4	12.3	13,201.7	13.1	12,714.3
Unmun	19.7	965.8	17.6	5,355.4	17.5	5,376.8	17.7	5,318.5		
Hoengseong	17.6	420.8	13.6	3,279.8	13.3	3,332.8				
Boryeong	13.2	729.8	11.4	3,269.1	12.7	3,161.0			12.5	3,123.5
Juam (R)	20.6	332.7	18.2	3,094.8	19.3	2,767.5				
Sayeon	13.4	594.7	11.4	2,763.3	15.2	2,230.2				
Milyang	19.3	274.9	17.4	2,057.6	18.1	1,969.5				
Daeam	12.6	367.2	11.1	1,779.9	11.8	1,736.3				
Buan	11.6	283.4	11.0	1,275.3	12.0	1,258.7	11.2	1,268.9		

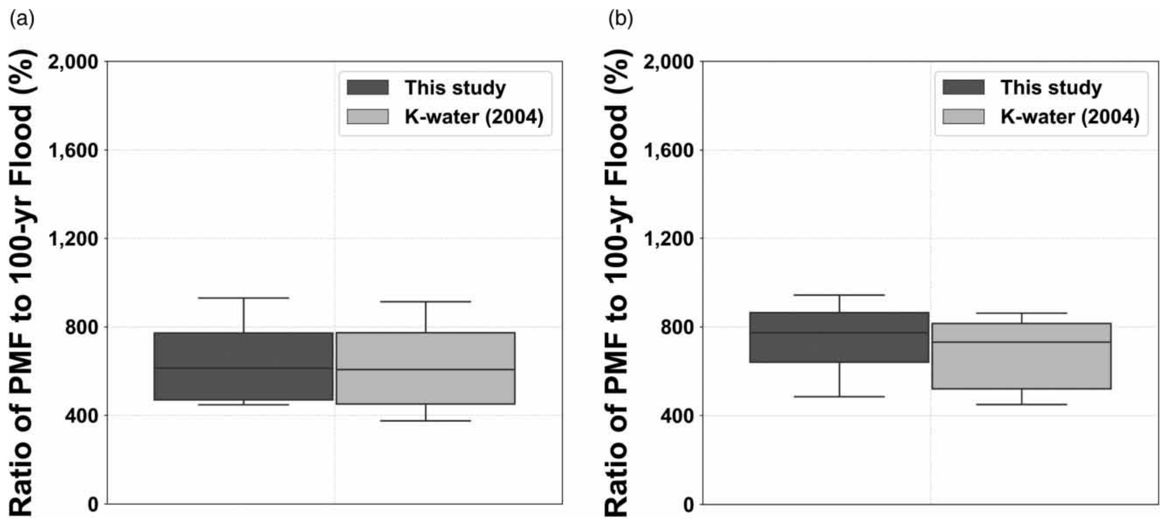

Figure 8 | Boxplots for the ratio of PMF to 100-year flood (Table 9) and their comparison with the previous study by K-water (2004) with respect to the dam basin areas: (a) Smaller than 1,000 km^2 and (b) Larger than 1,000 km^2.

The figure shows that the two groups did not show any significant difference. In particular, the results for the small basin area groups were quite similar to each other. Their medians were all around 6.1. On the other hand, some amount of difference could be found in the large area group; however, their difference seemed to not be so significant. The median of this study was slightly higher than that of K-water (2004) (i.e., 7.5 and 6.8, respectively), but their ranges were all found to be similar.

CONCLUSION

The PMF is considered when designing a dam. The PMF is the flood caused by the PMP, and a UH is generally used to derive the PMF for the given PMP. Since the response under the PMP condition becomes much faster and stronger than that under the

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ordinary condition, a method is needed to modify the UH parameters to reflect the PMP condition. In Korea, the Clark UH is mostly used for rainfall–runoff analysis. However, there are still no clear guidelines for determining the Clark UH parameters (i.e., the concentration time and storage coefficient) under the PMP condition, due to various limitations, like the record length of rainfall and runoff measurement. Thus, this study proposed a new method based on the channel velocity under the PMP condition. The derived channel velocity under the PMP condition was then used to modify the Clark UH parameters under the ordinary condition, into those under the PMP condition. The results derived by applying the proposed method to most dam basins in Korea were compared with those in the previous studies. Their comparison was also made with several consistency measures, like the PMF ratio to the 100-year design flood. The results of this study may be summarized as follows:

First, the peak flow velocity for the uppermost small sub-basin of each dam basin could be estimated by applying the rational formula and Manning's equation. This approach was found effective for the ungauged sub-basin without any runoff measurements. The concentration time of the Clark UH was also found to be very similar to that estimated by considering the peak flow velocity. Second, the Clark UH parameters under the PMP condition could be determined, based on the assumption that the peak flow velocity remains unchanged for the entire dam basin under the same rainfall event. The estimated parameters were found to be within the range 39–53% of those under the ordinary condition, whose mean value was about 44%. The derived UH by applying this mean ratio (i.e., the PMP-UH) shows that its peak time is just 44% of the UH under the ordinary condition (i.e., the ordinary-UH), while the peak flow is 227% of the Ordinary-UH. That is, the change from the ordinary condition to the PMP condition was found to be more extreme in Korea, than those in Australia and the United Kingdom.

These change ratios from the ordinary-UH to the PMP-UH were found to be inconsistent in the previous reports. The ratios of peak time in K-water (2004) were found to be within the range 29–189%, and the ratios of peak flow within the range 53–305% (on average, about 74 and 167%, respectively). It was also found that the PMF was underestimated in K-water (2004). This underestimation problem was slightly alleviated, but the inconsistency was the same in KDI (2007). The same problem could also be found in K-water (2008).

As a conclusion, the proposed method in this study was confirmed to provide an easier and more consistent estimate of the PMF. Another advantage is that the proposed method can be applied easily in ungauged basins. More extreme change from the ordinary-UH to the PMP-UH than those in Australia and the United Kingdom might be due to the climate in Korea. Located in the Asian Monsoon region, the PMF, as well as the PMP, was estimated to be quite higher than for the flood under the ordinary condition. It is also noticeable that the average ratio between the PMF and the 100-year flood was estimated to be similar to those in the previous reports. That is, on average, the size of the PMF was more or less the same as in the previous reports, but this study could solve the serious inconsistency problem.

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DATA AVAILABILITY STATEMENT

Data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Adib, A., Lotfirad, M. & Haghighi, A. 2019 Using uncertainty and sensitivity analysis for finding the best rainfall-runoff model in mountainous watersheds (Case study: the Navrood watershed in Iran). *Journal of Mountain Science* **16** (3), 529–541. https://doi.org/10.1007/s11629-018-5010-6.

Angel, J. R. & Huff, F. A. 1997 Changes in heavy rainfall in Midwestern United States. *Journal of Water Resources Planning and Management* **123** (4), 246–249. https://doi.org/10.1061/(ASCE)0733-9496(1997)123:4(246).

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ASCE 2017 *Standard Guidelines for the Design, Installation, and Operation and Maintenance of Urban Stormwater Systems*. American Society of Civil Engineers, Virginia, USA.

Beauchamp, J., Leconte, R., Trudel, M. & Brissette, F. 2013 Estimation of the summer-fall PMP and PMF of a northern watershed under a changed climate. *Water Resources Research* **49**, 3852–3862. https://doi.org/10.1002/wrcr.20336.

Chen, L. C. & Bradley, A. A. 2006 Adequacy of using surface humidity to estimate atmospheric moisture availability for probable maximum precipitation. *Water Resources Research* **42**, W09410. https://doi.org/10.1029/2005wr004469.

Chow, V. T. 1959 *Open-channel Hydraulics*. McGraw-Hill, New York, USA.

Chow, V. T., Maidment, D. R. & Mays, L. W. 1988 *Applied Hydrology*. McGraw-Hill, New York, USA.

Dhakal, N., Fang, X., Cleveland, T. G., Thompson, D. B., Asquith, W. H. & Marzen, L. J. 2012 Estimation of volumetric runoff coefficients for Texas watersheds using land-use and rainfall-runoff data. *Journal of Irrigation and Drainage Engineering* **138** (1), 43–54. https://doi.org/10.1061/(asce)ir.1943-4774.0000368.

Douglas, E. M. & Fairbank, C. A. 2011 Is precipitation in northern New England becoming more extreme? Statistical analysis of extreme rainfall in Massachusetts, New Hampshire, and Maine and updated estimates of the 100-year storm. *Journal of Hydrologic Engineering* **16** (3), 203–217. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000303.

FERC 2001 *Engineering Guidelines for the Evaluation of Hydropower Projects*. Federal Energy Regulatory Commission, Washington, DC, USA.

Ghumman, A. R., Khan, Q. U., Hashmi, H. N. & Ahmad, M. M. 2014 Comparison of Clark, Nash geographical instantaneous unit hydrograph models for semi arid regions. *Water Resources* **41** (4), 364–371. https://doi.org/10.1134/s0097807814040071.

Giannoni, F., Roth, G. & Rudari, R. 2000 A semi-distributed rainfall-runoff model based on a geomorphologic approach. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* **25** (7-8), 665–671. https://doi.org/10.1016/s1464-1909(00)00082-4.

Gori, A., Lin, N. & Xi, D. 2020 Tropical cyclone compound flood hazard assessment: from investigating drivers to quantifying extreme water levels. *Earth's Future* **8** (12), e2020EF001660. . https://doi.org/10.1029/2020EF001660.

IEA 1987 *Australian Rainfall and Runoff: A Guide to Flood Estimation*. Institution of Engineers, Australia, Canberra, Australia.

Jeong, J. H. & Yoon, Y. N. 2007 *Design Practices in Water Resources*. Goomi Press, Seoul, Korea.

Jeong, J. H., Keum, J. H. & Yoon, Y. N. 2002 Development of an estimation method for travel time. *Journal of Korea Water Resources Association* **35** (6), 715–727. https://doi.org/10.3741/JKWRA.2002.35.6.715.

Jothityangkoon, C., Hirunteeyakul, C., Boonrawd, K. & Sivapalan, M. 2013 Assessing the impact of climate and land use changes on extreme floods in a large tropical catchment. *Journal of Hydrology* **490**, 88–105. https://doi.org/10.1016/j.jhydrol.2013.03.036.

JSCE 1999 *The Collection of Hydraulic Formulae*. Japan Society of Civil Engineers, Tokyo, Japan.

Kampel, G., Goldsztein, G. H. & Santamarina, J. C. 2009 Particle transport in porous media: the role of inertial effects and path tortuosity in the velocity of the particles. *Applied Physics Letters* **95** (19), 194103. https://doi.org/10.1063/1.3263718.

KDI 2007 *Adequacy Review of Dam Design Criteria – Focus on Estimating PMP and PMF*. Korea Development Institute, Yeongi, Korea.

Kim, J., Ryu, G. & Jeong, J. 2017 A practical method to prevent an overestimation of peak discharge in a small watershed. *Journal of the Korean Society of Hazard Mitigation* **17** (4), 295–305. https://doi.org/10.9798/kosham.2017.17.4.295.

KISTEC 2013 *A Study on the Improvement of the Existing Dam Flood Assessment Method*. Korea Infrastructure Safety and Technology Corporation, Goyang, Korea.

Kjeldsen, T. R., Kim, H., Jang, C. H. & Lee, H. 2016 Evidence and implications of nonlinear flood response in a small mountainous watershed. *Journal of Hydrologic Engineering* **21** (8), 04016024. https://doi.org/10.1061/(asce)he.1943-5584.0001343.

K-water 2004 *Review of the Hydrological Stability of Dams and Establishment of a Basic Plan for Increasing Flood Control Capacity*. Ministry of Construction and Transportation, Seoul, Korea.

K-water 2008 *Establishment of Guidelines for Estimating Procedure of PMP and PMF*. Ministry of Land, Transport and Maritime Affairs, Seoul, Korea.

KWRA 2019 *Commentary of Rivers Design Standard*. Korea Water Resources Association, Seoul, Korea.

Lee, J. 2021 *Determination of Clark Unit Hydrograph Parameters for Estimating Probable Maximum Flood*. *PhD Dissertation*, Korea University, Seoul, Korea.

Lee, J. & Yoo, C. 2022 Use of basin outlet velocity to determine the basin concentration time and storage coefficient. *Hydrology Research* **53** (10), 1304–1320. https://doi.org/10.2166/nh.2022.066.

McCuen, R. H. & Bondelid, T. R. 1981 Relation between curve number and runoff coefficient. *Journal of the Irrigation and Drainage Division* **107** (4), 395–400. https://doi.org/10.1061/jrcea4.0001425.

ME 2019 *Standard Guidelines for Flood Estimation*. Ministry of Environment, Sejong, Korea.

ME 2020 *Hydrological Annual Report on Korea*. Ministry of Environment, Sejong, Korea.

MLTM 2012a *Hydrological Annual Report on Korea*. Ministry of Land, Transport and Maritime Affairs, Seoul, Korea.

MLTM 2012b *Design Flood Estimation Guidelines*. Ministry of Land, Transport and Maritime Affairs, Seoul, Korea.

MOCT 2001 *Commentary of Dam Design Criteria*. Ministry of Construction and Transportation, Seoul, Korea.

MOCT 2004 *National PMP Map Rebuild Report*. Ministry of Construction and Transportation, Seoul, Korea.

MOLIT 2016 *Hydrological Annual Report on Korea*. Ministry of Land, Infrastructure and Transport, Sejong, Korea.

MOLIT 2017 *Hydrological Annual Report on Korea*. Ministry of Land, Infrastructure and Transport, Sejong, Korea.

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Molnár, P. & Ramírez, J. A. 1998 Energy dissipation theories and optimal channel characteristics of river networks. *Water Resources Research* **34** (7), 1809–1818. https://doi.org/10.1029/98wr00983.

NERC 1975 *Flood Studies Report*. Natural Environment Research Council, London, United Kingdom.

Rodríguez-Iturbe, I. & Valdés, J. B. 1979 The geomorphologic structure of hydrologic response. *Water Resources Research* **15** (6), 1409–1420. https://doi.org/10.1029/wr015i006p01409.

Russell, S. O., Sunnell, G. J. & Kenning, B. F. 1979 Estimating design flows for urban drainage. *Journal of the Hydraulics Division* **105** (1), 43–52. https://doi.org/10.1061/jyceaj.0005144.

Sabol, G. V. 1988 Clark unit hydrograph and R-parameter estimation. *Journal of Hydraulic Engineering* **114** (1), 103–111. https://doi.org/10.1061/(asce)0733-9429(1988)114:1(103).

Uhlenbrook, S., Roser, S. & Tilch, N. 2004 Hydrological process representation at the meso-scale: the potential of a distributed, conceptual catchment model. *Journal of Hydrology* **291** (3–4), 278–296. https://doi.org/10.1016/j.jhydrol.2003.12.038.

Yigzaw, W. & Hossain, F. 2016 Land use and land cover impact on probable maximum flood and sedimentation for artificial reservoirs: case study in the Western United States. *Journal of Hydrologic Engineering* **21** (2), 05015022. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001287.

Yoo, C. 2009 A theoretical review of basin storage coefficient and concentration time using the Nash model. *Journal of Korea Water Resources Association* **42** (3), 235–246. https://doi.org/10.3741/jkwra.2009.42.3.235.

Yoo, C. 2011 Is the flow velocity the same upstream and downstream? *Water for Future* **44** (9), 89–99.

Yoo, C., Lee, J., Park, C. & Jun, C. 2014 Method for estimating concentration time and storage coefficient of the Clark model using rainfall-runoff measurements. *Journal of Hydrologic Engineering* **19** (3), 626–634. https://doi.org/10.1061/(asce)he.1943-5584.0000828.

Yoo, C., Lee, J. & Cho, E. 2019 Theoretical evaluation of concentration time and storage coefficient with their application to major dam basins in Korea. *Water Supply* **19920**, 644–652. https://doi.org/10.2166/ws.2018.156.

Yoo, C., Shin, H. & Lee, J. 2020 Evaluation of the storage effect considering possible redevelopment options of the Peace Dam in South Korea. *Water* **12** (6), 1674. https://doi.org/10.3390/w12061674.

Yoon, Y. N. 2007 *Hydrology*. Cheongmungak, Paju, Korea.

Zhang, M., Liu, N., Harper, R., Li, Q., Liu, K., Wei, X., Ning, D., Hou, Y. & Liu, S. 2017 A global review on hydrological responses to forest change across multiple spatial scales: importance of scale, climate, forest type and hydrological regime. *Journal of Hydrology* **546**, 44–59. https://doi.org/10.1016/j.jhydrol.2016.12.040.

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