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# Use of basin outlet velocity to determine the basin concentration time and storage coefficient

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## ABSTRACT

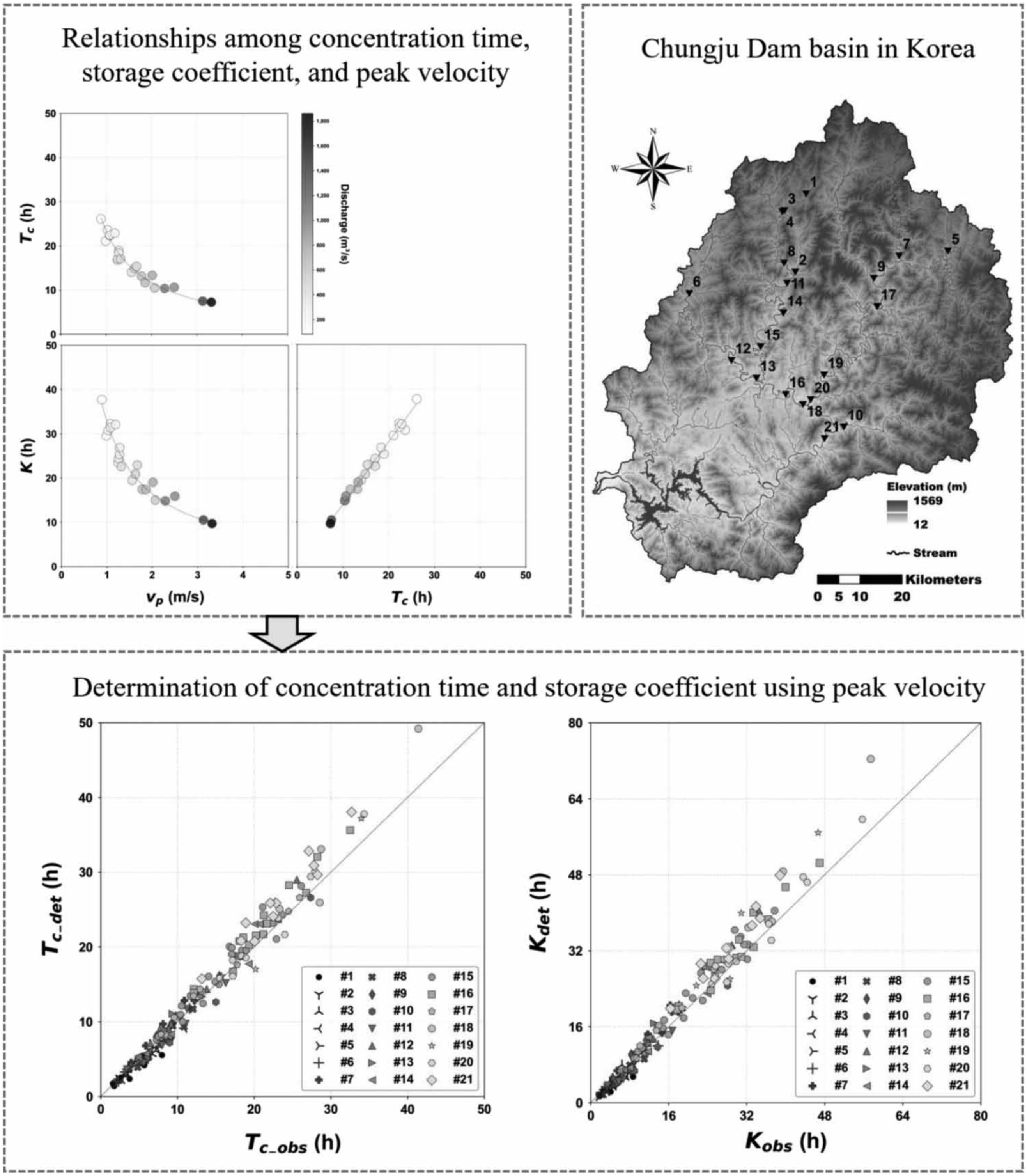
Most empirical formulae for the basin concentration time ($T_c$) and storage coefficient ($K$) focus on estimating the representative values under the ordinary condition, with their return period being a maximum of 100–200 years. Under more extreme conditions, those parameters should be modified to consider faster velocity conditions. The main objective of this study is to examine the possibility of determining these parameters corresponding to the given peak velocity ($v_p$) at the basin outlet. Two issues are involved in this problem; one is whether $T_c$ can be fully expressed by $v_p$, while the other is whether $K$ is still linearly proportional to $T_c$ under extreme conditions. In this study, these two issues are resolved by the theoretical review of these parameters, as well as an analysis of the rainfall–runoff events collected at the Chungju Dam basin, Korea. It is observed that as $v_p$ increases, $T_c$ and $K$ decrease. Their relationship is close to inverse but in linear proportion. That is, strong linear relationships are found among $T_c$, $K$, and $v_p$. As a result, the ratio of $K$ to $T_c$ is found to be almost identical, regardless of $v_p$. This ratio at a basin can be assumed as a basin characteristic that is unchanged, regardless of the size of rainfall events.

**Key words:** Chungju Dam basin, Clark unit hydrograph, concentration time, peak velocity, rainfall–runoff event, storage coefficient

## HIGHLIGHTS

- Strong linear relationships at the basin outlet are found among the basin concentration time, storage coefficient, and peak velocity.
- The ratio of the storage coefficient to the concentration time is found to be almost identical, regardless of the peak velocity.
- The ratio of the storage coefficient to the concentration time can be assumed as an unchanged basin characteristic, regardless of the size of rainfall events.

## GRAPHICAL ABSTRACT



## INTRODUCTION

A synthetic unit hydrograph (UH) is generally applied to estimate the runoff characteristics at an ungauged location. The synthetic UH is generally derived by considering basin characteristics rather than rainfall–runoff data, which may be classified as traditional, conceptual, probabilistic, and geomorphological models (Singh *et al.* 2014). Recently, due to the availability of high-resolution digital elevation model (DEM) and the development of geographic information system (GIS) analysis tools, more studies have been focused on the geomorphological models such as the geomorphological UH by Rodríguez-Iturbe & Valdés (1979) and width-function UH by Mesa & Mifflin (1986) (Noto & La Loggia 2007; Grimaldi *et al.* 2012a; Tarahi *et al.* 2022).

In Korea, while various UHs have been considered in the past, recently the Clark UH (Clark 1945) has mostly been used. The Clark UH is represented by two parameters, such as the concentration time (or the time of concentration) and the storage coefficient, which are based on the linear channel and the linear reservoir theory, respectively. These two parameters play a crucial role in estimating peak time and peak discharge. In an ungauged basin, these parameters are estimated using some empirical formulae whose validity has been proven. In Korea, the Kraven (II) formula (JSCE 1999) is used for the concentration time, which estimates the concentration time considering both the channel length and the average flow velocity. Here, the flow velocity is assigned differently according to the slope of the channel. While the Sabol formula (Sabol 1988) and the modified Sabol formula (Jeong 2006) are generally used for estimating the storage coefficient (MLTM 2012). These formulas link the concentration time with the storage coefficient by considering the basin shape factor.

As most empirical formulae are generally developed under the average runoff conditions, its application may bias or underestimate the design condition of particularly large-scale hydraulic structures. The upper limit for the application of those estimated parameters by the empirical formulae and the resulting UH is assumed to be 100–200 years of the return period (KISTEC 2013). Several studies have already proven that in a more severe situation with a longer return period than that under the average condition, the runoff response is faster (KDI 2007; K-water 2008; Kjeldsen *et al.* 2016). That is, the UH model parameters like the concentration time and storage coefficient tend to decrease as the scale of rainfall events increases.

Among the many causes of the nonlinear behavior of the rainfall–runoff process in a basin, the flow velocity must play the key role, as it varies considerably depending on the rainfall characteristics, even under the same basin condition. Simply put, high rainfall intensity leads to faster flow velocity. The shape of the UH also varies considerably depending on the flow velocity or the characteristics of the rainfall event. There are numerous computational definitions for the concentration time (McCuen 2009). However, in this study, the concentration time of the Clark UH is defined as the time that a raindrop spends from the hydrologically farthest point of the basin to reach the basin outlet (WMO 1974). Based on this definition, the concentration time can be directly related to the flow velocity on the hillslope, as well as in the channel. Many studies attempted to estimate the concentration time using the flow velocity (NRCS 1985; JSCE 1999; Du *et al.* 2009; Perdikaris *et al.* 2018). It is also possible to find some studies that considered the wave celerity (Saghafian *et al.* 2002; Wong 2003). On the other hand, the storage coefficient is generally assumed to be proportional to the concentration time (Russell *et al.* 1979; Hoggan 1989; Yoo 2009). Thus, the storage coefficient is also likely to be closely related to the flow velocity.

Those previous studies mostly focused on estimating the representative values under the ordinary condition. In the case of considering more extreme conditions, it should be possible to modify or re-estimate the concentration time and storage coefficient. Two issues are raised in this problem; under the somewhat extreme condition, the first is whether the concentration time is still fully expressed by the flow velocity, while the other is whether the storage coefficient is still linearly proportional to the concentration time. To resolve these two questions, this study investigates whether when the flow velocity information is available, these two Clark UH parameters can adequately be determined. In this study, first, the relationship between the concentration time and the flow velocity is theoretically explored. Also, by evaluating the relationship between the concentration time and the storage coefficient, this study tries to show that the storage coefficient is also dependent upon the flow velocity.

As an application example, this study considers the major rainfall events that have occurred in the Chungju Dam basin, Korea. Both the reliable rainfall and runoff measurements are available for this dam basin; also, very regular measurements of channel flow velocity are available. By analyzing the rainfall–runoff measurements, the two parameters of the Clark UH are estimated. These estimated parameters are then used to evaluate their relationships, their dependency on the flow velocity, and the empirical formulae generally used in Korea. Finally, to prove the applicability of the proposed method, the study results are compared with the observed.

## THEORETICAL BACKGROUND

Numerous approaches have been suggested for defining or estimating the concentration time. Depending on the selected approach of estimating the concentration time, as Grimaldi *et al.* (2012b) mentioned, there could be a large difference in the estimation of peak discharge. Among those approaches for estimating the concentration time, this study adopted the definition by WMO (1974), which has been the most widely used. Based on this definition, many studies have tried to estimate the concentration time by dividing the travel distance of raindrop by the average flow velocity (NRCS 1985; JSCE 1999; Du *et al.* 2009; Perdikaris *et al.* 2018), i.e.,

$$T_c = 0.2778\frac{L}{v_{av}} \tag{1}$$

where $T_c$ is the concentration time (h), $L$ is the travel distance (km), and $v_{av}$ is the average flow velocity (m/s) over the travel distance. As explained by Wong (2003), with higher rainfall intensity, the concentration time can be shorter. Many studies have also assumed that the flow velocity remains unchanged within the basin (Rodríguez-Iturbe & Valdés 1979; Molnar & Ramirez 1998; Giannoni *et al.* 2000; Kampel *et al.* 2009), while some studies recommended using the peak velocity as a representative one for the given rainfall event (Valdes *et al.* 1979).

The storage coefficient expresses the ability of effective rainfall to be temporarily stored in a basin before it exits the basin outlet. Thus, the storage coefficient has the unit of time. The storage coefficient is relatively conceptual, and the related studies are for a lesser duration than the concentration time. In general, it is known that the storage coefficient is proportional to the concentration time. For example, Russell *et al.* (1979) expressed the ratio of the storage coefficient to the concentration time as a constant:

$$\frac{K}{T_c} = \alpha \tag{2}$$

where $K$ is the storage coefficient (h), $T_c$ is the concentration time (h), and $\alpha$ is the so-called Russell coefficient. Russell *et al.* (1979) mentioned that the range of $\alpha$ for the urban basin is around (1.1–2.1) or (1.5–2.8) for natural basins, and (8–12) for forest basins. However, in Korea, the range of (0.8–1.2) is generally applied to the natural basin (Jeong & Yoon 2007).

In a similar study, Hoggan (1989) proposed the following relationship between the storage coefficient ($K$) and the concentration time ($T_c$):

$$\frac{K}{(T_c + K)} = M \tag{3}$$

where $M$ is assumed a constant that is determined for each basin. This equation also indicates that the ratio of the storage coefficient to the concentration time of a basin is constant, i.e., $\alpha = M/(1-M)$. NRCS (1985) and Seong (1999) also mentioned that among basins with hydrological similarity, the ratios are alike. Yoo (2009) also supported these studies by deriving the relationship between the storage coefficient and the concentration time of the Nash instantaneous UH (Nash 1959).

$$T_c/K = \sqrt{n-1} \tag{4}$$

where $n$ denotes the number of linear reservoirs. As $n$ is a unique parameter for a given basin, the ratio of the two parameters also remains unchanged. The above equation also indicates that $\alpha = \sqrt{n-1}$.

## STUDY BASIN AND DATA

### Study basin and rainfall–runoff data

This study selected the Chungju Dam basin in Korea as the study basin. The Chungju Dam basin consists of three sub-basins: The Upper Namhan River basin, the Pyeongchang River basin, and the Chungju Dam basin. The total basin area is 6,648 km$^2$, and the channel length is 282.2 km. In this study, 21 water level stations, as well as the basin outlet, of the Chungju Dam basin were considered, which are all managed by the Ministry of Environment and K-water. The basin area and channel length represented by each water level station vary from 55.9 – 4,690.0 km$^2$ and 14.5 – 189.1 km, respectively. Figure 1 shows the elevation of the Chungju Dam basin, the river network, and the location of the water level stations. Basin numbers are assigned in reverse order of area. That is, basin #1 was assigned to the smallest basin and basin #21 to the largest basin.

A total of 57 rain gauge stations, managed by the Ministry of Environment, Meteorological Administration, and K-water were considered to derive the areal average rainfall data. The runoff data were derived by applying the corresponding

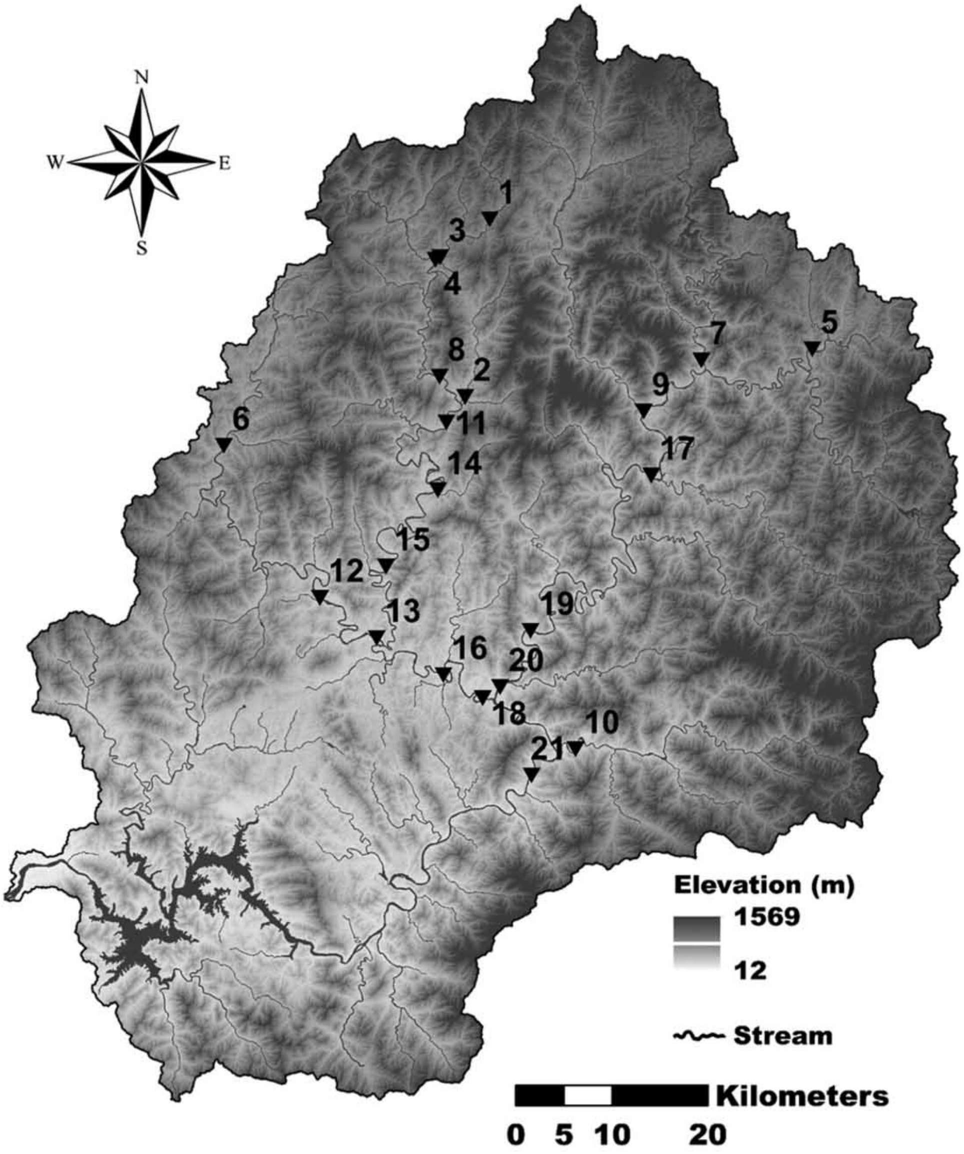


**Figure 1** | Location of water level stations in the Chungju Dam basin.

rating curve to each water level data. It was possible to find the water level data and rating curves from the water resources information system of Korea, the WAMIS (www.wamis.go.kr). The hourly data collected from the period of 1979–2018 (40 years total) were used in this study.

### Rainfall event and peak velocity

Independent rainfall events were first separated using the basin-average rainfall time series constructed for each basin. An appropriate minimum no rain period, the so-called inter-event time definition (IETD), should be determined to separate independent rainfall events. Referring to Park & Yoo (2012), this study applied 12 h as IETD and 1 mm as a threshold. However, as many events did not show sufficient direct runoff, especially when the total rainfall was less than 30 mm, only the rainfall events with total rainfall of 30 mm or more were considered in this study.

The peak velocity was selected as the velocity close to the peak time for each rainfall event. In case no observed velocity was available at the exact peak time, the nearest value in the rising limb was selected as the peak velocity. This velocity data could also be obtained from the WAMIS (www.wamis.go.kr), as well as from the Korea Annual Hydrological Report. The number of events considered in this study varies greatly by basin from 3 to 22, and the total number of events considered

**Table 1** | Basin characteristics and the number of rainfall events considered in this study

| # | Station | Area (km$^2$) | Length (km) | Shape factor | Channel slope (m/m) | # of events |
|---|---|---|---|---|---|---|
| 1 | Imokjeonggyo | 55.9 | 16.6 | 0.202 | 0.0079 | 7 |
| 2 | Sachogyo | 86.0 | 19.3 | 0.231 | 0.0169 | 3 |
| 3 | Jangpyeonggyo | 104.8 | 26.0 | 0.155 | 0.0152 | 7 |
| 4 | Baekokpogyo | 143.9 | 23.0 | 0.272 | 0.0143 | 6 |
| 5 | Songgyegyo | 157.4 | 14.5 | 0.750 | 0.0101 | 3 |
| 6 | Anheunggyo | 191.1 | 31.8 | 0.189 | 0.0050 | 3 |
| 7 | Songcheongyo | 349.5 | 62.8 | 0.089 | 0.0089 | 7 |
| 8 | Sunaegyo | 392.9 | 44.2 | 0.201 | 0.0086 | 10 |
| 9 | Najeongyo | 452.6 | 59.1 | 0.130 | 0.0081 | 3 |
| 10 | Okdonggyo | 482.6 | 46.0 | 0.228 | 0.0134 | 4 |
| 11 | Sangbangrimgyo | 527.2 | 51.9 | 0.196 | 0.0077 | 11 |
| 12 | Jucheongyo | 533.2 | 71.0 | 0.106 | 0.0043 | 9 |
| 13 | Sincheongyo | 599.4 | 84.1 | 0.085 | 0.0041 | 4 |
| 14 | Pyeongchanggyo | 695.7 | 74.8 | 0.124 | 0.0061 | 11 |
| 15 | Panungyo | 806.8 | 90.3 | 0.099 | 0.0049 | 22 |
| 16 | Bukssangri | 1,615.8 | 125.7 | 0.102 | 0.0038 | 15 |
| 17 | Jeongseonje1gyo | 1,688.4 | 103.5 | 0.158 | 0.0051 | 8 |
| 18 | Palgoegyo | 1,764.1 | 138.2 | 0.092 | 0.0044 | 4 |
| 19 | Geoungyo | 2,272.7 | 167.4 | 0.081 | 0.0047 | 4 |
| 20 | Yeongwoldaegyo | 2,440.4 | 186.5 | 0.070 | 0.0034 | 10 |
| 21 | Osari | 4,690.0 | 189.1 | 0.131 | 0.0031 | 11 |

is 162. Table 1 compares the number of rainfall events considered for each basin, including some basic information about the study basins.

### Estimation of the concentration time and the storage coefficient for rainfall events

The concentration time and storage coefficient for each event were estimated by applying the method proposed by Yoo & Shin (2010). This method recursively searches the convergent concentration time and storage coefficient using the relationship between the number of linear reservoirs and the storage coefficient of the linear reservoir of the Nash model. This is to overcome the problem of applying the optimization technique which selects optimal parameters separately. In addition, this study considered the *N*-day method and the straight-line method, to separate the direct runoff hydrograph from the total hydrograph and the NRCS-CN method and the Φ-Index method, for effective rainfall estimation. That is, a total of four combinations were considered in the parameter estimation, and the result with the minimum root mean square error was selected as the optimal one.

This study compared simulated and observed runoff hydrographs to evaluate the adequacy of the estimated parameters. Figure 2 shows some example cases of the Panungyo basin (#15), whose basic information is summarized in Table 2. As can be seen in Figure 2, there was no significant difference between the simulated and observed hydrographs. This result confirms that the parameters were properly estimated.

## RELATIONSHIPS AMONG CONCENTRATION TIME, STORAGE COEFFICIENT, AND PEAK VELOCITY

### Analysis of the observed data

The relationships among the concentration time, storage coefficient, and peak velocity were examined using their scatter plots. As an example, Figure 3 shows the results of the Panungyo basin (#15). As can be expected, as the peak velocity increases, the concentration time decreases; in more detail, the concentration time is inversely proportional to the peak velocity (Figure 3(a)). A similar relationship could also be found between the storage coefficient and the peak velocity

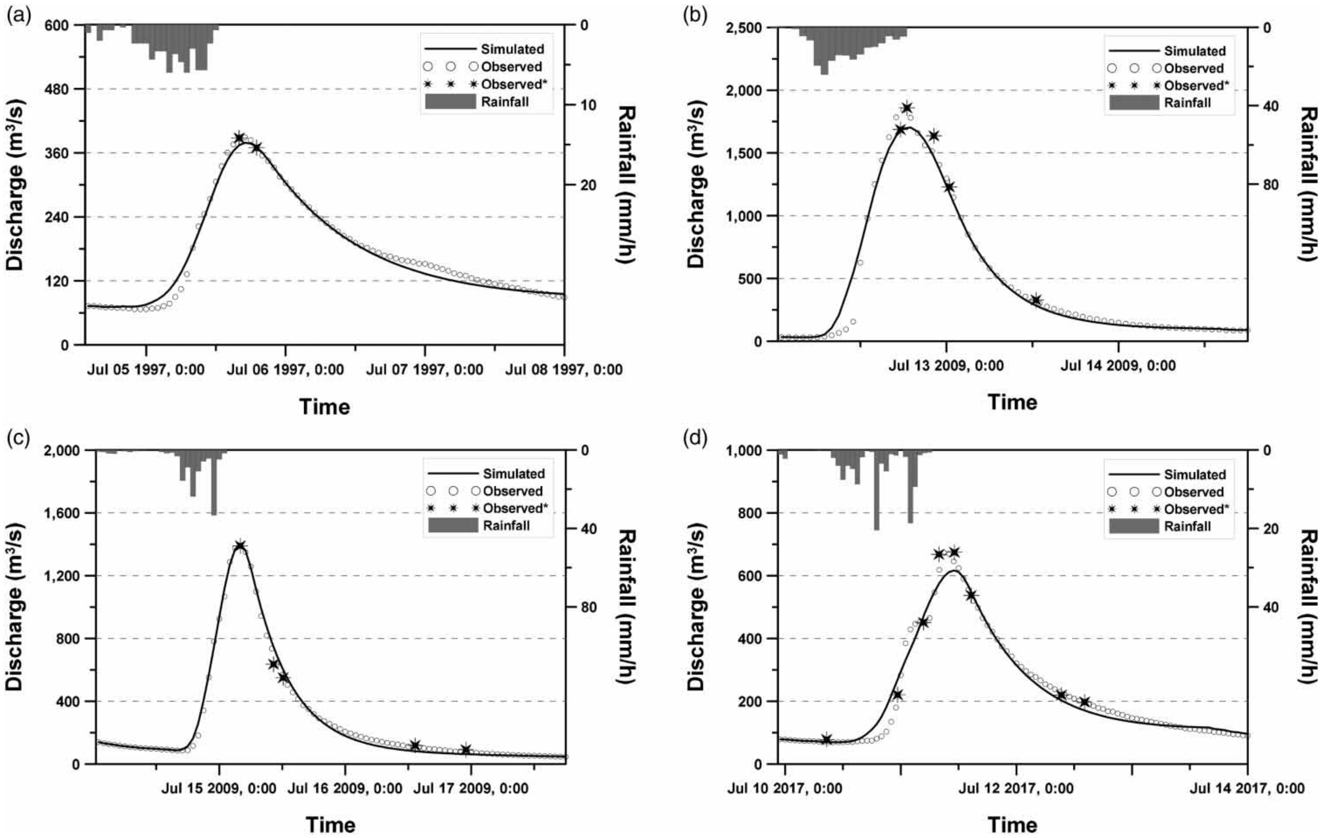


**Figure 2** | Comparison of the simulated hydrograph and observation data (Observed: discharge converted from the observed water level using the rating curve; Observed*: discharge calculated by multiplying the flow velocity and the cross-sectional area). (a) Event #1, (b) Event #2, (c) Event #3 and (d) Event #4.

(Figure 3(b)). The concentration time is linearly proportional to the storage coefficient (Figure 3(c)). Additionally, it was found that the peak velocity is proportional to the peak discharge. In Figure 3, the larger the peak discharge, the darker the circle's color. For example, the darkest color represents the event that the peak discharge was 1,861.2 m$^3$/s, and the peak velocity was 3.3 m/s. The travel time obtained by dividing the channel length by the peak velocity was calculated as 7.6 h, similar to the concentration time (i.e., 7.3 h) estimated by analyzing the rainfall–runoff analysis.

This study also tried to apply a regression line or curve for each case. For example, the regression model of the form $y = c/x$ was applied to Figure 3(a) and estimated the constant to be 84.5 km. In fact, this value is quite close to the channel length of the basin (i.e., 90.3 km). This result indicates that the concentration time could be expressed as the travel time from the

**Table 2** | Information and estimated parameters for the rainfall events as examples

| Category | Event #1 | Event #2 | Event #3 | Event #4 |
|---|---|---|---|---|
| Start of the rainfall event | 4 July 1997, 14:00 | 12 July 2009, 0:00 | 14 July 2009, 1:00 | 9 July 2017, 23:00 |
| End of the rainfall event | 5 July 1997, 12:00 | 12 July 2009, 18:00 | 15 July 2009, 1:00 | 11 July 2017, 6:00 |
| Duration (h) | 23 | 19 | 25 | 32 |
| Total rainfall (mm) | 60 | 176.3 | 124.9 | 100.8 |
| Peak velocity (m/s) | 1.6 | 3.3 | 3.1 | 1.9 |
| Peak discharge (m$^3$/s) | 388.2 | 1,861.2 | 1,391.1 | 675.2 |
| Peak time (h) | 28.0 | 19.0 | 28.0 | 34.0 |
| Time of concentration (h) | 14.1 | 7.3 | 7.5 | 11.7 |
| Storage coefficient (h) | 19.5 | 9.7 | 10.5 | 17.4 |

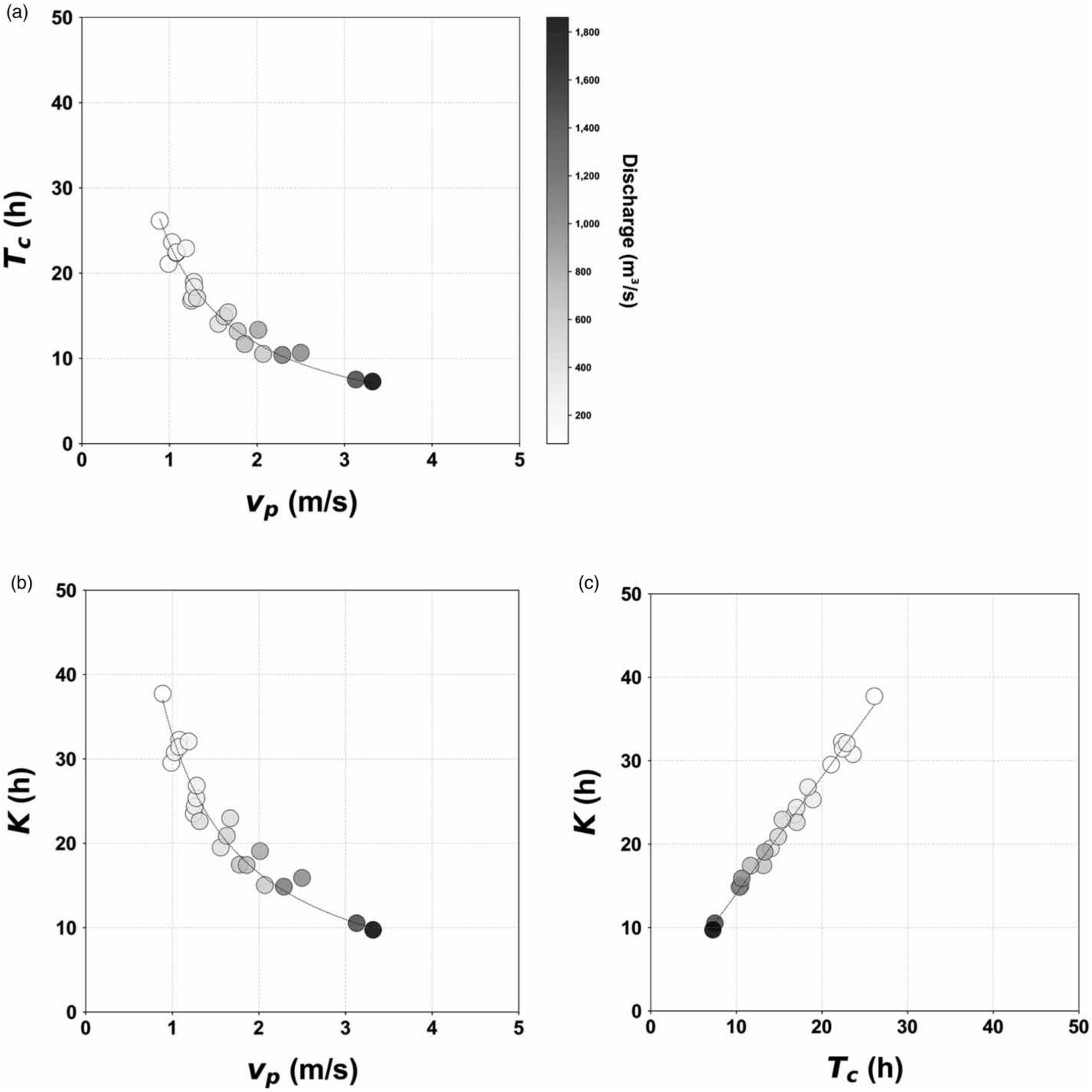


**Figure 3** | Scatter plots for the peak velocity, concentration time, and storage coefficient (basin #15). (a) $v_p$ *vs*. $T_c$, (b) $v_p$ *vs*. $K$ and (c) $T_c$ *vs*. $K$.

uppermost point of the basin to the basin outlet (i.e., $L/v_p$). The same regression model was also applied to Figure 3(b) to quantify the relationship between the storage coefficient and the peak velocity. The constant was determined to be 118.5 km, slightly larger than the previous case. That is, the storage effect in this basin seems to be higher than the concentration time.

The linear relationship between the concentration time and the storage coefficient in Figure 3(c) could also be quantified by the regression model of the form, $y = c \cdot x$. In this case, the constant was estimated to be 1.4. Simply put, the storage coefficient was found to be 1.4 times larger than the concentration time, over all ranges of observed peak discharges or peak velocities. Based on the very high coefficient of determination of 0.95 or higher, this linear relationship could be assumed to be reliable. That is, even though the peak discharge and the peak velocity increase, the ratio between the two parameters does not change significantly. This strong linear relationship could also be confirmed in other basins, whose results are

**Table 3** | Regression coefficient and the coefficient of determination for each regression model in Figure 4

| | $v_p$ (m/s) vs. (h) ($T_c = 0.2778 \cdot c/v_p$) | | $v_p$ (m/s) vs. $K$ (h) ($K = 0.2778 \cdot c/v_p$) | | $T_c$ (h) vs. $K$ (h) ($K = c \cdot T_c$) | |
|---|---|---|---|---|---|---|
| **Basin #** | **c (km)** | $R^2$ | **c (km)** | $R^2$ | **c (h/h)** | $R^2$ |
| 1 | 20.8 | 0.881 | 21.7 | 0.876 | 1.0 | 0.981 |
| 2 | 20.1 | 0.986 | 21.6 | 0.980 | 1.1 | 0.999 |
| 3 | 27.8 | 0.897 | 30.6 | 0.772 | 1.1 | 0.960 |
| 4 | 26.9 | 0.997 | 24.3 | 0.963 | 0.9 | 0.944 |
| 5 | 15.2 | 0.998 | 12.8 | 0.999 | 0.8 | 0.999 |
| 6 | 31.4 | 0.998 | 37.3 | 0.997 | 1.2 | 0.999 |
| 7 | 56.4 | 0.975 | 81.9 | 0.934 | 1.5 | 0.961 |
| 8 | 48.5 | 0.943 | 46.2 | 0.800 | 1.0 | 0.932 |
| 9 | 56.1 | 0.998 | 65.4 | 0.996 | 1.2 | 0.999 |
| 10 | 49.2 | 0.981 | 49.4 | 0.993 | 1.0 | 0.992 |
| 11 | 55.0 | 0.968 | 56.0 | 0.955 | 1.0 | 0.997 |
| 12 | 65.6 | 0.990 | 86.8 | 0.993 | 1.3 | 0.991 |
| 13 | 79.2 | 0.964 | 107.4 | 0.931 | 1.4 | 0.978 |
| 14 | 70.5 | 0.963 | 91.0 | 0.979 | 1.3 | 0.991 |
| 15 | 84.5 | 0.942 | 118.5 | 0.926 | 1.4 | 0.985 |
| 16 | 115.2 | 0.958 | 163.3 | 0.930 | 1.4 | 0.974 |
| 17 | 100.0 | 0.991 | 105.8 | 0.993 | 1.1 | 0.995 |
| 18 | 123.6 | 0.793 | 169.3 | 0.887 | 1.4 | 0.988 |
| 19 | 156.9 | 0.878 | 215.9 | 0.841 | 1.4 | 0.998 |
| 20 | 178.8 | 0.939 | 283.4 | 0.953 | 1.6 | 0.988 |
| 21 | 166.3 | 0.945 | 204.2 | 0.922 | 1.2 | 0.981 |

summarized in Table 3. In this table, basin #1 is the smallest one, while basin #21 is the largest one. As the basin becomes larger in the area, the ratio between the two parameters becomes larger to indicate a greater storage effect.

Additionally, this study conducted a hypothesis test to check if a constant relationship could be assumed between the concentration time and the storage coefficient. The test was done with the ratio data ($\alpha$) between the concentration time and the storage coefficient for each basin. In fact, the test was conducted by evaluating if the ratio shows any obvious trend (or any significant slope $\beta$), with respect to the peak velocity. The null hypothesis ($H_0$) was $\beta = 0$, and the alternative hypothesis ($H_1$) was $\beta \neq 0$. Student's distribution with $n - 2$ degrees of freedom was considered for this hypothesis test. The $t$-statistic for the test was calculated using the following equation:

$$t = \frac{\hat{\beta} - 0}{s_{\hat{\beta}}} \tag{5}$$

where $\hat{\beta}$ is the slope estimated through the least-squares method, and the constant '0' represents the null hypothesis $\beta = 0$. $s_{\hat{\beta}}$ is the standard deviation of $\hat{\beta}$, estimated with the observed data, and is calculated as follows:

$$s_{\hat{\beta}} = \frac{\sqrt{\dfrac{1}{n-2}\displaystyle\sum_{i=1}^{n}(\alpha_i - \hat{\alpha}_i)^2}}{\sqrt{\displaystyle\sum_{i=1}^{n}(v_i - \bar{v})^2}} \tag{6}$$

where $\alpha_i$ denotes the ratio of the two parameters, and $\hat{\alpha}_i$ denotes the value on the determined linear regression model. The regression variable $v_i$ is the peak velocity (m/s), and $\bar{v}$ is their average value. In addition, $n - 2$ is the degrees of freedom, and $n$ is the number of observations.

**Table 4** | Hypothesis test result on the slope of the regression line for each basin

| Basin # | Slope | *t*-statistic | *p*-value |
|---|---|---|---|
| 1 | 0.004 | 0.119 | 0.910 |
| 2 | −0.027 | −4.907 | 0.128 |
| 3 | 0.028 | 0.566 | 0.596 |
| 4 | 0.041 | 1.052 | 0.352 |
| 5 | −0.009 | −1.817 | 0.320 |
| 6 | 0.001 | 0.025 | 0.984 |
| 7 | −0.019 | −0.448 | 0.673 |
| 8 | 0.042 | 1.703 | 0.127 |
| 9 | −0.004 | −0.604 | 0.654 |
| 10 | 0.017 | 0.457 | 0.693 |
| 11 | 0.006 | 0.731 | 0.483 |
| 12 | 0.043 | 1.265 | 0.246 |
| 13 | 0.050 | 0.660 | 0.577 |
| 14 | 0.003 | 0.113 | 0.912 |
| 15 | 0.004 | 0.240 | 0.813 |
| 16 | 0.033 | 0.858 | 0.406 |
| 17 | 0.029 | 1.632 | 0.154 |
| 18 | −0.054 | −0.738 | 0.538 |
| 19 | 0.015 | 0.853 | 0.483 |
| 20 | −0.016 | −0.584 | 0.575 |
| 21 | 0.023 | 1.186 | 0.266 |

Table 4 summarizes the results of this hypothesis test. As shown in this table, it was confirmed that the ratio data ($\alpha$) between the concentration time and the storage coefficient could be assumed constant in all basins. In all basins considered in this study, the *p*-value was estimated to be far larger than 0.05; as a result, the null hypothesis could not be rejected.

## Observed parameters vs. estimated parameters by empirical formulae

Even in a given basin, different values of parameters were derived whenever analyzing a different rainfall event. In general, their representative values are determined as their means. In particular, when sufficient rainfall events are available, the mean value could be acceptable. However, when only a few events are available, the mean values can be somewhat biased (Yoo *et al.* 2007a). Based on Yoo *et al.* (2007b), at least 20 different rainfall events are required to estimate the acceptable mean values. In the case that the number of rainfall events is far smaller than 20, they proposed to use the mode, rather than the mean value. This study also considered this direction to determine the representative values of concentration time and storage coefficient for each basin. Table 5 summarizes the representative parameters determined for each basin and also provides their ratio ($\alpha$) for reference:

In Korea, the Kraven (II) formula (JSCE 1999) is mostly used to estimate the concentration time, while the Sabol formula (Sabol 1988), or the modified Sabol formula, is used for the storage coefficient (MLTM 2012). The Kraven (II) formula is expressed as follows:

$$T_c = 0.2778\frac{L}{V_{av}} \tag{7}$$

where $T_c$ means the representative concentration time (h) of the basin. In addition, $L$ is the channel length (km), and $V_{av}$ is the average flow velocity (m/s). Even though Equation (7) has the same form as Equation (1), $V_{av}$ is assigned differently according

**Table 5** | Representative UH parameters estimated by analyzing the observed data for each basin

| Basin # | $T_{c\_rep}$ (h) | $K_{rep}$ (h) | $\alpha_{rep} = K_{rep}/T_{c\_rep}$ (h/h) |
|---|---|---|---|
| 1 | 3.0 | 3.3 | 1.1 |
| 2 | 4.1 | 4.4 | 1.1 |
| 3 | 6.2 | 6.8 | 1.1 |
| 4 | 3.9 | 3.7 | 1.0 |
| 5 | 2.5 | 2.1 | 0.8 |
| 6 | 3.5 | 4.0 | 1.1 |
| 7 | 10.5 | 15.5 | 1.5 |
| 8 | 7.3 | 7.1 | 1.0 |
| 9 | 6.8 | 7.8 | 1.1 |
| 10 | 10.3 | 9.9 | 1.0 |
| 11 | 6.0 | 6.3 | 1.1 |
| 12 | 8.8 | 11.8 | 1.3 |
| 13 | 11.1 | 15.2 | 1.4 |
| 14 | 7.4 | 9.3 | 1.3 |
| 15 | 14.9 | 21.0 | 1.4 |
| 16 | 19.8 | 28.0 | 1.4 |
| 17 | 11.0 | 11.9 | 1.1 |
| 18 | 27.5 | 36.9 | 1.3 |
| 19 | 20.2 | 28.0 | 1.4 |
| 20 | 19.1 | 30.1 | 1.6 |
| 21 | 22.0 | 28.1 | 1.3 |

to the slope of the channel ($S$). For $S < 1/200$, the $V_{av}$ is assumed to be 2.1 m/s; for $1/200 \leq S \leq 1/100$, 3.0 m/s; and for $S > 1/100$, 3.5 m/s.

The Sabol formula (Sabol 1988), which links the concentration time to the storage coefficient by considering the shape factor of the basin, has mainly been used. However, when the shape factor is very small, the Sabol formula does not work well; consequently, its modified version has become more popular in Korea (MLTM 2012). The modified Sabol formula is as follows:

$$K = \frac{T_c}{\left(\dfrac{97.28}{SF^{-2.88} + 128.19} + 0.59\right)} \tag{8}$$

where $K$ is the representative storage coefficient (h) of the basin, $SF$ is the shape factor ($A^2/L$) of the basin, $A$ denotes the basin area (km$^2$), and $L$ represents the channel length (km). The ratio between the two parameters ($\alpha$) can also be expressed as follows:

$$\alpha = \frac{K}{T_c} = \frac{1}{\left(\dfrac{97.28}{SF^{-2.88} + 128.19} + 0.59\right)} \tag{9}$$

The above equation indicates that the ratio between the two parameters ($\alpha$) is constant.

Figure 4 compares the observed parameters and those estimated by applying the empirical formulae. In this figure, $T_c$ and $K$ refer to the concentration time and the storage coefficient estimated by applying the empirical formulae, while $T_{c\_rep}$ and $K_{rep}$ indicate those determined as the representative values of observed rainfall events, respectively. Also, $\alpha$

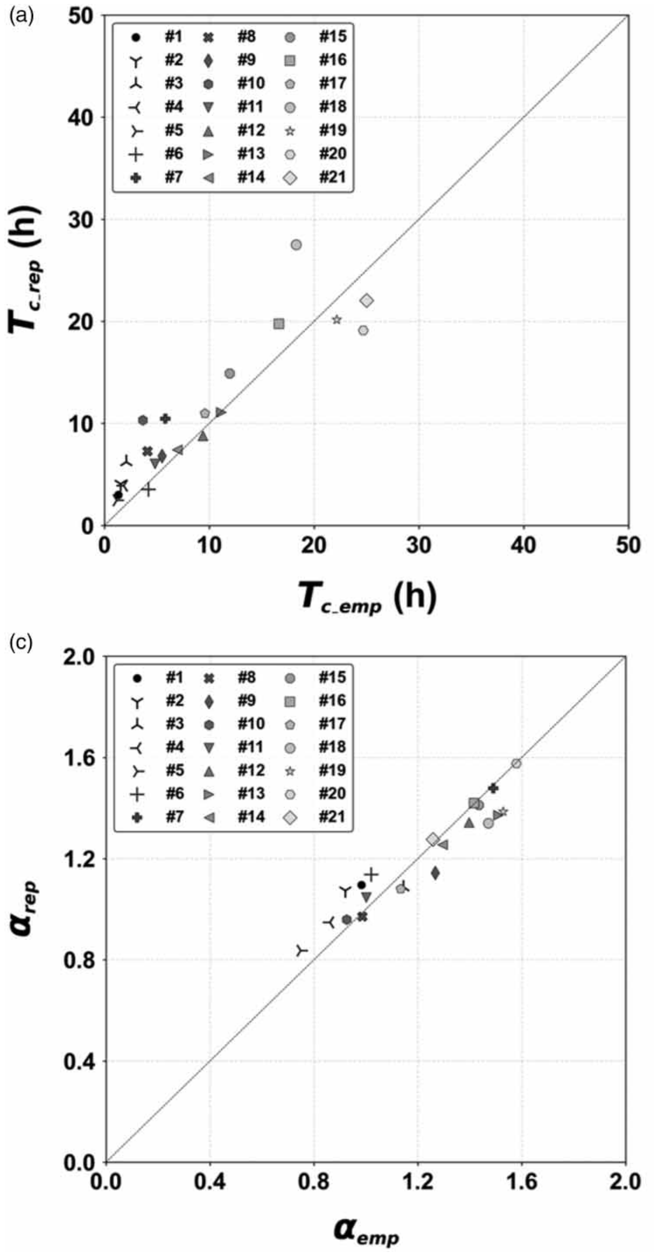


**Figure 4** | Comparison of the UH parameters estimated by the empirical formulas and those observed. (a) Concentration time, (b) Storage coefficient and (c) $\alpha$ (storage coefficient divided by concentration time).

and $\alpha_{rep}$ are their ratios, respectively. Overall, they match well, though there exists some variation. If considering that just a few numbers of rainfall events were considered in the determination of the parameters, this consistency proves the validity of both the representative values and the empirical formulae used in this study. The ratio values also showed strong consistency.

## DETERMINATION OF CONCENTRATION TIME AND STORAGE COEFFICIENT USING PEAK VELOCITY

The results derived in the previous section indicate that, under the condition that the only available information is the peak velocity, it is possible to determine the concentration time and the storage coefficient. The information of the peak velocity could be derived by analyzing the runoff data, if available, or by applying some appropriate empirical formulae. In this part of the study, the two parameters, the concentration time, and the storage coefficient of the Clark UH were derived using the available information of peak velocity, after assuming that the study basin is ungauged. The derived parameters were then compared with those determined by analyzing the observed data.

For basin #15, as an example, the observed peak velocity ranges from 0.9 to 3.3 m/s. With the observed peak velocity, the concentration time could easily be determined by dividing the channel length by the corresponding peak velocity. The determined concentration time ranged from 7.6 to 28.2 h. Then to determine the storage coefficient, it was required to determine the ratio between the storage coefficient and the concentration time. As the Kraven (II) formula for the concentration time and the modified Sabol formula for the storage coefficient were known to be valid in this basin, this study also considered these formulae. By applying these formulae, the concentration time was estimated to be 11.9 h, and the storage coefficient was 17.1 h. Thus, the ratio was determined to be 1.44. This ratio was also assumed to be unchanged, regardless of the peak velocity. Now the storage coefficient was determined to be within the range of 10.8–40.4 h.

Figure 5 compares the determined concentration time and storage coefficient using the peak velocity with those derived by analyzing the observed runoff data (i.e., the observed parameters). First, it could be confirmed that their relation is obviously linear. The mean difference between the observed concentration time and the determined concentration time using the peak velocity was just 8.7%, with a maximum of 20.2%. Although there was a case with difference of more than 20%, overall, the one-to-one relation was found to be very strong. The mean difference between the observed and the determined storage coefficients using the peak velocity was estimated to be slightly higher at 11.4% than that of the concentration time. The maximum difference was also slightly higher at 23.1%.

Figure 6 also replicates Figure 5, but for all the basins considered in this study. Although there are slight differences by the event and the basin, these cases generally show strong linearity, as seen in Figure 5 for basin #15. The determined concentration time using the peak velocity showed a difference of −36.3 to 23.0% by the event. On the other hand, the difference of the determined storage coefficient using the peak velocity was estimated to be slightly higher, which ranged from −42.3 to 29.5% by the event. The mean difference was estimated to be just 9.7 and 13.2% for the concentration time and the storage coefficient, respectively.

As the size of the basin increases, the mean difference of the parameters shows a tendency to lean toward the positive. Basin #1 showed the smallest difference of −14.8%, and basin #21 showed the largest of 13.8% for the concentration time. Similarly, basin #4 showed the smallest difference of −22.9%, and basin #13 showed the largest of 19.0% for the storage coefficient. That is, the method using the peak velocity might overestimate the UH parameters for those large basins, which could underestimate the peak discharge. However, this problem is also related to the applicable limit of the UH. The appropriate sub-basin division could alleviate the possible problem of the proposed method.

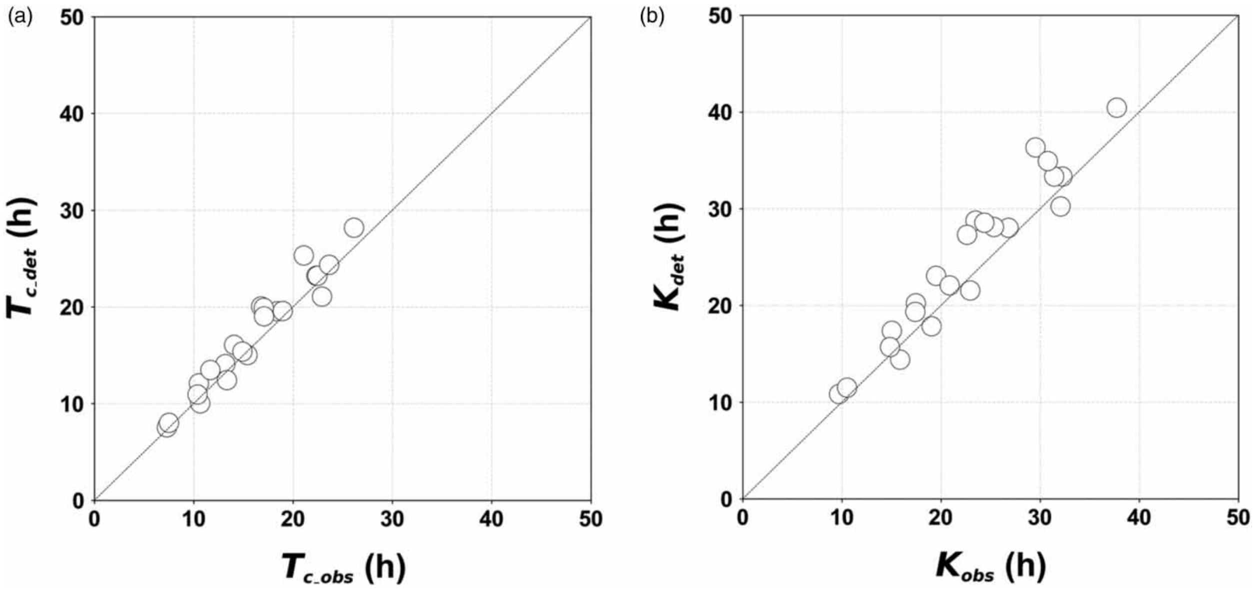


**Figure 5** | Comparison of the UH parameters determined using the peak velocity and those observed (basin #15). (a) Concentration time and (b) Storage coefficient.

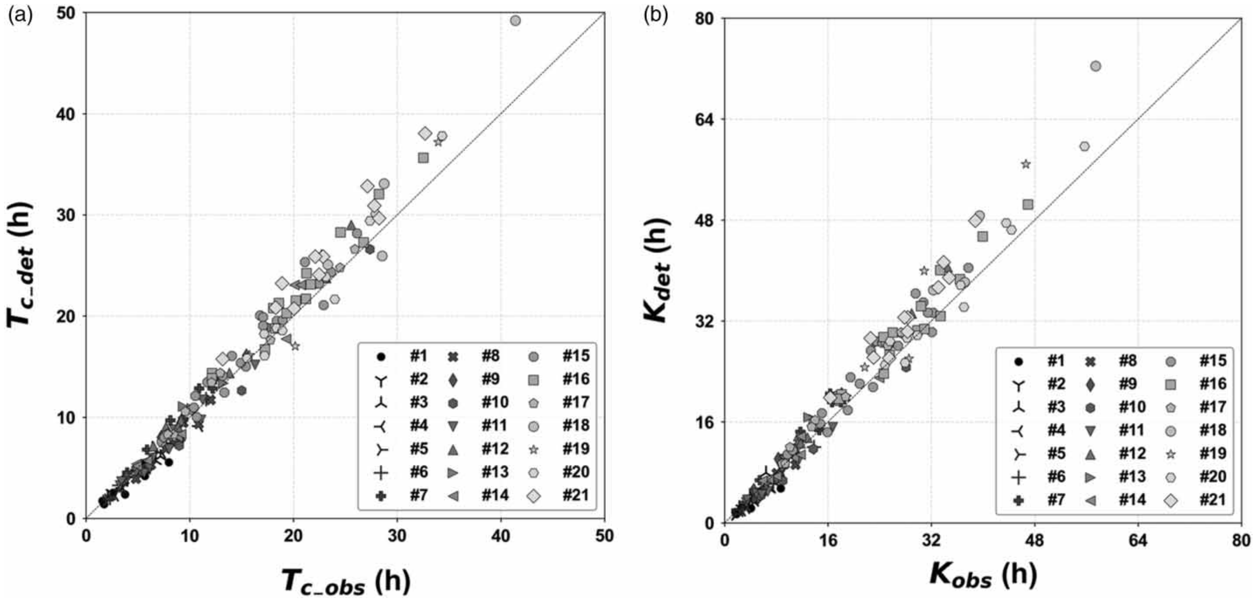


**Figure 6** | Same as Figure 5, but for all basins considered in this study. (a) Concentration time and (b) Storage coefficient.

Figure 7 additionally compares the observed peak discharges and peak times with those determined using the peak velocity in all basins and for all events considered in this study. As can be seen in this figure, these values match very well. The mean difference of the peak discharges was found to be just 1.7%, along with the range of −14.5 to +19.5%. Similarly, the mean difference of the peak time was also found to be just 1.7%, along with the range of −32.0 to +22.4%. It was also found that for those small basins, the peak discharge and the peak time were slightly underestimated, but as the basin size increased, these were slightly overestimated. As mentioned above, the appropriate sub-basin division could alleviate this possible error in the application of the proposed method. It is also true that if the peak velocity is estimated closer to the observed, the error could be smaller.

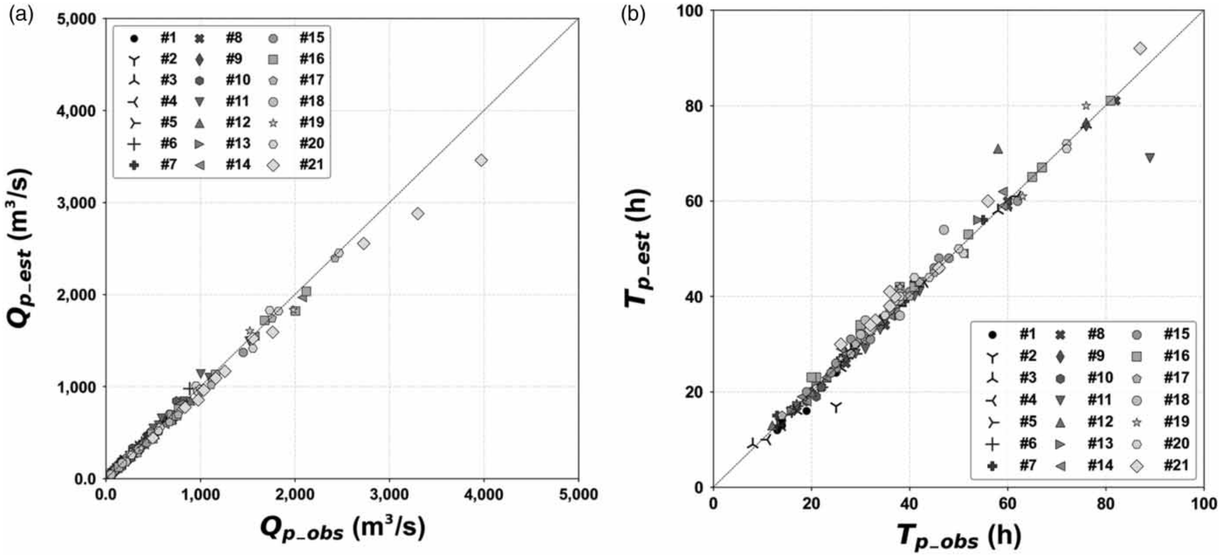


**Figure 7** | Comparison of the peak discharges and peak times estimated by applying the observed parameters and the determined parameters using the peak velocity. (a) Peak discharge and (b) Peak time.

## CONCLUSION

In general, most empirical formulae on the basin concentration time and storage coefficient focus on estimating the representative values under the ordinary condition. Under more extreme conditions, those parameters should be modified to consider faster velocity conditions on both the channel and the hillslope. The main objective of this study was to examine the possibility of determining the concentration time and storage coefficient corresponding to the given peak velocity at the basin outlet. Two issues were involved in this problem under somewhat extreme conditions: one was whether the concentration time could be fully expressed by the peak velocity; the other was whether the storage coefficient was still linearly proportional to the concentration time. In this study, first, the relationship between the concentration time and the peak velocity was theoretically explored. Also, by evaluating the relationship between the concentration time and the storage coefficient, this study tried to show that the storage coefficient is also dependent upon the peak velocity. This study also analyzed the observed rainfall–runoff events collected at the Chungju Dam basin, Korea. After estimating the representative parameters by analyzing the observed rainfall–runoff data, this study compared them with the values estimated by applying empirical formulae. Finally, this study determined the two parameters using the given peak velocity information, which were then evaluated by comparing them with the observed parameters, as well as with those estimated by applying the empirical formulae. The results of this study are summarized as follows:

First, the analysis of observed data at the Chungju Dam basin confirmed strong linear relationships among the basin concentration time, storage coefficient, and peak velocity at the basin outlet. It was also observed that as the peak velocity increased, the concentration time and storage coefficient decreased. Their relationship was close to inverse but linear proportion. The concentration time appeared very similar to the value obtained by dividing the channel length by the peak velocity. The relationship between the concentration time and the storage coefficient was also found to be very strongly linear.

Second, the ratio of the storage coefficient to the concentration time was found to be almost identical, regardless of the peak velocity. This result was also confirmed by the hypothesis test. That is, this ratio at a basin could be assumed as a basin characteristic that, regardless of the size of rainfall events, was unchanged. As a result, it could be assumed that with the given concentration time, the storage coefficient of a basin could be estimated very accurately.

Finally, the above results could also be verified in application to several stage-gauging stations within the Chungju Dam basin. The concentration time and the storage coefficient determined using the peak velocity showed a mean difference of about 9.8 and 13.2%, respectively, from the observed values. However, the difference was found to be large for the larger basin. The determined parameters using the peak velocity also showed the tendency to be slightly higher than that of the observed parameters, especially for those large basins, which resulted in slightly low estimates of peak flow and peak time.

It is now clear that using the given peak velocity information, the basin concentration time and storage coefficient can be reasonably estimated. However, it is not yet clear how to obtain the peak velocity information corresponding to the given rainfall event in an ungauged basin. The information of peak flow should be derived by applying the peak flow to the given basin outlet. It may be possible to obtain the information of channel shape and bed materials through a field survey, but the peak flow at the basin outlet still needs to be estimated. To use the results in this study, how to reasonably estimate the peak flow for the given design rainfall event must be given. This issue is especially important in hydrologic practices for designing hydraulic structures. This issue must be an important future research area for the authors of this study.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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