Theoretical evaluation of concentration time and storage coefficient with their application to major dam basins in Korea

Chulsang Yoo, Jiho Lee and Eunsaem Cho

ABSTRACT

This study theoretically evaluated the basin concentration time and storage coefficient with their empirical formulas available worldwide. The evaluation results were also validated in the application to major dam basins in Korea. The findings are summarized as follows. As a result of analytical analysis, the concentration time was found to be proportional to the main channel length under laminar flow conditions and to the square of it under turbulent flow conditions, but inversely proportional to the channel slope. It was also found that the storage coefficient and the concentration time are linearly but loosely related. Most empirical formulas for the concentration time concurred with the basic equation form, but just a few for the storage coefficient. Applications to major dam basins in Korea also showed that the concentration time agrees well with the result of theoretical analysis. However, the behavior of the storage coefficient varied much, basin by basin, indicating that additional factors may be needed to explain it.

Key words | basic equation form, concentration time, empirical formula, storage coefficient

INTRODUCTION

The runoff characteristics of a basin can be quantified by interpreting the components of a flood hydrograph. \( T_c \) and \( K \) are critical components when determining the peak flow and peak time of a flood hydrograph. The Clark instantaneous unit hydrograph (IUH), which is generally used for basin flood routing in Korea, can also be derived by these two parameters, \( T_c \) and \( K \) (Clark 1945). That is, under the assumption of linear system theory, these two parameters can sufficiently represent the characteristics of the rainfall–runoff process in a basin.

However, even though only two parameters are involved in the construction of the Clark IUH, it is not simple to estimate them. Actually, it may be impossible to determine the unique set of parameters that can be applied to various rainfall–runoff events. This is simply because the nonlinear basin system is assumed to be linear. It is well known that the rainfall–runoff process in a basin is nonlinear (Kundzewicz & Napiórkowski 1986; Sinha et al. 2013). Furthermore, as these two parameters are correlated with each other, their estimation procedure can be very complex. In practice, even for an observed rainfall–runoff event, it is practically impossible to estimate a unique set of \( T_c \) and \( K \).

On the other hand, in ungauged basins, empirical formulas are used to determine \( T_c \) and \( K \). However, as empirical formulas are strongly dependent on the basin or channel characteristics, and sometimes provide very different estimates, the background, such as basin area, basin slope, land use, land cover, etc., should be carefully checked when applying these formulas (Jeong & Yoon 2007; Yoo 2009).

The basin or channel characteristics involved in the empirical formulas for \( T_c \) and \( K \), such as basin area, shape factor, channel length, channel slope, rainfall intensity,
et al., are diverse. Nevertheless, it has been argued that the components of those formulas are very similar each other (Yoo 2009). This finding indicates that there exist major contributing factors to determine \( T_c \) and \( K \), as well as their basic equation forms. If this assumption is true, the regionalization for the consistent application of an empirical formula to a large basin will be practical. However, major contributing factors of empirical formulas for \( T_c \) and \( K \) have not been investigated in depth by previous researchers.

The main objective of this study is to evaluate the fundamental factors of \( T_c \) and \( K \) with their theoretical background and empirical formulas available worldwide. Ultimately this study is going to show if a valid basic equation form exists for \( T_c \) and \( K \). The result will then be applied to major dam basins in Korea to evaluate its applicability.

**MATERIALS AND METHODS**

**Theory for concentration time**

A theoretical background for \( T_c \) can be found in Singh (1976), where an equation for \( T_c \) was derived by analyzing surface flow using kinematic wave theory. Even though the equation was derived under some simplifying assumptions like rectangular and converging cross-section, it provided a basic idea about \( T_c \) in a basin. The equation is:

\[
T_c = i^{1/3} \left( \frac{L}{\eta^2} \right)^{1/4}
\]  

(1)

where \( T_c \) is the concentration time, \( L \) is the longest flow length of a basin, \( i \) is the rainfall intensity, \( \eta \) is the kinematic wave friction-related parameter varying in space (friction parameter), and \( m \) is a constant.

Lee et al. (2013) analyzed Equation (1) and derived an equation for \( T_c \) as a function of basin characteristics. Lee et al. (2013) considered the general form of the rainfall intensity formula (Sherman 1931) and the mean velocity formula by Chezy (1775) to transform Equation (1) into the following equation for \( T_c \) under laminar flow conditions (Equation (2)) and turbulent flow conditions (Equation (3)):

\[
T_c = \left( \frac{\beta v L}{g M} \right)^{1/3} = \left( \frac{\beta v L}{g M^{1/3}} \right) \left( \frac{L}{S} \right)^{1/3}
\]  

(2)

\[
T_c = \left( \frac{\beta L^2 e^{1/3}}{g M^{1/3} S} \right)^{1/3} = \left( \frac{\beta L^1/3}{g M^{1/3}} \right) \left( \frac{L^2}{S} \right)^{1/3}
\]  

(3)

where \( S \) is the channel slope and \( \beta, v, g, k, \) and \( M \) are all constants and \( \varepsilon \) is the equivalent roughness. As can be seen in Equations (2) and (3), \( T_c \) should be a function of \( (L/S) \) under the laminar flow condition and \( (L^2/S) \) under the turbulent flow condition. Here it is important to remember that \( T_c \) is expressed as a function of only the channel characteristics.

Furthermore, the definition of concentration time, which is the travel time of a rain drop to travel from the furthest location to the outlet of a basin, supports the mathematical expression as a function of \( L/S \) or \( L^2/S \) (Kirpich 1940; Izzard & Hicks 1947; Johnstone & Cross 1949; Kerby 1959; Carter 1961; Morgali & Linsley 1965; Espey & Winslow 1974; SCS 1973).

**Relationship between concentration time and storage coefficient**

Yoo et al. (2013) analyzed the Nash IUH (Nash 1957) to show the relation between \( T_c \) and \( K \). Nash (1957) assumed that a basin can be represented by serially connecting \( x \) linear reservoirs with its storage coefficient \( K_x \) (here, it should be noticed that \( K \) is different from \( K_x \) and the resulting Nash IUH can be expressed as follows:

\[
Q_e(t) = \frac{1}{K^x} \left( \frac{t}{K^x} \right)^{x-1} e^{-t/K^x} \Gamma(x)
\]  

(4)

where \( Q_e \) is the outflow at time \( t \), \( x \) is the number of linear reservoirs and \( \Gamma(\cdot) \) is the gamma function.

The advantage of using the Nash IUH is its availability for theoretical analysis. That is, the \( K \) and \( T_c \) of the Nash IUH can be derived simply by applying the definition of \( T_c \) (from the end of the effective rainfall to the deflection point of the falling limb of the runoff hydrograph) and the definition of \( K \) given by Sabol.
$T_c$ and $K$ of the Nash IUH are derived as follows (Yoo et al. 2013):

\[ T_c = K^* (x - 1) + \sqrt{x} - 1 \]  
\[ K = K^* (\sqrt{x} - 1 + 1) \]

It is also possible to derive the relation between Equations (5) and (6) as follows:

\[ \frac{T_c}{K} = \sqrt{x} - 1 \]

The above relation is especially significant as it is expressed as a function of only one parameter, the number of linear reservoirs $x$. If $x$ is assumed to be a unique value over a given basin, the ratio between $T_c$ and $K$ remains the same at any location in the basin. However, if $x$ varies by the location in the basin, the relationship between $T_c$ and $K$ also varies.

**Study basins**

A total of five dam basins in Chungju, Namgung, Andong, Imha and Hapcheon were considered. Among these five dam basins, only Chungju dam basin belongs to the Han river basin covering the central part of the Korean Peninsula. The remaining dam basins in Namgung, Andong, Imha and Hapcheon are located within the Nakdong river basin covering the south-eastern part of the Korean Peninsula. Figure 1 shows the location of the selected basins within the Korean Peninsula.

Each basin contains many stream gauge stations, among which this study selected only those less affected by dam or other hydraulic structures to secure the accurate rainfall–runoff data for reasonable parameter estimation. As a result, 18 stream gauge stations within Chungju, nine within Namgung, six within Andong, four within Imha and four within Hapcheon were selected. Table 1 summarizes the topographic characteristics of the sub-basins considered in this study. In Table 1, $A$ is the basin area (km$^2$), $L$ is the channel length (km), $S$ is the basin slope.

**Preparation of storm event data**

Hourly rainfall data were used in this study. The observation period of the data varies from 1 year to 36 years depending on the rain gauge station. In cases where several rain gauges were available, the basin average rainfall data were prepared by the Thiessen polygon method. Major storm events were then separated by applying some conditions like the mean rainfall intensity 10 mm/hr or maximum rainfall intensity 50 mm/hr. Additionally, only those storm events satisfying the AMC (Antecedent Moisture Condition) III condition were selected to make sure of enough runoff volume. As a result, each stream gauge station could secure storm events from a minimum 2 to a maximum 47, and they were used for the estimation of $T_c$ and $K$.

**EVALUATION OF EMPIRICAL FORMULAS**

**Concentration time**

Various empirical formulas for $T_c$ have been proposed globally and are summarized in Table 2. In the table, $T_c$ is the concentration time (hours), $A$ is the basin area (km$^2$), $L$ is the channel length (km), $S$ is the basin slope or channel slope, $N$ is the retardance coefficient, $V$ is the mean velocity.
Table 1 | Topographic characteristics of sub-basins considered in this study

<table>
<thead>
<tr>
<th>Basin</th>
<th>Stream gauge station</th>
<th>A (km²)</th>
<th>L (km)</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chungju dam</td>
<td>Imokjeong</td>
<td>55.8</td>
<td>16.6</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>Jangpyeong-gyo</td>
<td>105.1</td>
<td>26.0</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>Baekokpo</td>
<td>143.9</td>
<td>23.0</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>Anheung</td>
<td>187.0</td>
<td>31.8</td>
<td>0.0049</td>
</tr>
<tr>
<td></td>
<td>Songcheon</td>
<td>349.5</td>
<td>62.8</td>
<td>0.0089</td>
</tr>
<tr>
<td></td>
<td>Sanganmi</td>
<td>393.3</td>
<td>44.2</td>
<td>0.0085</td>
</tr>
<tr>
<td></td>
<td>Najeon</td>
<td>452.6</td>
<td>59.1</td>
<td>0.0081</td>
</tr>
<tr>
<td></td>
<td>Andong dam</td>
<td>123.4</td>
<td>21.6</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>Jisan</td>
<td>159.9</td>
<td>26.0</td>
<td>0.019</td>
</tr>
<tr>
<td></td>
<td>Geochang 2</td>
<td>180.7</td>
<td>29.5</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>Geochang 1</td>
<td>227.0</td>
<td>30.7</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>Hapcheon dam</td>
<td>925.0</td>
<td>64.2</td>
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</tr>
</tbody>
</table>

Table 2 | Empirical formulas for $T_c$

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Name</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kraven (I) (JSCE 1999)</td>
<td>$T_c = 0.0074 \frac{L}{S^{0.15}}$</td>
<td>Espey &amp; Winslow (1974)</td>
<td>$T_c = 43.75 \frac{L^{0.29}}{S^{0.15}}$</td>
</tr>
<tr>
<td>Kraven (II) (JSCE 1999)</td>
<td>$T_c = 0.0074 \frac{L}{V}$</td>
<td>SCS (1975)</td>
<td>$T_c = 1/3600 \sum \frac{L}{V}$</td>
</tr>
<tr>
<td>Rziha (1876)</td>
<td>$T_c = 0.0159 \frac{L}{S^{0.6}}$</td>
<td>SCS lag (1985)</td>
<td>$T_c = 0.257L^{0.8}(1000/CN) - 9^{0.7}$</td>
</tr>
<tr>
<td>Kirpich (1940)</td>
<td>$T_c = 0.0663 \frac{L^{0.77}}{S^{0.385}}$</td>
<td>Ahn &amp; Lee (1986)</td>
<td>$T_c = 5.6256 - \frac{L^{0.9417}}{A^{0.3666} S^{2.2659}}$</td>
</tr>
<tr>
<td>Johnstone &amp; Cross (1949)</td>
<td>$T_c = 0.543 \left(\frac{L}{S}\right)^{0.5}$</td>
<td>FAA (1970)</td>
<td>$T_c = 0.000524(1 - C)L^{0.8}$</td>
</tr>
<tr>
<td>Kerby (1959)</td>
<td>$T_c = 0.6059 \left(\frac{L \cdot N}{S^3}\right)^{1.214}$</td>
<td>USGS (2000)</td>
<td>$T_c = 1.54 \frac{L^{0.875}}{S^{0.181}}$</td>
</tr>
<tr>
<td>Kerby-Hathaway (Hathaway 1945)</td>
<td>$T_c = 0.83 \left(\frac{nL}{S^{0.47}}\right)$</td>
<td>Yoon &amp; Park (2002)</td>
<td>$T_c = 1.08 - \frac{A^{0.09} L^{0.16}}{S^{0.12}}$</td>
</tr>
<tr>
<td>Carter (1961)</td>
<td>$T_c = 58.1 \frac{L^{0.6}}{S^{0.3}}$</td>
<td>Jung (2005)</td>
<td>$T_c = 0.119 \frac{L^{0.777}}{S^{0.712}}$</td>
</tr>
<tr>
<td>Morgali &amp; Linsley (1965)</td>
<td>$T_c = 1.396 \times 10^{-6}L^{0.6}H^{0.6}$</td>
<td>California DoT (1955)</td>
<td>$T_c = 0.0663 \left(\frac{L}{H}\right)^{0.385}$</td>
</tr>
<tr>
<td>Izzard &amp; Hicks (1947)</td>
<td>$T_c = 0.00547(0.0178I + C)L^{0.35}$</td>
<td>Kim (2015)</td>
<td>$T_c = 0.089 \frac{A^{0.427}}{S^{0.239}}$</td>
</tr>
<tr>
<td>MOCT (1974)</td>
<td>$T_c = 1.68 \left(\frac{L}{V}\right)^{0.5}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
(m/sec), \( i \) is the rainfall intensity (in/hr), and \( n \) is the Manning’s roughness coefficient.

The empirical formulas for \( T_c \) summarized in Table 2 are compared with those in the theoretical analysis. Most of the empirical formulas are expressed as a function of both \( L \) and \( S \). As, theoretically, \( T_c \) should be represented by a function of \( L^2/S \) for turbulent flow and by a function of \( L/S \) for laminar flow, those empirical formulas in Table 2 can be compared effectively on the plane of exponents of \( L \) and \( S \). As, theoretically, \( T_c \) should be represented by a function of \( L^2/S \) for turbulent flow and by a function of \( L/S \) for laminar flow, those empirical formulas in Table 2 can be compared effectively on the plane of exponents of \( L \) and \( S \). Figure 2(a) shows the empirical formulas for \( T_c \) and \( K \) expressed as a single value in Figure 2. Since the exponents of \( L \) and \( S \) in the empirical formulas considered in this study do not exceed the value of 2, the ranges of the \( x \)-axis and \( y \)-axis are set from 0 to 2.

The dotted lines in Figure 2 are the reference lines for the functions with slopes 2 and 1, respectively, representing the ratios between exponents of \( L \) and \( S \) for the turbulent and laminar flows, respectively. Those empirical formulas in Table 2 can be compared effectively on the plane of exponents of \( L \) and \( S \), as shown in Figure 2(a). Each empirical formula for \( T_c \) and \( K \) is expressed as a single value in Figure 2. Since the exponents of \( L \) and \( S \) in the empirical formulas considered in this study do not exceed the value of 2, the ranges of the \( x \)-axis and \( y \)-axis are set from 0 to 2.

The dotted lines in Figure 2 are the reference lines for the functions with slopes 2 and 1, respectively, representing the ratios between exponents of \( L \) and \( S \) for \( L^2/S \) and \( L/S \). These reference lines are based on the theoretical review that \( T_c \) and \( K \) should follow a function of \( L^2/S \) for the turbulent flow and a function of \( L/S \) for the laminar flow. That is, the nearer to the reference line the point (indicating an empirical formula) is located, the better it is matched to its own theoretical background.

As can be seen in Figure 2(a), formulas like Kirpich (1940), Kraven (I) (JSCE 1999), Kraven (II) (JSCE 1999), California DoT (1955), Kerby (1959), SCS (1975), Morgali & Linsley (1965), Carter (1961), MOCT (1974), Espey & Winslow (1974), and Kerby-Hathaway (Hathaway 1945) are found to be matched well to the theoretical result for turbulent flow. That is, the ratio of exponents of \( L \) and \( S \) is 2. Clearly, these formulas were developed for the condition of heavy rainfall in a steep upstream basin. On the other hand, the empirical formulas like Johnstone & Cross (1949) and Izzard & Hicks (1947) are found to follow the case of laminar flow; that is, the ratio of exponents of \( L \) and \( S \) is 1. Some other formulas like Rziha (1876), FAA (1970) and SCS lag (1985) are found to be in between the turbulent and laminar flow conditions.

**Storage coefficient**

The empirical formulas for \( K \) identified in this study are summarized in Table 3, where \( K \) represents the storage coefficient (hour), \( C \) is the runoff coefficient, \( L \) is the channel length (km), \( A \) is the basin area (km²), \( S \) is the channel slope, and \( b \) and \( a \) are the correction factors.

Based on the theoretical analysis in the previous section, it was found that \( K \) can be proportional to \( T_c \). Thus, the forms of empirical formulas can be analyzed similarly to those for \( T_c \). Like Figure 2(a), Figure 2(b) compares empirical formulas of \( K \) in Table 3 on the plane of exponents of \( L \) and \( S \).
and $S$. Also, each point in Figure 2(b) indicates an empirical formula located by the exponents of $S$ and $L$.

In Figure 2(b), formulas like Clark (1945), Russell (Russell et al. 1979), Sabol (1988) and Jung (2005) closely match the theoretical result. The empirical formulas like Clark (1945) and Jung (2005) show a ratio of exponents of $L$ and $S$ of 2. In the Russell (Russell et al. 1979) and Sabol (1988) formulas, the relationship between $T_c$ and $K$ is only given by a proportionality constant. The formula by Yoon & Park (2002) shows a slightly higher ratio of exponents (approximately 2.5), and the Kim (2015) formula is between turbulent and laminar flow (approximately 1.5). However, the ratio of exponents is 4 for the Linsley (1945) formula and is even higher for the Yoon et al. (1994) and Go (2014) formulas.

### Relationship between concentration time and storage coefficient

When comparing the empirical formulas for $T_c$ and $K$, it is obvious that the empirical formulas for $T_c$ more closely concur with the theoretical result. More variation was found in the empirical formulas for $K$. For example, $A$ is considered important in many empirical equations including Linsley (1945), Laurenson (1962), Kim (2015), etc. The exponents used for $A$ in the Linsley (1945), Laurenson (1962), and Kim (2015) formulas are rather high at 0.5, 0.27, and 0.238, respectively. Additional consideration of $L$ to $A$ also indicates that the basin shape factor plays an important role, which can be found in the formulas by Linsley (1945), Yoon et al. (1994), Go (2014), and Kim (2015).

Also, based on Figure 2(b), it can be easily conjectured that $K$ in a basin is not that simple like $T_c$. A linear relationship between the two may not be satisfied in most river basins. Also, $K$ in a basin may not be simplified as a function of channel characteristics. Characteristics of basin shape and channel network, as adopted in many empirical formulas, may improve the accuracy of their application. At this moment, it may not be concluded that $K$ in a basin is simply proportional to $T_c$.

### EVALUATION FOR MAJOR DAM BASINS IN KOREA

#### Estimation of concentration time and storage coefficient

This study estimated $T_c$ and $K$ of an observed storm event using the method proposed by Yoo et al. (2015). This method is a recursive approach considering the structure of the Nash IUH (Nash 1957). Yoo et al. (2015) showed that the Nash IUH has a distinct relationship between $T_c$ and $K$, as in Equation (7). Also, as shown in Equations (5) and (6), $T_c$ and $K$ are correlated nonlinearly. In fact, $T_c$ shows more sensitivity to $x$ than $K$ does. This difference causes the strong nonlinear behavior of these two parameters when they are estimated from rainfall-runoff...
measurements. $K$ can show rather stable behavior without significant variation, but $T_c$ cannot. However, the method by Yoo et al. (2015) was found to overcome this problem when estimating $T_c$ and $K$ using the observed rainfall–runoff data.

**Results and discussion**

Empirical equations for $T_c$ and $K$ were derived for each basin using those estimated using the observed data. Figure 3 compares the resulting empirical equations on log-log paper.

As can be seen in Figure 3, both derived empirical equations for $T_c$ and $K$ are well matched to the observed values. Especially, $T_c$ seems very well explained by $L^2/S$ in all basins. All the empirical equations are found to have similar slopes on log-log paper. On the other hand, the empirical equations for $K$ show different behavior; especially the slopes and intercepts are found to be different basin by basin. That is, $K$ seems to vary much basin by basin. In fact, this phenomenon was also found in the previous section where various forms of empirical formulas were analyzed. Differently from $T_c$, more various forms of empirical formulas exist, and they also consider other basin characteristics like $A$ and shape factor. Simply $L$ and $S$ may not be enough to explain $K$.

Finally, this study evaluated the relationship between $T_c$ and $K$, which was found to be linear. The coefficients of determination of those regression lines are from 0.932 to 0.995. However, it also true that each line is different from the others. The difference may be quantified by the Russell parameter (Russell et al. 1979), which is the relation between $K$ and $T_c$ or simply the slope of the line in this figure. The highest Russell parameter was found in Hapcheon dam basin, which is 1.262, and in Chungju dam basin it was the smallest at 0.986. Even though the Russell parameter in Hapcheon dam basin is a bit higher than 1.2, all basins are included in the range 0.8 ~ 1.2 of natural basins in Korea (Jeong & Yoon 2007).

**CONCLUSIONS**

This study tried the theoretical evaluation of $T_c$ and $K$ with more than 20 empirical formulas available worldwide. The evaluation result was also confirmed in the application to major dam basins in Korea. The findings of this study are as follows:

1. $T_c$ could be expressed as a function of channel characteristics: $L$ and $S$. Especially, $T_c$ was found to be expressed as a function of $L/S$ under laminar flow conditions and $L^2/S$ under turbulent flow conditions.
(2) Most empirical formulas for $T_c$ are found to follow the basic equation form considered in this study, however, those for $K$ are found to vary considerably. It seems that $K$ may not be explained fully by $L^2/S$. Additional factors may be needed to effectively explain the storage effect of a basin.

(3) In the application to several dam basins in Korea, it was found that both $T_c$ and $K$ could be well modeled by the factor $L^2/S$. Especially, the relationship between $T_c$ and $L^2/S$ was very consistent in all basins, but the behavior of $K$ varied much basin by basin.

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REFERENCES


California DoT 1955 California Culvert Practice. Department of Public Works, Division of Highways, Sacramento, CA, USA.


Chezy, A. D. 1775 Memoire sur la vitesse de l’eau conduite dans une régole. Reprinted in Annales des Ponts et Chaussées 60 [2121].

Clark, C. O. 1945 Storage and the unit hydrograph. Transactions of the American Society of Civil Engineers 110, 1419–1446.


JSCE 1999 The Collection of Hydraulic Formulae. JSCE, Tokyo, Japan.


Kirpich, Z. 1940 Time of concentration of small agricultural watersheds. Civil Engineering 10 (6), 362.


Linsley, R. 1945 Discussion of storage and the unit hydrograph by C. O. Clark. Transactions of the American Society of Civil Engineers 110, 1452–1455.


Rziha, F. 1876 Eisenbahn-Unter-Und Oberbau (Vol. 1). Verlag der KK Hof-und Staatsdr., Vienna, Austria.


Sherman, C. W. 1931 Frequency and intensity of excessive rainfalls at Boston, Massachusetts. Transactions of the American Society of Civil Engineers 95, 951–960.


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