Velocity and time of concentration of a basin – A renewed approach applied in the Rio Grande Basin, Ecuador

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Abstract. After a review of the existing formulas for the time of concentration of a basin, it has been established that there is no unique formula that may be applied to a wide range of basins with different geomorphological parameters. So far, the results obtained according to the equations of different authors are completely different and in some cases even inapplicable. Therefore, a new practical formula has been obtained based to the theoretical analysis of the Chezy equation in order to determine the velocity of a flow at a control point, using the single empirical coefficient k. With this formula, the average runoff velocity is reached, which, in turn, allows the calculation of the concentration time of a basin. The proposed equation has been compared with the results obtained by other authors, with values which are acceptable for their application in studies and projects at the pre-design level, for example, with the field data obtained by López (2005) compared with the results of the proposed equation, we received an r² = 0.99. The given formula has been applied in a variety of river basins across the world and the resulting values have been compared with the existing ones. Lastly, the new formula has been applied to the Rio Grande Basin in western Ecuador.

1. Introduction

The time of concentration of a watershed is one of the most important parameters for designing hydrological infrastructure such as dams, irrigation channels, water intakes, as well as bridges, highways among other strategic structures [1-5]. The time of concentration cannot always be determined directly because it would imply to measure the time for a precipitation that generates the flow of design. Therefore, such measurement needs to be estimated based on travel times throughout a watershed [6-9]. According to [10] time of concentration is able to be estimated by applying the kinematic wave theory as it has been used previously in a variety of studies [11-13]. Reference [14] applied this theory in overland planes and subject to uniform rainfall excess. However, the reference [15] indicated limitations of such methodology in practical estimations of time of concentration in small watersheds. On the other hand, the Natural Resources Conservation Service (NRCS) uses the Watershed Lag method as developed by Reference [16], which apparently demonstrates limitations related to the size of a watershed [17].

Based on the reference [8], estimations of time of concentration, may present a wide range of variation measures. Such discrepancies may reach even a 500% of difference among several methodologies. This becomes a serious issue for planning and designing water related infrastructure, as such incongruities may result in undersized or oversized structures. Consequently, such calculation generates risk in terms of potential underestimated or overestimated costs, loss of infrastructure and
damage to the nearby population. An adequate example of such wrong estimation may serve the case of the La Plata River in Argentina. This river is commonly overflowing although several infrastructures have been constructed to control the seasonal floods [18]. In Venezuela as a result of unsuitable estimations of potential flooding, the “El Guapo” dam failed to control the total water volume for which its spillway has been built, by being flooded by three times the calculated and expected volume [19]. Such overflowing is generally rare, but not unfeasible [19]. Obviously, these two examples may not be only attributed to an inadequate calculation of time of concentration, but such parameters certainly affect in some significant degree the uncertainty of hydrological parameters that it depends upon. In fact, it contributes to false measurements of water volumes and flows involved in the design of a hydraulic infrastructure.

Furthermore, the reference [8] highlighted that there are eight different definitions for time of concentration, which carry several methods of estimations. These methodologies are used based on which adapt better to local or regional watershed characteristics. However, in the current study, we have used the time in which a drop of water takes to travel the entire main channel from the highest point of a watershed all the way down to the control point of the basin. Based on this definition, it is necessary to know the parameters of the basin’s morphometric, and hereby particularly the main course length and the average runoff rate of the watershed. So far, it has been relatively common for a variety of studies and even US state organizations like the Texas Department of Transportation to use the Kirpich formula [20] for the time of concentration [2, 21-24], while other studies and institutions like the USDA use the Mockus formula [16, 25-30]. The Kirpich method however, has been unable to be applied in some cases due to equation limitations such as some parameters like the area of the basin (A) is restricted between 0.4 to 241 km$^2$, the slope “J” serves only between 0.02 to 0.002 m/m and the length of the main basin “L’” ranges strictly between 1.6 to 80 km [20]. According to Reference [31] the Mockus study can be applied to basins of up to 49 km$^2$ [31]. Therefore, some formula modifications are required to extend the use of a renewed and more precise estimation of the time of concentration.

At a pre-design stage, the sizing of any hydraulic infrastructure requires that equations establish the time of concentration to the highest veracity or closest point compared to the determined field data. To fulfill such purpose, it is relatively common in the field to use a combination or application of several formulas of a number of authors and hereby to estimate the average value, although such practice is not recommended [8].

Therefore, the main aim of this study has been to propose a semi-empirical equation to determine the velocity of a flow and concentration time of a basin that is applicable to a wider range of watersheds and hydraulic conditions. Such new formula shall be tested in the Rio Grande Basin of Ecuador and other worldwide known rivers.

2. Methodology
There is a wide range of equations up to date, which have been applied to calculate the time of concentration of a watershed. The regular parameters used for such calculations are: $A =$ Area of the basin in km$^2$; $L =$ Length of the main basin in km; $J =$ slope m/m; $v =$ Average flow velocity; $n =$ Runoff roughness; $t_c =$ time of concentration in hours. Some of the most used equations are:

Kirpich [20]  
\[ t_c = 0,06635L^{0.77}/J^{0.385} \]  

Kerby, [32]  
\[ t_c = 36,36(n \times L)^{0.467}/J^{0.235} \]  

Chow, [33]  
\[ t_c = 0,2734L^{0.64}/J^{0.32} \]  

Giandoti, [34]
\[ t_c = \frac{4\sqrt{A + 1.5L}}{25.3\sqrt{JL}} \]  
\[ (4) \]

Soil Conservation Service (USDA), [27]

\[ t_c = 0.917 \frac{L}{\sqrt{J}} \]  
\[ (5) \]

Bransby Williams, [35,36]

\[ t_c = \frac{L}{90 + D} \sqrt{\frac{A^2}{100 + J}} \]  
\[ (6) \]

Here, D is the diameter of the basin equivalent to area A.

Ventura – Heras, [37]

\[ t_c = (0.05 ... 0.5) \frac{\sqrt{A}}{100 + J} \]  
\[ (7) \]

Pasini, [38]

\[ t_c = (0.04 ... 0.13) \frac{(AL)^{1/3}}{\sqrt{100 + J}} \]  
\[ (8) \]

California Culvert Practice, [39]

\[ t_c = \left( \frac{0.87075 L^3}{\Delta H} \right)^{0.385} \]  
\[ (9) \]

Clark, [40]

\[ t_c = 0.335 \left[ \frac{A}{(100 + J)^{0.5}} \right]^{0.593} \]  
\[ (10) \]

Ribeiro, [41]

\[ t_c = \frac{0.27 L}{(1.05 - 0.2 A v A)^{0.04}} \]  
\[ (11) \]

Here, \( A_v \) is the area covered by vegetation.

Henderson – Wooding, [37]

\[ t_c = \frac{0.016 \left[ \frac{n L}{305 \Delta L} \right]^{0.6}}{I^{0.4}} \]  
\[ (12) \]

Here, ‘I’ corresponds to the rain intensity in mm/hour.

Témez, [42]

\[ t_c = 0.3L^{0.76}/I^{0.19} \]  
\[ (13) \]

There are several dozens more of such equations. However, listing them would just evidence an increase of the degree of uncertainty of the time of concentration. The main deficiency of the equations is that they are empirically developed for certain types of basins, but their application has been introduced for all required cases. In order to increase applicability, a general equation is required and this may be possible through runoff velocity, as proposed by several studies [43-44].

\[ tc = 0.28 \frac{L}{V} \]  
\[ (14) \]

Reference [44] suggests taking velocity V, equal to 70% of the values listed in table 1.
Table 1. Maximum speed values (m/s) proposed by [44].

| River-bed and relief conditions | Rivers with depths $h \leq 1$m | Rivers with depths $h >1$m |
|---------------------------------|--------------------------------|---------------------------|
| Swampy                          | 0.3 to 0.5                     | 0.4 to 0.8                |
| Channel of plain                | 0.6 to 1.0                     | 0.8 to 1.2                |
| Semi-mountainous and relief     | 1.0 to 2.0                     | 1.5 to 2.5                |
| with hummocks                   |                               |                           |
| Mountainous                     | 1.5 to 2.5                     | 2.0 to 3.0                |

Table 1 is a guide to set up a speed. However, having a variation range will imply considerable errors. Therefore, it requires a formula to determine the speed with a better accuracy. Based on such assumption, we encountered some equations, which determine the velocity of a flow through the parameters of a section or basin, such as following ones:

Leopold [45]

$$V = 0.566 \, Q^{0.10} \tag{15}$$

Sokolovsky, [46]

$$V = 0.15 \, J^{1/3}Q^{0.25} \tag{16}$$

Dubaj, [47]

$$V = \left(\frac{J^{0.5}Q^{0.67}}{n}\right)^{0.6} \tag{17}$$

The equation by Veksler and Donenberg [48] correspond to the same equation by Chezy [49] where $R$ has been replaced by $h$,

$$V = \frac{h^{2/3}\sqrt{J}}{n} \tag{18}$$

In the same way Jarret [50,53] proposed for mountain-rivers the following equation,

$$V = 3.17 \, J^{0.12}R^{0.83} \tag{19}$$

Rickenmann, [51] proposes to calculate the velocity of muddy flows with the following equation,

$$V = 2.12\sqrt[3]{JQ} \tag{20}$$

Recently, for mountain channels [52] proposes the following equations,

$$V = 1.34 \, J^{0.32}Q^{0.34}d_{50}^{-0.22} \tag{21}$$

$$V = 1.56 \, J^{0.33}Q^{0.34}d_{95}^{-0.25} \tag{22}$$

$$V = 1.62 \, J^{0.33}Q^{0.34}d_{90}^{-0.25} \tag{23}$$

Where, $d_{50}$, $d_{95}$ y $d_{90}$ are the diameters (m) of the granulometric composition of the river bed for the percentages indicated in the subscript.

2.1. Equation of the proposed speed

In natural or artificial channels the area and the hydraulic radius may be expressed as,

$$A = k_1 \, h^2$$

$$R = k_2 \, h$$

Based on Manning [54] the velocity of a channel is,

$$V = R^{2/3} \frac{J}{n} \tag{24}$$
Replacing $R$,

$$V = \left( k_2 h \right)^{2/3} \frac{f}{n}$$  \hspace{1cm} (25)

Of the flow condition,

$$Q = AV = k_1 h^2 V$$

From where,

$$h = \left( \frac{Q}{k_1 V h} \right)^{1/2}$$  \hspace{1cm} (26)

Replacing equation (25) in equation (26),

$$V = \left( \frac{k_2}{k_1^{1/2}} \frac{Q}{V} \right)^{2/3} \frac{f}{n}$$

Clearing speed and replacing, $\left( k_2/k_1^{1/2} \right)^{1/2}$ by $k$, we obtain,

$$V = k Q^{0.25} J^{0.375} n^{0.75}$$  \hspace{1cm} (27)

We have not used the Manning-Strickler formula to directly determine equation (27), as Chezy’s equation is explicitly integrated into the Manning-Strickler equation. Chezy is named for the initial origin of the formula, but by using the $C$ coefficient according to Manning implicitly we have the Manning-Strickler equation. With the given equation, we are able to determine the velocity in any section of a watershed if the components of the basin are known. The velocity obtained corresponds to a section of a prismatic channel and is a theoretical velocity. In practice, the variation of the section area, slope variation, the presence of sinuosities and other disturbances other than roughness should be considered in the coefficient $k$ and this value should be lower than that of a prismatic channel.

From the analysis of the geometric shapes of prismatic channels and natural channels, we have $k = 0.7$ to $0.3$ [53], where the first represents the boundary for very enclosed mountain channels and the second represents fairly open riverbeds. For a base trapezium channel $b = 2h$ and side slopes $1:1$, $k = 0.599$. For 21 rivers in the State of Colorado the values of $k$ in the metric system are from 0.473 to 0.350 with an average of 0.401 [53].

| Table 2. Field data from Reference [55] compared with those determined with equation (27). |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| $Q$ (m$^3$/s) | $H$ (m) | $J$ (m/m) | $R$ (m) | $V$ (m/s) | $n$ | $k$ data | $k$ equation (28) | $V$ equation (27) |
|----------------|--------|------------|--------|----------|-----|-----------|------------------|------------------|
| 1              | 3.13   | 0.36       | 0.0099 | 0.36     | 0.74| 0.068     | 0.418            | 0.392            |
| 2              | 1.03   | 0.26       | 0.0101 | 0.26     | 0.51| 0.080     | 0.428            | 0.392            |
| 3              | 1.11   | 0.24       | 0.0099 | 0.24     | 0.5 | 0.077     | 0.401            | 0.392            |
| 4              | 0.76   | 0.19       | 0.0096 | 0.19     | 0.42| 0.077     | 0.376            | 0.392            |
| 5              | 0.5    | 0.16       | 0.0099 | 0.16     | 0.36| 0.081     | 0.368            | 0.392            |
| 6              | 0.32   | 0.16       | 0.008  | 0.16     | 0.25| 0.105     | 0.376            | 0.392            |
| 7              | 0.47   | 0.17       | 0.0102 | 0.17     | 0.33| 0.094     | 0.377            | 0.392            |
| 8              | 0.35   | 0.15       | 0.0092 | 0.15     | 0.29| 0.093     | 0.369            | 0.392            |
| 9              | 0.39   | 0.15       | 0.0107 | 0.15     | 0.32| 0.091     | 0.369            | 0.392            |
| 10             | 1.118  | 0.24       | 0.0108 | 0.24     | 0.5 | 0.080     | 0.401            | 0.392            |
| 11             | 0.59   | 0.18       | 0.0104 | 0.18     | 0.37| 0.088     | 0.378            | 0.392            |
| 12             | 0.68   | 0.2        | 0.0103 | 0.2      | 0.39| 0.089     | 0.389            | 0.392            |
| 13             | 2.05   | 0.32       | 0.0102 | 0.32     | 0.59| 0.080     | 0.414            | 0.392            |
| 14             | 1.58   | 0.29       | 0.0098 | 0.28     | 0.49| 0.086     | 0.395            | 0.392            |
| 15             | 1.97   | 0.3        | 0.009  | 0.31     | 0.56| 0.078     | 0.407            | 0.392            |
| 16             | 2.23   | 0.33       | 0.0099 | 0.33     | 0.65| 0.073     | 0.422            | 0.392            |
| Average Values | 1.142  | 0.231      | 0.010  | 0.231    | 0.454| 0.084     | 0.393            | 0.392            |
|                |        |            |        |          |      | 0.448     |                  |                  |
Table 2 documents the field results, obtained by Reference [55], in which the speeds and the roughness coefficients of Manning have been determined and when comparing them with the results obtained using equation (27), it is noted that there is a good coincidence. For a study section in a basin in the first kilometers of the channel, we probably have mountain conditions, with small contribution areas, but with large slopes while for farer sections, we certainly have conditions of plain with large areas and small slopes. Roughness and slope are already considered in the equation of velocity, while the parameters which are not taken into account are the area of the basin and the sinuosity of the channel.

In order to establish an equation for \( k \), it is necessary to have all the information of equation (27) and those related to the basin. Based on the scarce complete information available for some river basins of Russia [56], North America [53,57], Spain [52,55,58] and others, an approximation has been determined for \( k \) as a function of area within equation (28): However, it has not been possible to establish a correlation with the sinuosity of the channel.

\[
k = 0.5 - 0.023 \ln A
\]  

(28)

Although, \( k \) may vary for different flows at the same point, it can practically be taken as a constant. If we compare this equation with the data of Reference [52] determined in the field for the Bellera River, for a basin of \( A = 110 \) Km\(^2\) we obtained a very good correlation (table 2, figure 1).

\[
k_c = 0.35 - 0.016 \ln A
\]  

(29)

For the purpose of determining the runoff time [44] it is recommended to take 70% of the actual speed of a runway located in the study section, so that the coefficient for the runoff rate would be,

\[
ts_c = 0.28 \frac{L}{V}
\]

Taking the concentration time equation in hours

\[
ts_c = 0.28L \frac{n^{0.75}}{k_c Q^{0.25} J^{0.375}}
\]

(30)

Where, “L” represents the main channel length (km); “Q” is the average flow of the design (m\(^3\)/s); “J” represents the mean slope of the basin (m/m); “n” the roughness coefficient for the channel or design flow.

Having the gauges facilitates the application of the equation, especially to establish the coefficient of roughness “n”. If no field data are available, the roughness coefficient may be taken from Reference
[59], or [57], among several others.

2.2. The case study of the Río Grande Basin in Ecuador

The basin of the Río Grande has been chosen due to the fact as it contains gaps in the zone of closure of the dam of the same name (figure 2). This basin until that point reaches an area (A) of 157.12 km², having a length of the main channel being (L) of some 21.8 km. The length of the basin (Lc) reaches 14.08 km, with an average annual flow (Qo) of 3.92 m³/s. The nascent of the Río Grande is located at the height of 460 m.a.s.l and, as soon as it has traveled 2 km, it is already at the level 175 m.a.s.l. (J = 0.02). In the residual 14.8 km that are missing until the closing site, the slope is J = 0.0034. The average slope of the basin is therefore reaches some 0.0257 (J), with an average width (B) of 157.12 / 14.08 = 11.16 km [60]. Table 3 lists the results of the gauging and theoretical flow rates as carried out in the Río Grande and calculates the parameter k according to the area of the watershed. It also establishes that the proposed equation reflects a good coincidence.

![Figure 2. Location of the Río Grande Basin, slightly east of Chone, in Manabí Province, western Ecuador [60].](image)

**Table 3.** Data of volumes for the Río Grande and values of k as well as of the proposed velocity.

| Flow  | V (m/s) | R (m) | h (m) | J (m/m) | n | k seating | k equation (28) | V equation (27) |
|-------|---------|-------|-------|---------|---|-----------|------------------|------------------|
| 0.541 | 0.289   | 0.218 | 0.37  | 0.00046 | 0.0269 | 0.399     | 0.384           | 0.278           |
| 0.528 | 0.292   | 0.211 | 0.37  | 0.00048 | 0.0266 | 0.396     | 0.384           | 0.283           |
| 6.042 | 0.564   | 0.441 | 0.61  | 0.00056 | 0.0243 | 0.367     | 0.384           | 0.589           |
| 5.609 | 0.536   | 0.432 | 0.55  | 0.00050 | 0.0239 | 0.366     | 0.384           | 0.563           |
| 45.984| 0.736   | 2.023 | 2.65  | 0.00027 | 0.0357 | 0.506     | 0.384           | 0.558           |

With the values of the parameters of the basin being A = 157.12 km²; L = 21.8 km; J=0.0275; n = 0.0275; Q=3.92 m³/s, we apply equation (29), with k = 0.269; Ec. (27), V = 1.421 m/s and Equation (30), with t being 4.29 hours. Once we calculate the concentration times of the basin in hours with the given equation (1) to equation (13), we obtain a great dispersion of the values. Hence, the selection of the most adequate equation remains challenging (table 4). Designers have opted for an average value that may result to be most likely far from reality. The calculation with equation (30) allow appreciating the concentration time through a speed value that need to be in a range considered as real or very likely and possible to reality.
The proposed new equation allows determining the speed, theoretically, at any point of a channel of a basin for the purpose of pre-design of hydraulic works.

Likewise, it allows us to determine the time of concentration of a basin based on average values of

Table 4. Concentration time values in hours with other proposed equations.

| Equation | Tc in hours | Equation | Tc in hours | Equation | Tc in hours | Equation | Tc in hours |
|----------|-------------|----------|-------------|----------|-------------|----------|-------------|
| Equation (1) | 2.91      | Equation (2) | 1.13      | Equation (3) | 6.34    | Equation (4) | 4.37     | Equation (5) | 3.20     | Equation (6) | 1.68     | Equation (7) | 2.44     |
| Tc in hours | 1.22      | Equation (8) | 3.21      | Equation (9) | 5.08    | Equation (10) | 6.51     | Equation (11) | 2.75     | Equation (12) | 6.26     | Equation (13) | 4.29     |

From field studies for the Rio Grande Basin, we observed that Giandotti's Equation (4) gave the closest results to the values obtained with the equation proposed by us (equation 30). Furthermore, we have used literature data in order to compare them with the data obtained with our formula, demonstrating that our equation has been able to be used for large basins (table 5). Although these values may be referential since in the listed rivers appear a great number of hydraulic structures that modify the natural conditions of the rivers, it also indicates the degree of applicability of the proposed formula. Additionally, the proposed equation has no limits with respect to the size of the watershed or modify the speed of the flow through the channel. Such limits do appear in the application of the other presented equations. This is based to the fact, that most of the equations consider the depth of the flow for the determination of the speed, which is a parameter that almost always is unknown in the design of projects. Our equation depends on the physical parameters flow, slope, roughness and area of the watershed that are easier to appreciate. The possible limitation of the proposed equation is the existence of hydraulic structures along the channel, which modify the speed of the flow through the channel.

Table 5. Calculated data of velocities and times of concentration of a variety of rivers worldwide with our formula compared with other studies. The concentration time of the references has been determined with indirect methods, in most cases with data of average speed of the references below the table.

| River    | A    | Q    | L    | J    | n* | K    | V    | Tc (hours) | Tc (days) | Tc^* (days) |
|----------|------|------|------|------|----|------|------|------------|------------|-------------|
| Amazonas** | 7180000 | 220000 | 6436 | 0.000016 | 0.037 | 0.10 | 0.40 | 4530.7 | 189 | 134 |
| Amur**   | 1855000 | 128000 | 2824 | 0.000108 | 0.037 | 0.12 | 0.49 | 1618.3 | 67 | 60 |
| Dneper** | 5040000 | 167000 | 2287 | 0.000100 | 0.040 | 0.14 | 0.32 | 2025.0 | 84 | 90 |
| Ebro ***** | 8610000 | 600000 | 950 | 0.001950 | 0.040 | 0.17 | 0.90 | 296.7 | 12 | 13 |
| Lena**   | 24900000 | 1635000 | 4400 | 0.000038 | 0.037 | 0.11 | 0.34 | 3671.7 | 153 | 147 |
| Madgalena***** | 25743800 | 8000000 | 1540 | 0.002400 | 0.040 | 0.15 | 1.66 | 259.9 | 11 | 15 |
| Mississippi***** | 29810000 | 1679000 | 3734 | 0.000119 | 0.040 | 0.11 | 0.48 | 2183.3 | 91 | 90 |
| Moscú** | 17600000 | 1090000 | 502 | 0.000031 | 0.040 | 0.19 | 0.14 | 986.1 | 41 | 39 |
| Ob** | 29900000 | 12492000 | 3650 | 0.000040 | 0.037 | 0.11 | 0.31 | 3263.5 | 136 | 130 |
| Volga** | 13610000 | 8060000 | 3530 | 0.000070 | 0.040 | 0.12 | 0.36 | 2719.5 | 113 | 102 |

Note: Tc^* are the calculated data of the literature as listed as follows: *[33] with an n= 0.033 to 0.045 for channels of more than 25 m width; **[61]; ***[62]; ****www.geoenciclopedia.com. *****[63]; ******[64]; *******[65].

3. Conclusions

The proposed new equation allows determining the speed, theoretically, at any point of a channel of a basin for the purpose of pre-design of hydraulic works.

Likewise, it allows us to determine the time of concentration of a basin based on average values of
the parameters of a channel and the area of the basin and the results obtained are within a range consistent with other formulas.

We encountered that the empirical coefficient $k$, for the determination of the speed of a channel or for the time of concentration depends on the area of the basin, whether it is small or large.

The equation for the time of concentration has been used in the Rio Grande Basin and other rivers known worldwide for comparison, we are able to conclude that the proposed speed equation allows to be used as a first approximation for any section of a track along a river basin.

Finally, we were able to determine that in very small basins there may be factors that significantly change the value of $k$.

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