Towards robust operational estimation of the time of concentration in ungauged basins

TOWARDS ROBUST OPERATIONAL ESTIMATION OF THE TIME OF CONCENTRATION IN UNGAUGED BASINS

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KEY POINTS

- *Use of literature formulas in relation to basin morphological scaling laws.*
- *Considerations on the feasibility of employing formulas beyond their calibration range in terms of basin areas.*
- *Practical indications for estimating average travel velocities in design applications.*

1 INTRODUCTION

Estimation of design flood hydrographs in ungauged basins requires the identification of parameters of the basin hydrological response. These parameters are extracted from relationships that are often empirical and lack solid foundations in the specific physical characteristics of the basin. The characteristic time of the instantaneous unit hydrograph (IUH) is certainly one of the parameters that suffer from the greatest uncertainty. Indirect approaches for its estimation involve the application of empirical or analytical formulas, but in engineering practice the justification for relying on one or more formulas often rests on heuristic grounds, lacking solid scientific considerations to guide the selection of the most appropriate formulation.

In this paper we refer to the catchment-averaged velocity approach proposed by *Evangelista et al.* (2023) for selecting robust formulas and suggest some considerations that can drive the end users toward an operational approach to a robust estimation of the time of concentration.

2 IDENTIFICATION OF ROBUST FORMULAS FROM THE LITERATURE

The methodology presented in *Evangelista et al.* (2023) relies on a comparison of the magnitude and basin-wide variation of the average velocities produced by a given formula with values observed in the literature, which is thought of as a more meaningful comparison rather than a comparison in terms of travel times. To this end, 29 formulas has been selected from the literature, all containing parameters related to the basin's length and slope. Starting from the celerities obtained as the ratio between the length of the basin's drainage path and the response times provided by each formula and using the morphology of the river network of 135 basins in northwestern Italy, we compared the variability of estimated mean travel velocities. Observations from the literature (e.g. *Leopold and Maddock*, 1953; *Jowett*, 1998) highlight slightly increasing velocities as basin area increases. Therefore, an increasing pattern with basin size is accepted, while decreasing velocities are considered to be not consistent with observations. A separate discussion should be made for small basins, which are characterized by steep slopes on the one hand, and a hydrological response mainly governed by hillslope flow, on the other hand. Velocities produced over small basins (i.e. over basin areas smaller than 30 km^2, for which no observations are available) should be therefore approached with caution. For safety reasons, it is reasonable to assume that velocities in small basins might remain relatively constant.

In this way, only 5 out of 29 empirical formulas examined proved to be more robust and consistent with observed data, and therefore recommended. These are the formulas proposed by *Chow* (1962), *NERC* (1975), *SCS* (1954), *McEnroe and Zhao* (1999) and *Watt and Chow* (1985).

3 OPERATIONAL CONSIDERATIONS

3.1 Are formulas suitable for use outside their range of calibration?

Considering the five formulas mentioned in the previous section, a straightforward question arises: for which specific category of basins is their application recommended? Traditionally, when using literature formulas, the user makes sure that the size of the target basins reasonably aligns with the size of the basins the formula is calibrated on. However, the rationale behind the identification of these formulas as the most robust is conceptually independent of the specific range of basin sizes being considered. As discussed in section 5 of *Evangelista et al.* (2023), an analytical explanation can be derived to clarify why some formulas show increasing (or constant) velocities as basin area increases, thereby matching empirical observations, while others do not. These reasons lie in the morphological scaling laws of the basin, particularly in the relationship that links basin characteristic length and slope, which can be reasonably expected to follow a "universal" pattern regardless of the basin size.

In Figure 1 a scatter plot illustrates the correlation between the length and slope of main channel for the basins used to calibrate three out the five recommended formulas. The top-right figure presents the variability in basin areas. These data, extracted from the original papers, show that, while basin areas span quite different values, the length-slope scaling relationships appear to be fully comparable, even though the basins under consideration are located in very different geographical regions. The NERC formula is calibrated on basins across the United Kingdom, Watt and Chow used basins spanning from the western United States to Canada, while the McEnroe and Zhao formula is built on data from rural catchments in Kansas.

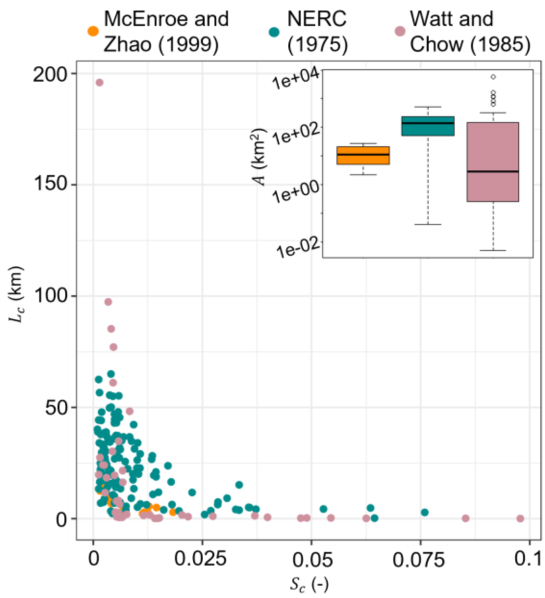

Figure 1. Empirical relationship between length and slope of main channel for the basins used to calibrate the McEnroe and Zhao, NERC and Watt and Chow formulas. The top right corner shows the variability in basin areas for the samples used to calibrate these three formulas.

Therefore, we believe the emphasis should be on congruence in length-slope scaling, rather than focusing solely on variations in basin area compared to the sample used for calibration.

3.2 How to manage the information on average travel velocities?

An additional consideration pertains to the following question: what might the user gain from this research if opting not to use any of these five formulas? The findings from this work can inform about recommended safety velocity values, tailored to the specific basin areas under consideration, to be considered for design purposes.

In Figure 2a, the correlation between basin area and a characteristic factor of the basin is illustrated for the 135 basins in northwestern Italy. This characteristic factor is defined as the ratio of a characteristic length to the square root of a characteristic slope, and it has been selected to represent the variability of velocity values across different watersheds, due to its strong correlation with the basin area (refer to *Evangelista et al.*, 2023 for further details). Figure 2b shows the linear regression lines that interpolate the velocity values obtained for each basin using the five formulas mentioned above. The line referring to the SCS formula is represented as a dashed line as we have no information about the number and the characteristics of the watersheds on which the formula is calibrated.

One can notice that the remaining four formulas, two by two, run parallel to each other. Among these, the NERC formula is calibrated using data from 132 medium to large basins. On the other hand, formulas by Chow and McEnroe and Zhao are calibrated on 20 and 19 basins respectively, in both cases smaller than 30 km^2. The basin sample on which formula by Watt and Chow is built is quite wide in terms of areas, encompassing 44 basins with sizes ranging up to 5840 km^2. However, roughly 70% of these basins have an area much smaller than 100 km^2.

The intersection points between the formulas with increasing and constant behavior, which represents the transition between small to medium-large basins, occurs at approximately $L_c/S_c^{0.5}$ equal to 100, which corresponds to a basin area of around 200 km^2, as shown in Figure 2a. A practical suggestion could then be to consider, for basins smaller than 200 km^2, a velocity at least equal to that provided by the Watt and Chow formula, which represents the lower limit among those calibrated on small basins (first constant segment of the red line in Figure 2c). For basins larger than 200 km^2, the lower limit is given by the NERC formula (second increasing segment of the red line in Figure 2c).

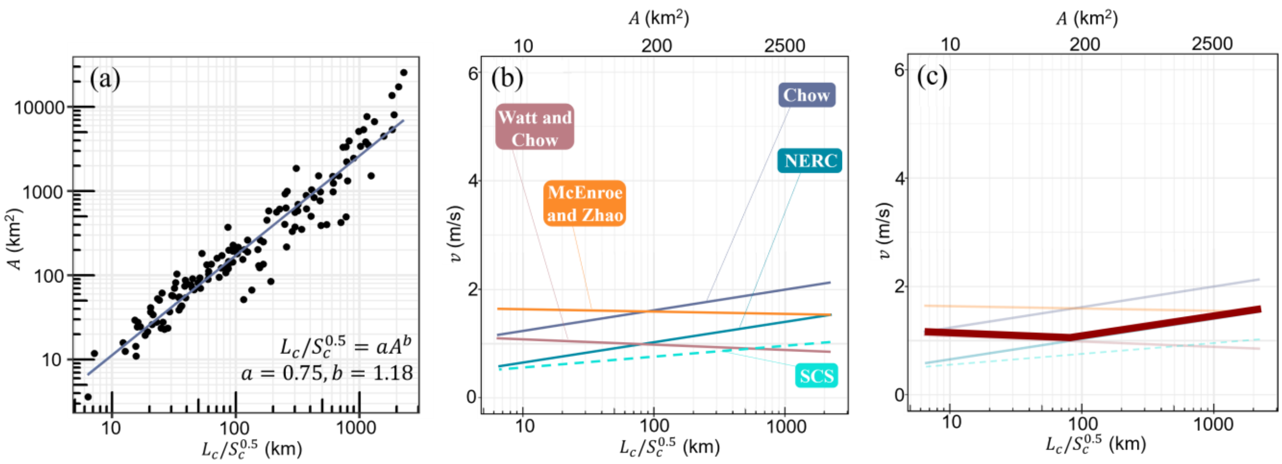

Figure 2. Panel (a) shows the relationship between the basin area and a characteristic basin factor for 135 basins in northwestern Italy. Panel (b) shows the 5 recommended formulas in a velocity-basin factor graph. In Panel (c) lower recommended velocity limits depending on the basin area are depicted. For basins smaller than 200 km^2, the limit is defined by the Watt and Chow formula, while the NERC formula is adopted for larger basins.

The introduction of a lower limit for velocities, intended to discourage values below this threshold, is thought as a safety measure. Any upper limit, on the other hand, should be determined on a case-by-case basis, considering the specific basin under consideration.

4 CONCLUSIONS

The time of concentration or, more in general, the basin flood response time, still emerges as a parameter deserving comprehensive and in-depth investigations. Our analyses have delved into procedures for its estimation using existing formulas with a focus on minimizing subjectivity and ensuring scientific rigor. Following these procedures, only five formulas from the literature, out of the 29 investigated, were identified as more robust, consequently earning a recommendation for practical application. With reference to the range of application of a given formula, our findings suggest that emphasis should be placed on the similarity with morphological scaling laws of basins used for calibration, rather than merely on their areas. Furthermore, by reasoning about the average basin-scale velocities that each formula produces over 135 basins in northwestern Italy, we identified lower bound values for the average velocity, which may be useful for design purposes.

The considerations outlined here are intended to provide possible directions for enhancing the estimation of time of concentration in ungauged basins, offering useful insights applicable to common engineering practices.

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