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The connection between time of concentration and rainfall intensity based on rainfall-runoff modeling

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Abstract— The study aims to examine the relation between rainfall intensities and times of concentration based on rainfall-runoff modeling using the recently developed features of the Hydrologic Engeneering Center – Hydrologic Modeling System (HEC-HMS) modeling software. The time of concentration is generally considered a constant characteristic of a catchment. However, various publications have shown that response time is a dynamic property and a function of rainfall intensity. Model simulations were performed to gain more insight into the relationship mentioned. The applicability of the dynamic time of concentration was examined with the help of a recent version of the HEC-HMS software that can interpret the dynamic relationship between time of concentration and rainfall intensity. The models were built for characteristic and dynamic cases. In the characteristic case, the time of concentration values of the catchments were calculated using the commonly applied Wisnovszky empirical equation, while in the dynamic case, the applicability of the rainfall intensity, i.e., the time of concentration function, was examined. The applicability of the new HEC-HMS feature was reviewed, and the relationship between the time of concentration and rainfall intensity was confirmed. The dynamic approach improved the models' performance, especially where the Wisnovszky equation yields an inadequate estimation of the time of concentration based on the results.

Key-words: rainfall, rainfall-runoff, modeling, event-based, lumped, time of concentration, rainfall intensity, HEC-HMS

1. Introduction

Numerical modeling became one of the most important tools in hydrological sciences. The rapid development of informatics has allowed us to use different software to build various models for countless purposes, even simulating highly complex phenomena. Several hydrological programs enable us to build accurate and efficient models. A precise hydrological model depends critically on available data (*Beven*, 2012). If our input data is unreliable, it can lead to numerous uncertain parameters and an inaccurate or falsely accurate model. Therefore, the thorough analysis of different data types and the approaches of inserting input data in a model can help the users select the most appropriate sources and tools for their tasks.

One of the most significant parts of hydrological modeling is rainfall-runoff modeling. In the case of such models, the unit hydrograph theory became the most commonly used hydrograph modeling technique. The unit hydrograph represents a discrete transfer function for effective rainfall to reach the basin outlet, lumped to the catchment scale (*Beven*, 2012). Response time parameters are essential when using unit hydrograph theory in modeling. These parameters can be the lag time, the time to peak, the time to equilibrium, or the time of concentration (τ or T_C). The most commonly applied parameter is the time of concentration, which can also be defined in many ways (*Nagy* and *Szilágyi*, 2020). In this study, time of concentration is reviewed as the period of time required for storm runoff to flow to the outlet from the point of a drainage basin having the longest travel time (*WMO*, 1974). In both Hungarian and international engineering practice, it is usually considered a constant characteristic of a catchment; however, this simplification results in unreliable model simulations in the case of extreme precipitation events. Many publications have shown that the response time is a dynamic property, as it decreases exponentially with increasing rainfall intensity (*Szilágyi*, 2007; *Reed et al.*, 1975; *Saghafian et al.*, 2002; *Zhang et al.*, 2007; *Mathias et al.*, 2016; *Cuevas et al.,* 2019). Unfortunately, the intensity of current rainfall events varies noticeably due to climate change (*Mattányi et al.*, 2015). Higher intensity leads to a shorter response time, which has a significant effect on the hydrograph shape. It results in a steeper rising limb and a higher flood peak; the latter is a crucial value in the case of any designing parameter. This aspect also justifies the need to better understand response time and its relationship with rainfall intensity.

The problem of time of concentration estimation is also widely discussed worldwide. In international publications, several different empirical equations can be found. Due to the many definitions and methods found to determine the time of concentration, the estimation is one of the most uncertain elements of modern hydrology and is also generally reviewed as a paradox (*Grimaldi et al.,* 2012; *Michailidi et al.*, 2018). This research applies the Clark Unit Hydrograph method, a modified version of the UH theory. Short-term water storage throughout a watershed – in the soil, on the surface, and in the channel – plays an important role in transforming precipitation excess into runoff. The linear reservoir model is a common representation of the effect of this storage. (*Feldman*, 2000)

The Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) modeling software was applied to analyze the characteristic and dynamic approaches of time of concentration estimation. HEC-HMS is a US-developed software, and its application is widespread both abroad and in Hungary. The program is freely available and can be easily downloaded and installed from the Hydrologic Engineering Center's website. The software's recent versions include the so-called "variable parameter" method in the Clark Unit Hydrograph method, which means applying a dynamic time of concentration. This latest option can help us produce more realistic and precise models in the future. The following chapters examine the characteristic and dynamic approaches of time of concentration with the help of literature review and simulation runs using the recent modules of HEC-HMS. Thereby, the performance of the rainfall-runoff models is analyzed, and the rainfall intensity-time of concentration relationship is further confirmed.

2. Study area and materials

Two different river catchments (Zala and Kiskomárom) were examined in western Hungary (*Fig. 1*) The catchment of Zala with the outlet point of Zalalövő has an area of 188 km^2. In contrast, Kiskomárom has an area of 99 km^2. According to the Köppen climate classification, the catchments' climate is predominantly warm-summer humid continental (*Peel et al.,* 2007). The region has high precipitation rates; the long-term mean annual precipitation is above 800 mm at Zala and around 660 mm at Kiskomárom. In both cases, the maximum precipitation values occur in June and July, while January has the least precipitation. Precipitation occurs 100–110 days per year and can exceed 10 mm on 20 days annually. The region's maximum precipitation values were 80–120 mm/day (*NYUDUVIZIG,* 2016).

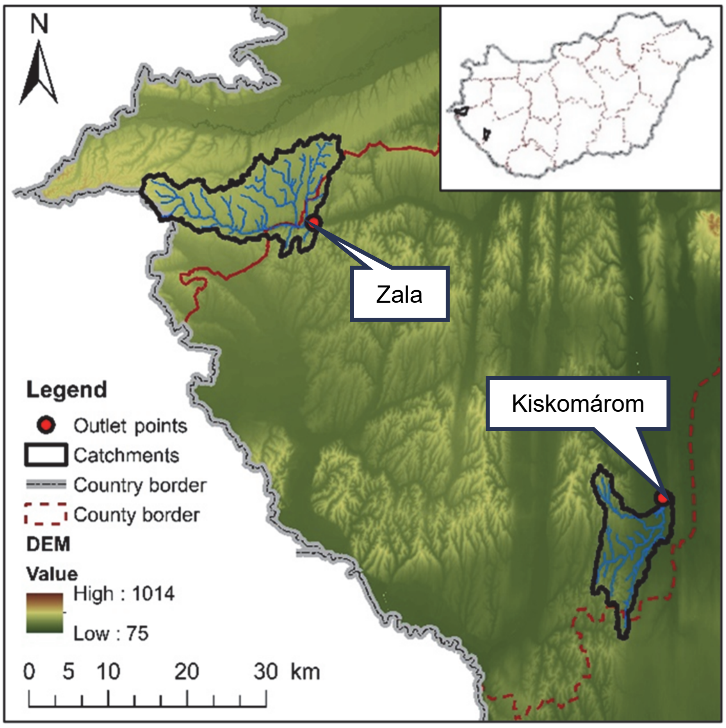

Fig. 1. Study catchments in Hungary.

A watershed's land use and soil characteristics are significant during rainfall-runoff modeling. Based on the CORINE Land Cover maps, the ratio of artificial surfaces is very similar between the two catchments; at Kiskomárom it is 4%, while at Zala this value is 5%. Agricultural areas are more significant at Kiskomárom (61%), while this rate is significantly lower at Zala (36%). Consequently, the rate of forests and semi-natural areas is notably higher at Zala (60%) than at Kiskomárom (34%) (*CORINE*, 2018). Regarding the soil texture of the study area, Kiskomárom is covered mostly with loam, but a smaller area of sand, and clay loam can also be found. Zala is almost completely covered with loam or clay loam. A negligible area of coarse fragments is present at the eastern part of the catchment (*AGROTOPO*, 2016).

In a previous study by *Nagy* (2018), an exponential relationship between rainfall intensity and time of concentration was detected. This study included the analysis of rainfall-runoff events at six Hungarian catchments, out of which two were selected for the present study. The precipitation and discharge time series, the suitable events for modeling, and the geometric models of the catchments were already available from this previous study. The local water directorates from staff gauges of Zalakomár and Zalalövő provided discharge time series (*Nagy,* 2018). Precipitation data were collected from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5-Land re-analysis database (*Muñoz Sabater*, 2019), which is the database of an independent organization, supported by plenty of European countries, providing grid-based precipitation data with a spatial resolution of 0.1° (~ 9 km). All data was used with an hourly time resolution.

Seven events were selected for model calibration for both catchments, while six were chosen to validate the model. The events were selected from the snow-free (or summer) season between 2006 and 2014 to avoid the complex process of snowmelt modeling. This way, the number of free parameters is reduced, which can lead to more reliable results regarding the research of time of concentration and its relationship to rainfall intensity. During the selection of the events, it was essential to avoid possible measurement errors seen from the analysis of runoff rates and the shapes of the hyeto- and hydrographs. Runoff rates can be calculated as the observed runoff volume divided by the precipitation volume. If a runoff rate is above one, the precipitation and/or runoff data is insufficient, while values within 0.01 and 0.2 are typical for summer events (*Kovács*, 1979). The events selected in this study showed reasonable values regarding the runoff rates ranging from 0.05 to 0.24.

3. Methods

The HEC-HMS software was applied in this study, including the Clark Unit Hydrograph transform method. This method can be used to perform simulations with a characteristic value of time of concentration (*standard method*) or with a dynamic approach (*variable parameter method*). The standard method was applied for the characteristic case, in which the time of concentration and storage coefficient are the input parameters. The Wisnovszky equation estimated the characteristic value of time of concentration, while the storage coefficient was calibrated by trial and error. For the dynamic approach, the *variable parameter* method was selected. In this case, the curves of time of concentration – rainfall intensity and storage coefficient – rainfall intensity were calibrated.

3.1. Characteristic case

The time of concentration can be determined through measurements or by semi-empirical or empirical methods. The most common method for calculating the time of concentration in Hungary is the empirical equation introduced by *Wisnovszky* in 1958, which was derived from the Chézy equation and based on the observations regarding the geometry of Hungarian catchments:

$$\tau=\frac{L^2}{\sqrt{A*I}}\ [min], \tag{1}$$

where L is the length of the longest flow path [km], I is the slope of the longest flow path [-], A is the catchment area [km ^{2}].

In this study, Eq.(1) was applied in the characteristic case as it is the most commonly applied form of the Wisnovszky formula. However, Eq.(1) is only a simplified version of the formula introduced by Wisnovszky. The original equation had a multiplier dependent on the catchment size. Based on the publication, the complete equation is applicable for catchments with areas between 500 and 2000 km^2. Wisnovszky stated that it cannot be proved that his equation gives a better result than the other former equations he presented in his publication (*Wisnovszky*, 1958). The uncertainty of the time of concentration calculated by the Wisnovszky equation was proved in 2016 by *Nagy et al*. Based on their results, the equation does need revision and it can also be stated that we cannot expect to find a universal formula for all Hungarian watersheds (*Nagy et al.,* 2016). In 2021, *Nagy* and *Szilágyi* further confirmed the need for revision of the Wisnovszky equation and found that error in the estimation of time of concentration can be more than halved using the appropriate morphological parameters (*Nagy* and *Szilágyi,* 2021a). Despite the described problems, the current study analyzes the applicability of the Wisnovszky equation in the characteristic case, since the Hungarian engineering practice generally still uses this formula. In HEC-HMS, the characteristic value of time of concentration can be applied within the Clark Unit Hydrograph standard method.

3.2. Dynamic case

The reason for the dynamic property of the response time is related to the dynamic property of the aquifer: the subsurface soil saturates faster during high-intensity rainfall events, resulting in surface runoff sooner. This dynamic behavior of the aquifer and its effect on runoff generation is often overlooked (*Szilágyi*, 2007). The dynamic property of the response time of a catchment is acknowledged in many international studies. In general, it is most often associated with the characteristics of rainfall in the formulas and methods which have been published in recent decades (*Izzard* and *Hicks*, 1946; *Henderson* and *Wooding,* 1964; *Morgali* and *Linsley*, 1965; *Aron et al*., 1991; *Corps of Engineers*, 1954; *Askew*, 1970; *Kadoya* and *Fukushima*, 1977; *Papadakis* and *Kazan*, 1987; *Loukas* and *Quick*, 1996; *Schmidt* and *Schulze*, 1984*; McCuen et al*. 1984; *Nagy et al.*, 2022). It should also be noted that these formulas could not be applied in Hungary without analyzing their applicability. To the authors' best knowledge, no formula has been developed in Hungary that considers rainfall intensity when calculating the time of concentration.

Starting from HEC-HMS version 4.3 (*Scharffenberg et al.,* 2018), the so-called variable parameter method is available within the Clark Unit Hydrograph (UH) method, which deals with dynamic response characteristics. In this study, HEC-HMS version 4.7. was applied. UH theory assumes a linear relationship between precipitation and the runoff response. This assumption can lead to errors in timing and peak magnitude when simulating events that result from extremely large excess precipitation rates. When using the Clark Unit Hydrograph, tables relating the time of concentration and storage coefficient to the excess precipitation can be used to vary the runoff response throughout the simulation. The *Index Excess* is an excess precipitation rate that is used to relate the time of concentration and storage coefficient defined in the editor against the variable parameter relationships. Typically, this rate is 1 mm/hour, indicating the intensity of rainfall. The variable parameter relationships must be defined as monotonically increasing percentage curves. The x-axis of the percentage curves defines the excess precipitation rate relative to the index excess. The y-axis of the percentage curves defines either the time of concentration or storage coefficient for each percent excess precipitation rate (again, relative to the index excess). (*Scharffenberg et al.*, 2020) The starting values of the variable parameter method can be determined easily. However, the calibration of the curves can be difficult as the whole range of rainfall intensities has to be considered for an accurate model for all events with different rainfall characteristics.

The approach of dynamic calculation can provide a method for using UHs for a range of flood events. The variable Clark Unit Hydrograph method could be the most useful for modeling extreme events since it can apply the dynamic relationship. The linearity assumption with UHs often leads modelers to arbitrarily adjust the UH parameters when using models for simulating extreme floods.

3.3. Applied model

The rainfall-runoff model applied in this study is deterministic, event-based, and lumped. *Fig. 2* is a flowchart of the calculation steps in HEC-HMS, including the selected methods. The effect of s*urface, routing,* and *loss/gain* methods were taken into consideration within the loss method. The parameters for the *canopy*, *loss,* and *baseflow* method were calibrated. The *transform* method is the key component of the study. It performs the actual surface runoff calculations contained within the subbasin. Out of the nine available transform methods, the Clark Unit Hydrograph method was applied. With the Clak method, the user is not required to develop a unit hydrograph through the analysis of past observed hydrographs; instead, a time versus area curve (time-area curve) is used to develop the translation hydrograph resulting from a burst of precipitation. The resulting translation hydrograph is routed through a linear reservoir to account for storage attenuation effects across the subbasin (*Scharffenberg*, 2020). In practice, this method can be used to perform simulations with a characteristic value of time of concentration (*standard method*) or with a dynamic approach (*variable parameter method*).

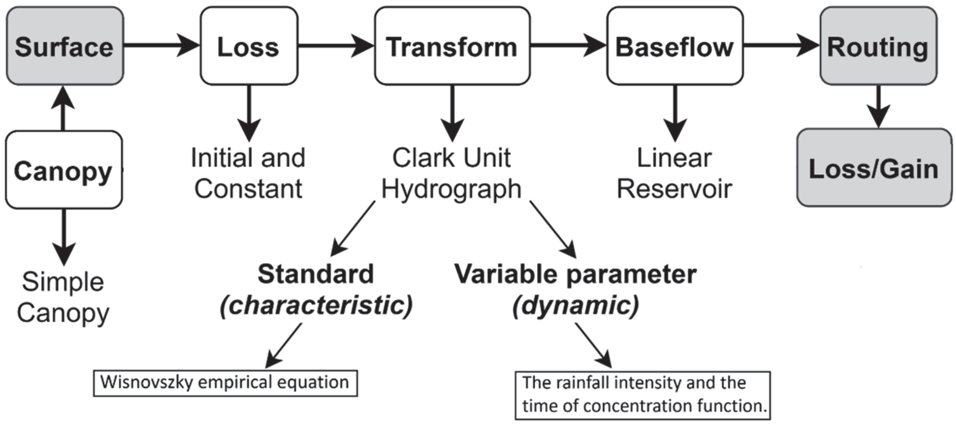

Fig. 2. Scheme of the rainfall-runoff model created in HEC-HMS.

The model performance was evaluated by two metrics: the Nash-Sutcliffe efficiency coefficient (*NSE*) and the differences between measured and observed peak times. The *NSE* values were reviewed for each simulation calculated according to the following formula:

$$NSE = 1 - \frac{\sum_{t=1}^{T}\left(Q_m^t - Q_0^t\right)^2}{\sum_{t=1}^{T}\left(Q_0^t - \bar{Q}_0\right)^2}, \;\; T = 1,2,\dots,n. \;, \qquad (2)$$

where $\bar{Q}_0$ is the mean of observed discharges, Q_m is the modeled discharge, Q_0^t is the observed discharge at time *t, n* the number of the observed discharges (*Nash* and *Sutcliffe*, 1970).

The value of *NSE* can vary between $-\infty$ and 1.0. If $NSE < 0$, calculation with the average of the observed time series gives a better approximation than the model, which means that the model performance is unsatisfactory. If the value is between 0 and 0.5, the results are satisfactory, while between 0.5 and 0.8, the model simulation results are good. Above 0.8, the model performance is excellent. The perfect fit occurs when $NSE = 1$; therefore, the higher the value of *NSE*, the better the model. (*Nash* and *Sutcliffe*, 1970) The results were also categorized by noting the differences between observed and modeled time of peak discharges (Δt [hr]). When Δt is close to zero, it is considered excellent. The model is categorized as good if the difference is smaller than three hours. Values between three and five hours were labeled satisfactory, while differences above five hours were categorized as unsatisfactory.

4. Results and discussion

The results of the simulations can be seen in *Fig. 3/a*, where the lighter the color, the better the model performance is. The ID-s of the events of Zala start with Z, while the events of Kiskomárom have an ID starting with K. In *Fig. 3/b*, the results are summarized according to the previously described categories of unsatisfactory, satisfactory, good, and excellent. The dynamic case's *NSE* values are improved both at Zala and Kiskomárom, which is also shown in the categories, where more events shifted towards the excellent category. The differences between peak times in the case of the calibration events also improved based on the categories. However, it is visible that in the case of events K26 and K28, the dynamic case yielded significantly worse results. The greatest improvements due to applying the dynamic approach can be seen during the calibration at the Zala catchment.

During validation, the events of the Zala catchment have worse or only slightly improved values of *NSE* in most cases. However, the events of Kiskomárom have enhanced *NSE* values after applying the dynamic approach since the categories of the events are moving more towards the direction of excellent. Reviewing the differences in peak time can show similar but less significant tendencies.

Overall, it is visible that applying the dynamic approach results in better *NSE* and Δt values in most of the cases, as the increasing number of simulated events falling into the excellent or good category clearly shows.

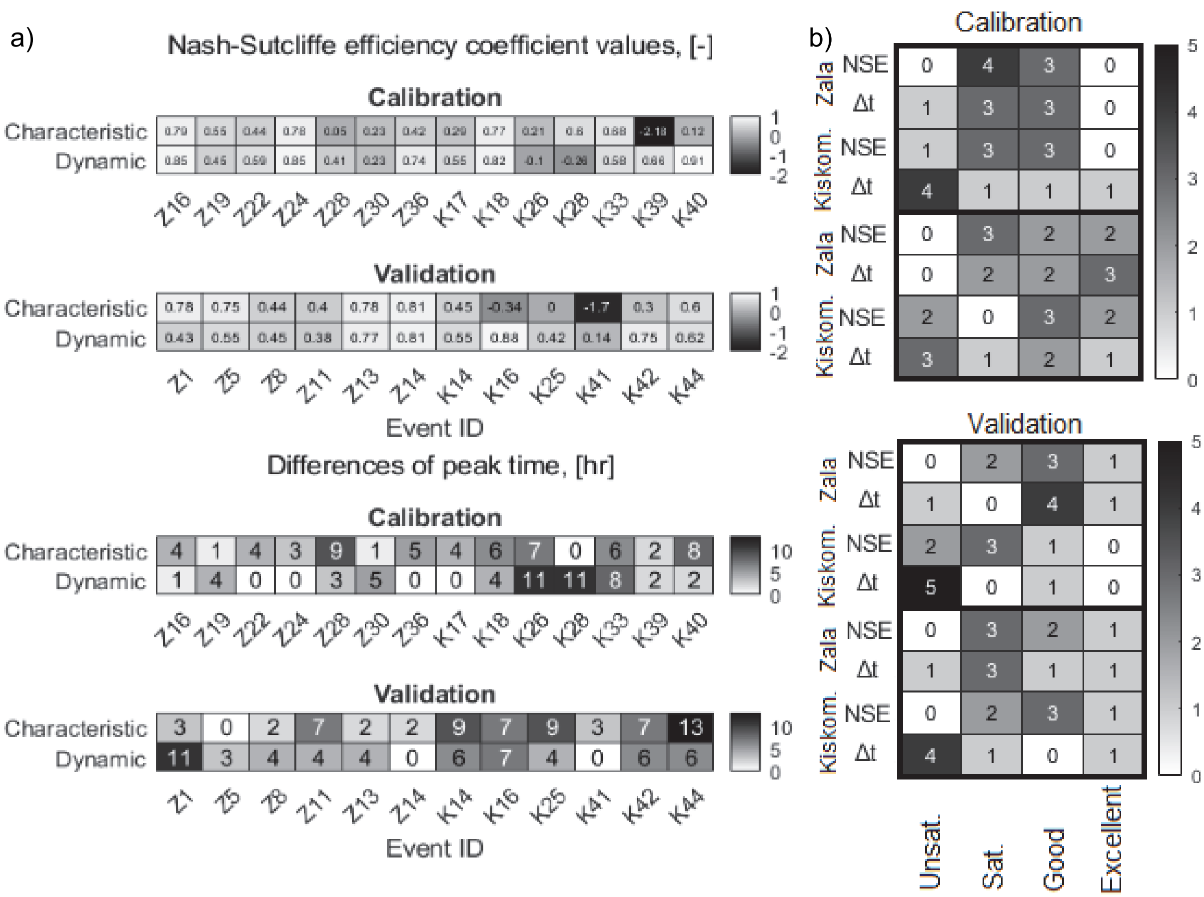

Fig.3. a) Results of simulations (*NSE* and Δt). b) Categorization of results.

To summarize the results, the model performance according to the NSE and the differences in the time of peak discharges can be improved using the dynamic approach of the time of concentration, especially when the Wisnovszky equation yields an inadequate estimation. The calibration is more difficult to perform than in the characteristic case as a whole range of rainfall characteristics has to be taken into consideration. However, if the proper curves are applied, the simulations can give significantly better results. *Fig. 4* shows the calibrated percentage curves for the time of concentration and storage coefficient. It is notable that the curves of the two catchments are different as the catchments have different characteristics.

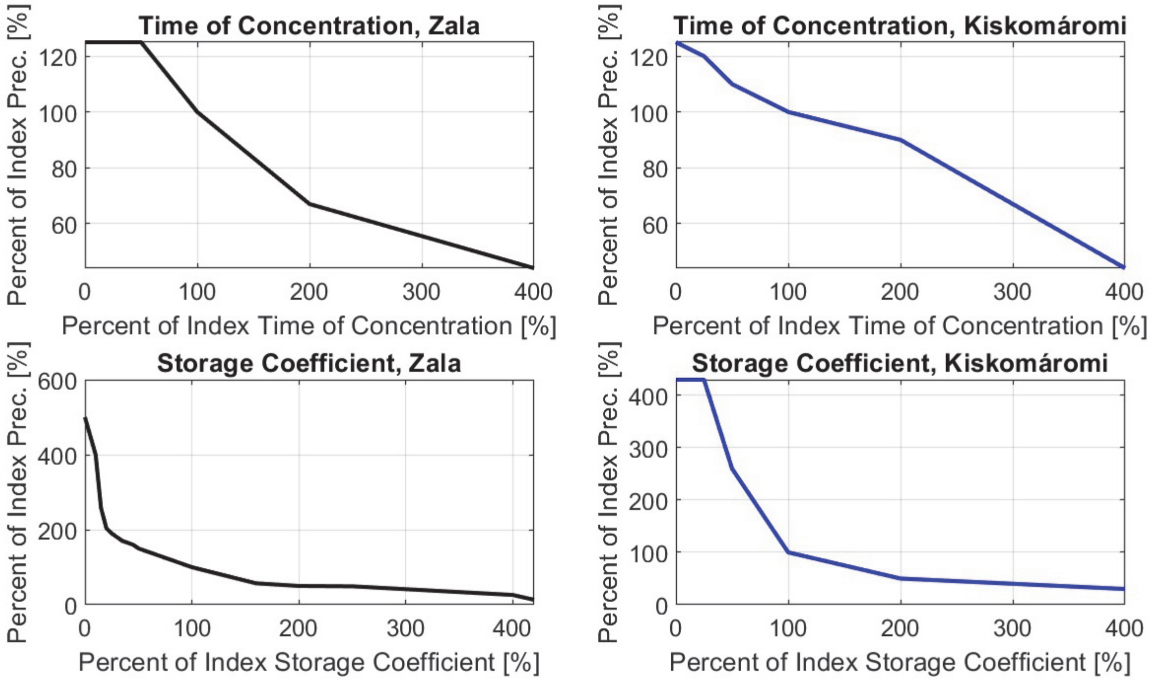

Fig.4. The calibrated percentage curves of the time of concentration and the storage coefficient.

In the current study, the dynamic approach did not improve the results in a few cases. The reason could be that the curves were not calibrated suitably for the rainfall characteristics of the given events. To avoid the mentioned errors, reviewing the possibility of applying measured data for the input curves to improve the model performance in a future study would be practical. Another interesting aspect for the extension of the study is the analysis of rainfall data. In the ECMWF rainfall database, the high-intensity rainfall events can be underestimated if a local rainfall event has a smaller spatial scale than the grid size of the ECMWF data (*Nagy* and *Szilágyi*, 2021b). In a following study, it would be interesting to see the calibration process and the simulation results using rainfall gauge data, which could further confirm the current paper's outcome.

The variable parameter, a recent feature of HEC-HMS, proved to be applicable, while the need to revise the commonly applied Wisnovszky equation is further emphasized. In addition, the results verify the dynamic relation between the time of concentration and the rainfall intensity. Since the Wisnovszky equation proved to give inaccurate estimations in general, and the value of time of concentration is confirmed to vary with rainfall intensity, using the dynamic approach is highly recommended in the Hungarian modeling practice, despite the complexity of the calibration.

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