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Analyzing the connection between rainfall intensity and time of concentration using rainfall-runoff modeling

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Abstract

Name: Klaudia Négyesi
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Supervisor: Eszter Dóra Nagy, *Department of Hydraulic and Water Resources Engineering*
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My study aims to examine the relation of rainfall intensity and time of concentration. Latter is the most important parameter describing the response of a river catchment. The research is based on rainfall-runoff modeling. The time of concentration is generally considered to be a constant characteristic of a catchment, both in Hungarian and international engineering practice. However, publications have shown that in fact the response time is a dynamic property, as it decreases exponentially with the increasing rainfall intensity. [1] In this study, the researched response time parameter is the time of concentration, which plays an important role in both designing and modeling. Nowadays, due to the varying rainfall intensity caused by climate change, it is essential to understand the relationship between rainfall intensity and time of concentration. In order to gain more insight to the mentioned relationship, I performed model simulations following the literature research.

During this research, I examined the applicability of dynamic time of concentration with the help of *Hydrologic Engineering Center – Hydrologic Modeling System* (HEC-HMS) rainfall-runoff modeling software, which is commonly used both in Hungary and abroad. HEC-HMS is a software developed in the US with many built-in functions that helps the user to create the most suitable rainfall-runoff models for the examined catchments. The latest version of the software has the option of using dynamic time of concentration. Exploring this new feature is an opportunity to create more reliable models in the future. With the help of HEC-HMS, I built rainfall-runoff models for both the characteristic and dynamic cases, for which the selected catchments have visible decrease in time of concentration as the rainfall intensity increases. The selection was based on the results of a previous study [2] therefore, the precipitation and discharge time series, the suitable events for modeling and the geometric models of the catchments were already available. This way, I was able to focus on creating the rainfall-runoff models and analyzing the results of the model simulations. To increase the representativeness of the results, I analyzed Hungarian catchments of different sizes and geographical locations. As part of the research, I compared the effectiveness of the Wisnovszky empirical equation (characteristic case) which is commonly applied in Hungarian practice and the applicability of the rainfall intensity - time of concentration function (dynamic case).

As a result of this study, we learnt more about the relationship of time of concentration and rainfall intensity, moreover, we learnt about its applicability in modeling practice with the help of the new HEC-HMS module. Applying the dynamic time of concentration improved the model performance, especially where the Wisnovszky equation yields an inadequate estimation of the time of concentration. Despite the complexity of the calibration, the dynamic approach is highly recommended in the Hungarian modeling practice based on the results presented in this study.

Absztrakt

Név:	Négyesi Klaudia
Dolgozat címe:	A csapadékintenzitás összegyülekezési időre gyakorolt hatásának vizsgálata csapadék-lefolyás modellezés segítségével
Konzulens:	Nagy Eszter Dóra, *Vízépítési és Vízgazdálkodási Tanszék*
Félév:	2021/22/1. félév

A dolgozatom célja a csapadékintenzitás és a vízgyűjtők legfontosabb válaszidőt leíró paraméterének, az összegyülekezési időnek a vizsgálata csapadék-lefolyás modellezés segítségével. A vízgyűjtők válaszidejét a hazai és nemzetközi mérnöki gyakorlatban is rendszerint a vízgyűjtők statikus jellemzőjének tekintik. Számos publikációban bizonyították, hogy a valóságban a válaszidő dinamikus jellemző, ugyanis exponenciálisan csökken a csapadékintenzitás növekedésével. [1] Az általam vizsgált paraméternek, avagy az összegyülekezési időnek fontos szerepe van tervezési és modellezési feladatoknál egyaránt. A klímaváltozás hatására változó csapadékintenzitás külön indokolja, hogy jobban megismerjük a csapadékintenzitás és az összegyülekezési idő kapcsolatát. Mindehhez a szakirodalmi források feltárása után elengedhetetlenek a modell vizsgálatok.

Kutatásom során a hazai viszonylatban is használatos *Hydrologic Engineering Center – Hydrologic Modeling System* (HEC-HMS) csapadék-lefolyás modellező szoftver segítségével mérlegeltem a dinamikus összegyülekezési idő figyelembevételének lehetőségeit. A HEC-HMS egy amerikai fejlesztésű program, amely számos funkcióval segíti a vizsgált vízgyűjtőkhöz legalkalmasabb modellek felépítését. A szoftver legújabb verziójában már elérhető az a lehetőség, amelyben dinamikus összegyülekezési időt alkalmazhatunk, így ennek megismerése elősegítheti a megbízhatóbb modellek előállítását a jövőben. A szoftver alkalmazása során csapadék-lefolyás modelleket állítottam elő statikus és dinamikus esetre is, melyhez olyan vízgyűjtők kerültek kiválasztásra, melyeknél jól megfigyelhető az összegyülekezési idő csökkenése a csapadék intenzitásának növekedésével. A kiválasztás korábbi vizsgálatok eredményeire alapozva történt [2], így a csapadék és vízhozam idősorok, a modellezésre alkalmas események és a vízgyűjtők geometriai modelljei rendelkezésre álltak. Ilyen módon a HEC-HMS program segítségével a modellépítésre és a modellfuttatások eredményeinek előállítására fókuszálhattam a kutatás során. Az eredmények reprezentativitásának növelése érdekében különböző méretű és földrajzi elhelyezkedésű, hazai vízgyűjtőket elemeztem. A vizsgálatok részeként összehasonlítottam a hazai gyakorlatban alkalmazott Wisnovszky-féle empirikus összefüggés (statikus eset), illetve a csapadékintenzitás-összegyülekezési idő függvény alkalmazásának (dinamikus eset) hatékonyságát.

A dolgozat eredményeképp többet tudtunk meg az összegyülekezési idő és a csapadékintenzitás kapcsolatáról, illetve a dinamikus összegyülekezési idő alkalmazási lehetőségéről az új HEC-HMS modul által. Az dinamikus összegyülekezési idő adaptálásával javítható volt a modell teljesítménye, különösen akkor, amikor a Wisnovszky féle összefüggés nem megfelelő becslést adott az értékére. Eredményképp elmondható, hogy a kalibrálás nehézségeinek ellenére a dinamikus megközelítés különösen ajánlott a magyar modellezési gyakorlatban.

1. Introduction

Nowadays, modeling is one of the most important tool in engineering sciences. The rapid development of informatics has allowed us to use different software to build up a variety of models for different purposes, even simulating highly complex phenomena. We can find several programs also in the field of hydrology which allows us to build accurate hydrological models. For a precise and well-functioning model, the quality of data is a key factor. If our data is not reliable it can lead to numerous uncertain parameters and therefore an inaccurate or falsely accurate model. Therefore, the thorough analysis of different modeling approaches can help the users to select the most appropriate tools for their tasks.

One of the most significant part of hydrological modeling is rainfall-runoff modeling. To create such models, the parameters describing the response time of a river catchment are essential. In this study, I examine the available approaches of time of concentration estimation including its relationship with rainfall intensity. The catchment response time is usually considered to be a characteristic value of river catchments in both Hungarian and international engineering practice. However, many publications have shown that in fact the response time is a dynamic property, as it decreases exponentially with the increasing rainfall intensity. [1] [3] [4] [5] [6] [7] Unfortunately, the intensity of current rainfall events is noticeably changing due to the climate change [8], which can lead to quicker and more severe floods. This aspect also justifies the need for a better understanding of response time and the relationship between rainfall intensity and time of concentration.

In my study, I use the *Hydrologic Engineering Center – Hydrologic Modeling System* (HEC-HMS) modeling software to analyze the characteristic and dynamic approaches of time of concentration estimation. This software is especially important since its latest versions include the so-called "variable parameter" method in case of the Clark Unit Hydrograph method, which means the application of a dynamic time of concentration. The cognition of this new option can help us producing more realistic and precise models in the future. The following chapters examine the characteristic and dynamic approaches to include time of concentration in the model with the help of literature review and simulation runs. Thereby, not only the performance of the rainfall-runoff models but our knowledge of the rainfall intensity-time of concentration relationship can be increased.

2. Study catchments

To increase representativeness, two different river catchments were examined during the study. I chose two Hungarian catchments of different sizes and characteristics. The catchment of Zala river was modeled with the outlet point of Zalalövő. This gauging station can be found at the 100.2 river kilometer. The catchment has an area of 188.4 km^2 and it is located in western Hungary, in the western part of Vas County. The other catchment is the catchment of Kiskomárom stream with the outlet point of Zalakomár, where the gauging station is at the 11.1 river kilometer. The catchment's area is 98.8 km^2 and it belongs to Zala County located more at the south-western part of the country.

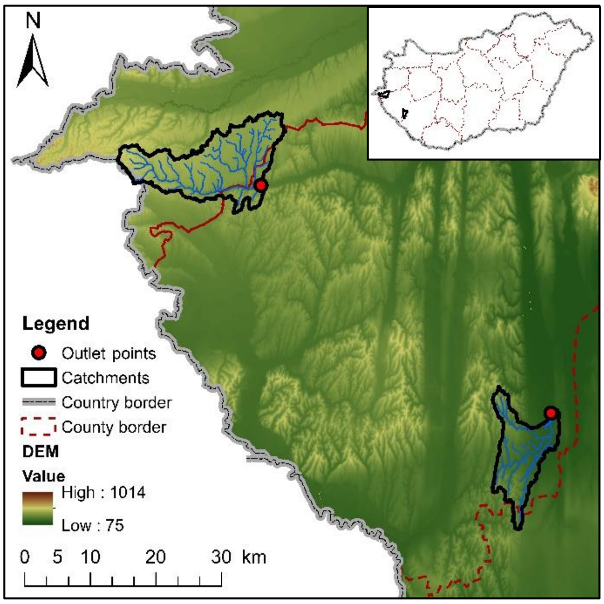

Figure 1. Study catchments.

2.1. Topography and land use

As mentioned above, the study catchments are located in the western part of Hungary. The digital elevation models (DEMs) and elevation histograms of the catchments can be seen in *Figure 2*. The DEM used is the freely available EU-DEM raster database with a resolution of 25x25 m. [9] As the figure shows, Zala has higher differences in elevation. The lowest point of Zala is at 185.12 m.a.s.l., while the highest point is at 323.52 m.a.s.l.. The mean value of Zala catchment is 246.96 m.a.s.l..

In case of the Kiskomárom catchment, it is visible that the differences in height are less notable. The catchment is divided, the western part has higher portion of high elevation cells, while the eastern part is dominated by low elevation cells. The lowest point is at 109.47 m.a.s.l. and the highest point is at 273.15 m.a.s.l. The mean value at Kiskomárom is 162.18 m.a.s.l.

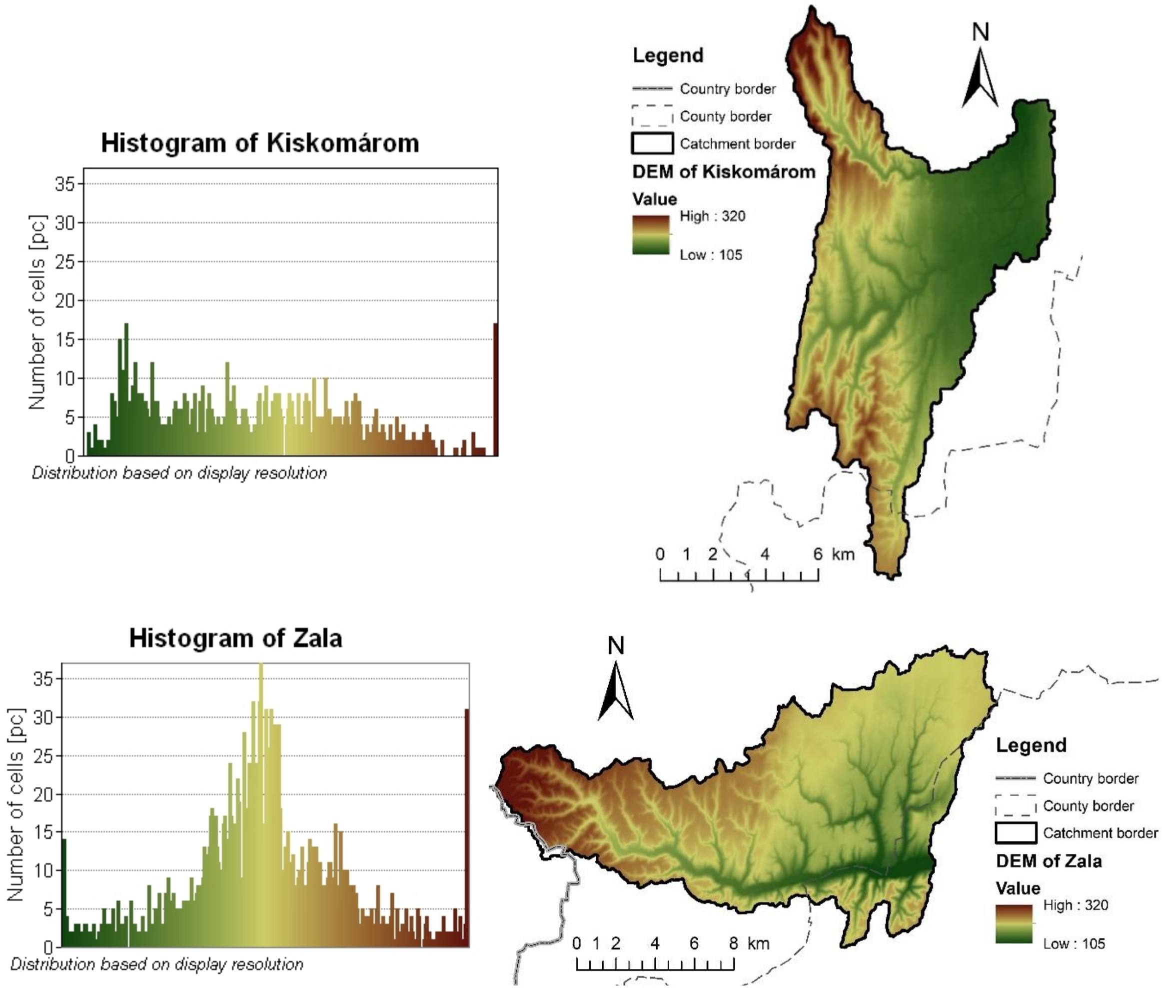

Figure 2. Digital elevation model (right) and elevation histogram (left) of Kiskomárom (top) and Zala (bottom) catchments.

Figure 3. shows the land cover maps of the two catchments, which were created using the CORINE Land Cover maps. [10] The land cover types listed in the legend can be divided into three major categories: artificial surfaces, agricultural areas, forests and semi natural areas. Using ArcGIS the exact rates of these categories were calculated.

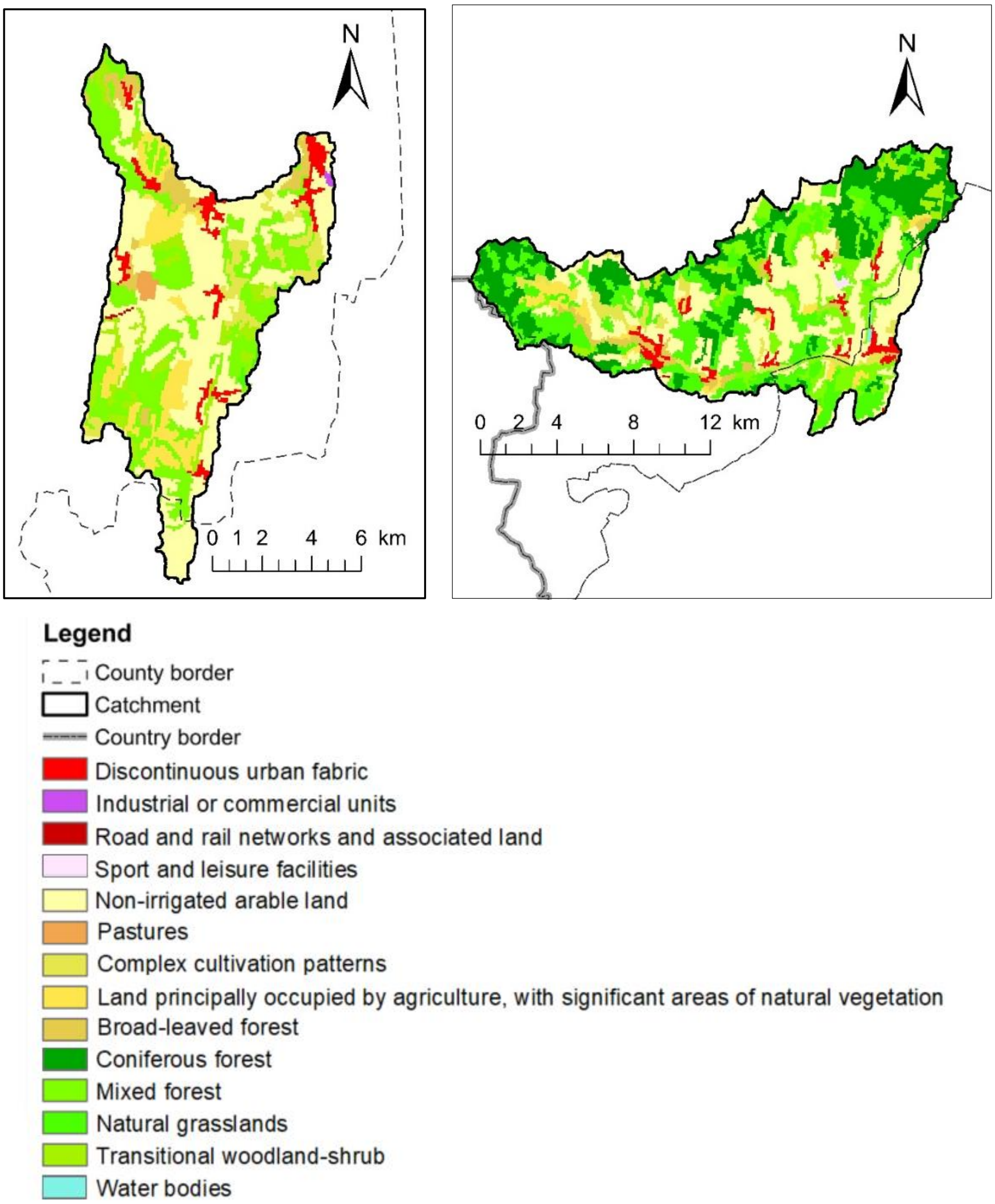

Figure 3. Land cover maps of Kiskomárom (left) and Zala (right) catchments.

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%) where the ratio is twice larger than the rate at Zala (36%). Consequently, the rate of forests and semi natural areas is notably higher at Zala (60%) than at Kiskomárom (34%).

2.2. Geology and soil

The main geological units of the study catchments can be seen in *Figure 4*. The dominant geological units are the same at both catchments because of their western location in the country. In this region, glacial and alluvial deposits are common and they form the largest geological unit of Zala. Loess and loess-like deposits can also be recognized and they are more dominant at Kiskomárom. [11]

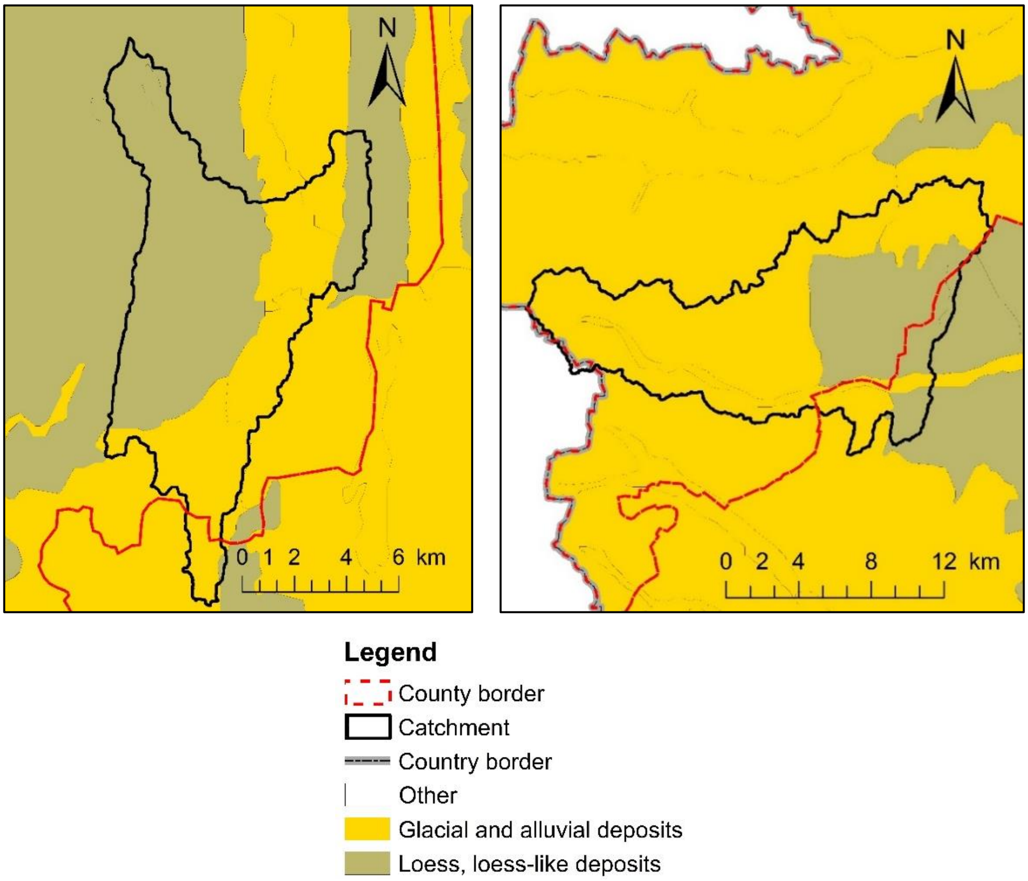

Figure 4. Geological units of the Kiskomárom (left) and Zala (right) catchments.

For the task of rainfall-runoff modeling, it is also essential to know the soil texture of the study area. *Figure 5* presents the distribution of soil texture categories in case of the catchments. [11] As the maps show, Kiskomárom is covered mostly with loam but a smaller area of sand and clay loam can also be seen. Zala is almost completely covered with loam or clay loam. At the eastern part of the catchment, a negligible area of coarse fragments is visible. Based on the information provided by these maps, the two catchments should have similar infiltration properties.

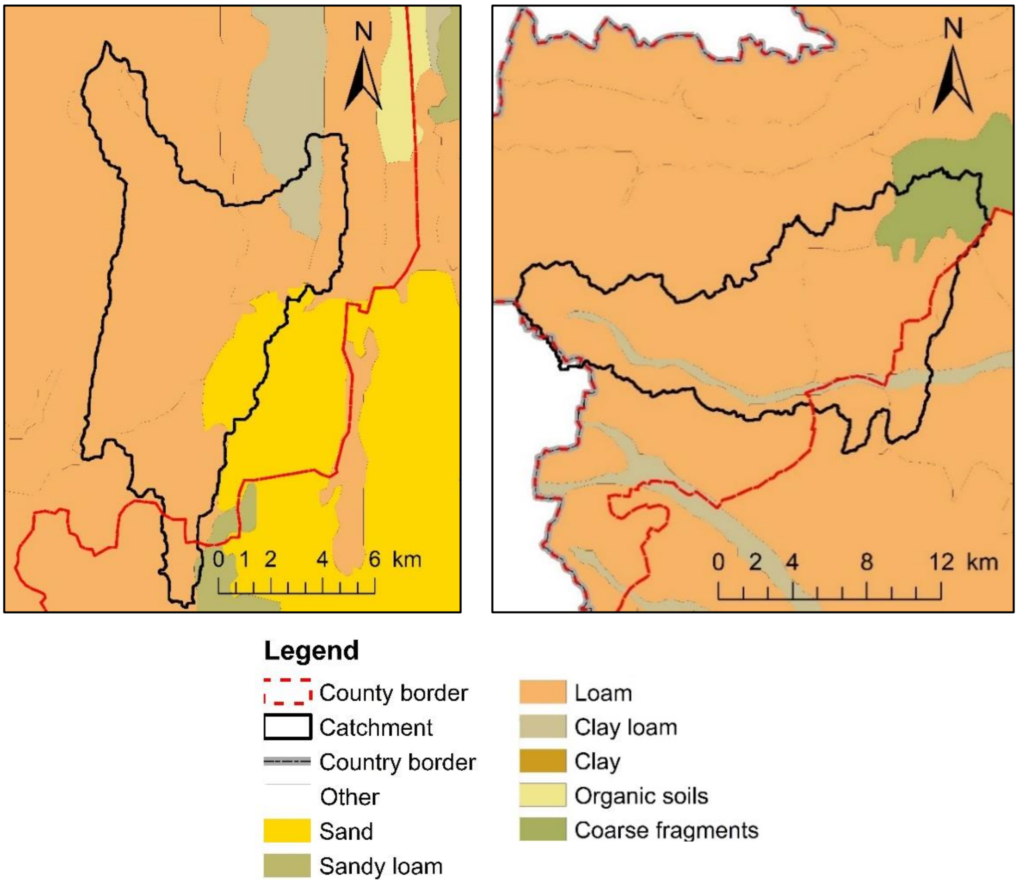

Figure 5. Soil texture maps of Kiskomárom (left) and Zala (right) catchments.

In *Figure 6*, two maps can be seen characterizing the soils water retention capabilities at the catchments. [11] The western part of Kiskomárom is dominated by soils with moderate infiltration rate, permeability and hydraulic conductivity; high field capacity and good water retention. The eastern part of the catchment has soils with good or high infiltration rates, permeability, hydraulic conductivity and poor or good water retention. A negligible area shows soils with unfavorable water management - low infiltration rate, very low permeability and hydraulic conductivity.

Zala can be divided into two main areas according to its water retention capability. The western part has soils with unfavorable water management, which means that the infiltration rate is low, permeability and hydraulic conductivity is very low, while the water retention is high. The eastern part has soils which have moderate infiltration rate, permeability and hydraulic conductivity, high field capacity and water retention. This implies that the infiltration rate should be lower at the Zala catchment.

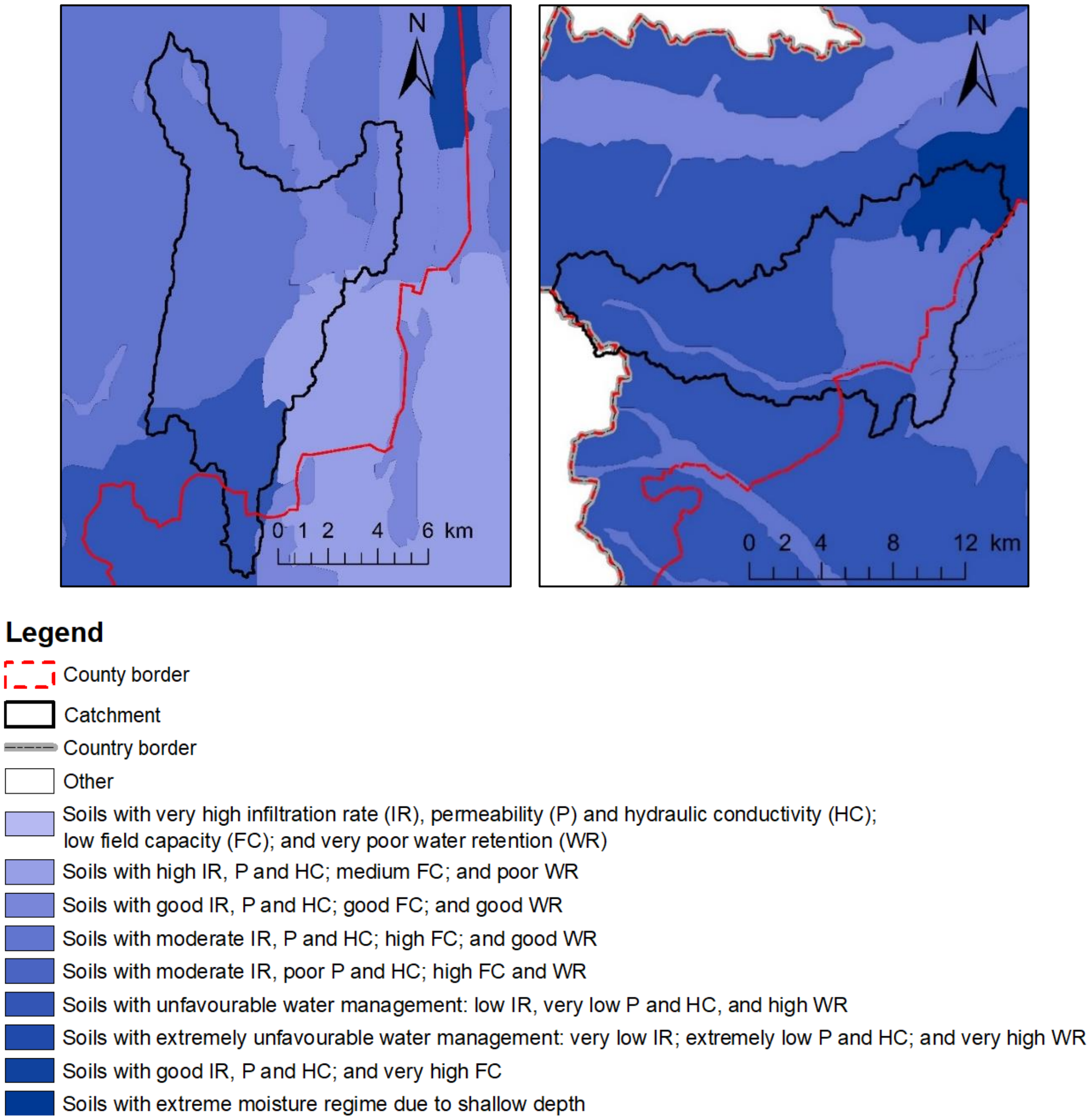

Figure 6. The soil's water retention capabilities at Kiskomárom (left) and Zala (right) catchments.

2.3. Climate

The climate of the two catchments are moderately cool and moderately humid. Compared to other parts of the country, there is less continental influence in this region while the ocean has a greater role in determining the climate.

The study area of Zala can be considered cool and humid with mild winters, while Kiskomárom is moderately warm but it can also be categorized as humid with mild winters. The region of the studied catchments can be classified as one of the most overcast, foggy areas of Hungary. The annual average of cloud cover is between 65-55%. Due to the overcast, the hours of sunshine per year is about 1900-2000, but this is even less in the westernmost areas like Zala (1800-1900 hours).

In terms of temperature, the average value in January varies between -1.5 and -2.0 ˚C at Zala while at Kiskomárom it does not exceed -1 ˚C. The annual average temperature in July is lower at the western part of the region. For that reason, the average values at Zala are between 19.5-20.0 ˚C while at Kiskomárom they are between 20.0-20.5 ˚C.

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 values of precipitation occur in June and July while January has the least amount of precipitation. Precipitation occurs 100-110 days per year and it can exceed 10 mm on 20 days annually. The maximum values of precipitation were between 80-120 mm/day in the region.

The area also has a high amount of snow as a result of more frequent precipitation during winter. At Zala, we can expect 45-50 snow covered days while at Kiskomárom it is usually 40-45 days in a year. Snow depth increases to the southern parts of the region such as Kiskomárom resulting a 30-40 cm thick snow cover. At Zala, the maximum average of snow depth is around 25-30 cm.

The dominant wind direction is northerly wind due to the deflecting effect of the Alps and the north-south-facing arrangement of the mountains in the area. The second dominant wind direction is the southerly wind. The average wind speed is relatively low due to the windshield effect of the Alps. [12]

2.4. Morphology

According to Beven, the development, testing and application of rainfall-runoff models is strongly constrained by the availability of data for model inputs, boundary conditions and parameter values. [13] The specification of morphological characteristics can help the parametrization of the rainfall-runoff model to a large extent as DEMs can provide reliable information about the size of the catchment area, flow path and slope. Using ArcGIS these parameters were determined for the two catchments. (*Table 1.*)

Table 1. Characteristics of the catchments.

Name of catchment	Area [km^2]	Impervious area [%]	Longest flow path [km]	Slope [-]
Kiskomárom	98.8	5	23.3	0.007
Zala	188.4	3	30.1	0.005

Besides the parameters measurable on DEMs, we can acquire other important information for the rainfall-runoff modeling from the land use maps (discussed in 2.1. chapter) and from field visits. All precipitation becomes excess precipitation and subject to direct runoff on impervious areas. Land use maps can be used to estimate the impervious area of a catchment, on which no loss calculations are carried out. This value was calculated according to the high resolution imperviousness density maps. [14] The values are 5% at Kiskomárom and 3% at Zala.

Google Earth street view images can provide useful replacement for field visits in the study area. [15] In *Figure 7*, pictures of Kiskomárom channel and Zala can be seen. The left pictures were taken near or – in case of Kiskomárom – at the location of the gauging station. As mentioned above, the gauging station can be found at Zalakomár in case of Kiskomárom and at Zalalövő in case of Zala. Both of the gauges are in decent condition but it is visible that vegetation is significant in the stream bed. The pictures on the right were taken at a location away from the gauging stations. Kiskomárom's picture is located at Zalaszentjakab while the picture of Zala was taken at Nagyrákos. Both of the pictures show a high amount of vegetation in and near the stream bed.

Figure 7. Google Earth photos of the channels at Kiskomárom (top) and Zala (bottom) catchments. [15]

The information received from the pictures is useful for the parameters of canopy method as the presence of plants in the landscape are represented in this method. Plants intercept precipitation, reducing the amount of precipitation that arrives at the ground surface. Plants also extract water from the soil in a process called transpiration. [16] According to these processes, the high amount of vegetation was taken into consideration during the parametrization of the model.

3. Available data

In a previous study, exponential relationship between the rainfall intensity and time of concentration was detected. This study included the analysis of rainfall-runoff events at 6 Hungarian catchment, out of which two was 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 according to the previous study. [17]

3.1. Discharge and precipitation time-series

Discharge time-series were provided by the local water directorates from staff gauges of Zalakomár and Zalalövő. The discharge time-series were calculated using the rating curve of the gauging section and the measured water level. I had precipitation data from gauging stations and also from the European Centre for Medium-Range Weather Forecasts (ECMWF) Era5-Land re-analysis database. Latter is an independent organization, supported by plenty of European countries, providing grid based precipitation data. The available data was pre-processed using MATLAB mathematical computing software. All of the time-series were used with an hourly time resolution. The summary of the data characteristics can be seen in *Table 2.*

Table 2. Summary of the discharge and precipitation data.

	Name	**Spatial resolution**	**Time window**	
Discharge	Staff gauge of Zalakomár	staff gauge	01/01/2001 00:00	31/12/2017 23:15
	Staff gauge of Zalalövő		01/01/2001 00:00	31/12/2017 17:30
Precipitation	Gauging stations Kiskomárom	gauging stations	02/01/2006 07:00	31/12/2017 23:00
	Gauging stations Zala		01/01/2011 00:00	31/12/2017 23:00
	ECMWF Kiskomárom	0.1°	01/01/2001 01:00	01/05/2019 00:00
	ECMWF Zala		01/01/2001 01:00	01/05/2019 00:00

3.2. Geometric models

The geometric models of the catchments were earlier created during the mentioned study using ArcGIS using the EU-DEM data. The model was created by catchment delineation which specified the catchment area, the longest flow path, and the channel network. After passing the accuracy check it was suitable for creating the HEC-HMS basin model which contributes to the rainfall-runoff model.

4. Methodology

The aim of the study as mentioned before is examining the relation of rainfall intensity and time of concentration. For the studied catchments, two rainfall-runoff models were built, one for examining the results of the characteristic case and one for studying the dynamic case. To assess the model performance two different metrics were analyzed.

4.1. Characteristic case

The response time of catchments can be characterized by a number of different parameters: lag time, time to peak, time to equilibrium and time of concentration (τ or T_C). The most commonly used parameter is the time of concentration.

Time of concentration is one of the most important basic concepts of watershed characteristics. The time of concentration is basically the period of time that is necessary for a particle to flow down from the furthest point to the outlet point on the surface. The furthest point of a catchment is the point from which it takes the longest time for runoff to reach the outlet point. This point is located in most cases at the border of the catchment but this point does not necessarily have to be interpreted geometrically. It should be interpreted hydraulically, which means it is affected by other factors, such as topography or roughness. However, finding the hydraulically furthest point is a difficult task and has uncertain results. For that reason, it is common practice to use the geometrically furthest point instead, as its value well approximates the hydraulically furthest point. [18]

Response time parameters, such as time of concentration can be determined through measurements or by semi-empirical, empirical methods. In the case of measurements, a tracer substance can be used on the real catchments or even under laboratory conditions using small sample models. In addition, the values calculated using the observed precipitation and runoff time-series can also be considered as measured values. Empirical methods are purely statistical relationships while semi-empirical methods are derived from certain hydraulic formulas, e.g., the Chézy equation. The categories of empirical and semi-empirical methods are often blurred, so the distinction between them is difficult. [19]

The most common method for calculating the time of concentration in Hungary is the empirical equation introduced by Wisnovszky [20], which was also derived from the Chézy equation:

$$\tau = \frac{L^2}{\sqrt{A * I}} \; [min], \qquad (1)$$

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

The formula is based on the observations regarding the geometry of Hungarian catchments but it is important to emphasize that if the valley cannot be characterized by a single slope, it is necessary to calculate the time of concentration of sub-catchments. The time of concentration for the whole catchment can be calculated as the sum of the sub-catchments' time of concentration. [18]

Iván Wisnovszky published his empirical equation in 1958. Nowadays, the fact that equation (1) is only a simplified version of the whole relation, has been left out from the textbooks. In the original equation, it was also multiplied by (1.04-A/5850). Wisnovszky explained in his publication that this multiplier is not required if *A*, the catchment area is between 0 and 500 km^2. In the case of catchments smaller than 500 km^2, the multiplier is almost 1. Below this limit, the error because of the neglect is less than 4%. This is not a problem because due to other uncertainties, the calculation of time of concentration cannot be more accurate. Based on the publication, the complete equation is applicable for catchments with a size of 500-2000 km^2. It is also important to point out that the equation cannot be used for catchments larger than 2000 km^2. According to the study, if the average slope is less than 1 ‰, the uncertainty of the time of concentration is higher due to the increase in the number of the influencing factors. In case of his new equation, Wisnovszky stated that it cannot be proved that its application gives a better result than the other equations he presented in the publication (*Salcher formula, Reinhold formula, Snyder formula, Sherman formula and Linsley relation*). The mentioned equations include parameters such as coefficient of roughness, rainfall intensity, constants for streambed materials, slope, area coefficients and constants. However, the advantage of Wisnovszky's formula is that it does not contain an arbitrary parameter. [20]

The uncertainty of the time of concentration calculated by the Wisnovszky equation has been proved recently by a publication. Based on their results, the equation does need revision and it can also be stated that a universal formula created for Hungarian watersheds cannot be expected. [21] Besides, the problem of time of concentration calculation is widely discussed, even abroad. Researching the international literature, I have found a total of 31 different empirical equations. Examples include the formulas derived from the kinematic wave equation, Kirpich formula, Ven te Chow formula, Carter formula, Temez formula, Yen & Chow formula and many other empirical formulas. [22][23][24] As many formulas and definitions can be found to determine time of concentration, this issue is one of the most uncertain elements of modern hydrology and it is also generally called a paradox based on international literature. [23][25] It is important to mention that these equations cannot be used without suspicion in the case of Hungarian catchments because empirical correlations are theoretically valid only for catchments with a given geographical location and property, for which they have been originally developed. As a result, it is not possible to directly adopt the formulas during the examination and modeling of Hungarian catchments, as it is necessary to prove the applicability of the equations in Hungary beforehand.

The available formulas can be grouped according to different application aspects. Certain equations can be applied based on the flow path length, while other formulas contain parameters such as the size of the catchment, values describing the land use (urban or agricultural), or even values expressing the spatial location of the catchment. There are formulas that have been established based on data from catchments in the United States, Italy, India, Spain, or Turkey. [22] In case of most formulas - unlike the Wisnovszky formula - not only the longest flow path, size and slope are essential for the calculation but for example the significant diameter of the catchment area, the elevation differences between the furthest point and the outlet point, the average elevation, the Manning's roughness, etc. is also needed. [22] It is crucial to point out that there are many empirical equations in the international literature, even for catchments with the same location. This also highlights the problem that in Hungary there is only one equation accepted and widely used for all catchments. As a result, there may be catchments where the value of the time of concentration determined by the Wisnovszky equation may not be appropriate.

A publication examines the time of concentration based on different definitions and resulting from the above-mentioned Wisnovszky formula. Several morphological catchment characteristics were taken into consideration and 4 - 4 parameters suitable for calibrating a new equation were identified applying different selection methods. A comprehensive analysis of the results showed that neither the linear correlation method nor the principal component analysis leads to the identification of the optimal parameter combination. It was found that the error of the Wisnovszky equation can be more than halved using the appropriate morphological parameters. [19]

Time of concentration plays an essential role in the unit hydrograph (UH) theory. In this research, the Clark Unit Hydrograph method is applied which is a modified version of the UH theory. Short-term storage of water throughout a watershed – in the soil, on the surface, and in the channel – plays an important role in the transformation of precipitation excess to runoff. The linear reservoir model is a common representation of the effect of this storage. [26]

In 2017 a study was published to discuss the Clark Unit Hydrograph method of HEC-HMS in details. [27] Clark derived the unit hydrograph of linear watershed response to excess precipitation via the Muskingum channel routing analogy by considering the inhomogeneous ordinary differential equation (ODE) of the lumped continuity

$$\frac{dS(t)}{dt} = I(t) - Q(t), \qquad (2)$$

where $dS(t)/dt$ is the time-rate of change in stored water volume (S) within the catchment (or within the channel reach),

I is excess precipitation for the watershed (or inflow rate to the channel),

Q is stream discharge at the outlet (or outflow from the channel),

t is time-reference.

The Muskingum method relates storage to a weighted average of the in- and outflow rates of the channel section

$$S(t) = K[xI(t) + (1 - x)Q(t)] \qquad (3)$$

where K is a constant storage coefficient and $0 \leq x \leq 1$.

After introducing the basic equations the study leads to the possible instability issues of the HEC-HMS model. By replacing the time rate of change with finite differences for Δt time increments and taking arithmetic averages for $I(t)$ and $Q(t)$ from consecutive values separated by Δt in time, the well-known Muskingum routing equation results as

$$Q_t = c_0 I_t + c_1 I_{t-\Delta t} + c_2 Q_{t-\Delta t} \qquad (4)$$

where

$$c_0 = -(Kx - 0.5\Delta t)/(K - Kx + 0.5\Delta t) \qquad (5)$$

$$c_1 = (Kx + 0.5\Delta t)/(K - Kx + 0.5\Delta t) \qquad (6)$$

$$c_2 = (K - Kx - 0.5\Delta t)/(K - Kx + 0.5\Delta t) \qquad (7)$$

$$1 = c_0 + c_1 + c_2. \qquad (8)$$

By consideration that precipitation is typically represented as a constant (in the form of pulses) over each Δt, i.e., $I_t = I_{t-\Delta t}$ for the given time period and taking $x = 0$ which thus represents a linear storage element where outflow is proportional to storage, equation (4) can be written as

$$Q_t = \left[1 - \frac{\Delta t}{K + 0.5\Delta t}\right] Q_{t-\Delta t} + \left[\frac{\Delta t}{K + 0.5\Delta t}\right] I_t = (1 - c_A) Q_{t-\Delta t} + c_A I_t \qquad (9)$$

Note that here I_t is the constant pulse value valid for the (t–Δt, t) interval. As the coefficient c_A depends on Δt and K as well, $c_A \leq 1$ is required in order to avoid possible negative outflows which thus yields $\Delta t/K \leq 2$ as a general requirement for numerical stability.

Stability issue only emerges because of the unnecessary introduction of finite differences for obtaining the routing scheme of equation (9). The study shows that solution of equation (2) for the linear storage element, i.e., $S(t) = KQ(t)$, can be obtained from where a generalized solution for a homogeneous cascade (i.e., K is the same for each linear storage element of the cascade) of serially connected linear storage elements is given by explicitly taking into account how input (inflow or precipitation) and output (flowrate) are represented by measurements in a discrete-time framework. It states that this solution is recommended over the HEC-HMS routing scheme as it is unconditionally stable. [27] Despite the less than ideal routing scheme of HEC-HMS, I applied this software for my study as it is the most wide-spread program because of its accessibility and easy usage. Moreover, in spite of the possible instability issues it can provide satisfactory results.

4.2. Dynamic case

As mentioned above, publications have shown that in fact, the response time is a dynamic property, as it decreases exponentially with the increasing rainfall intensity. The reason is that the aquifer becomes closer to saturation faster during high intensity rain events, since initially more water can infiltrate into the soil–aquifer system. This dynamic behavior of the aquifer and its effect on runoff generation is often overlooked. It is an important feature, however, without accounting for its effect (exerted through infiltration and saturation excesses) on runoff generation the apparent nonlinearity of the modeled storm response, and so that of hillslope or watershed response in general, could not be understood and interpreted correctly. It is also important to note that a lower intensity precipitation event can cause infiltration and/or saturation excess in more/less abundance and sooner/later in time than a more/less gentle rain. The computed hydrographs have two characteristics: the peak UH value decreases with decreasing excess precipitation intensity while the UH not only becomes more spread out (as follows from the previous property since mass must be conserved) but also the time-to-peak interval becomes longer. If watershed response was linear the unit hydrographs ought to be virtually overlapping independently of the triggering rainfall intensity. [1]

However, the dynamic value of time of concentration is acknowledged in many other international studies. In general, it is most often associated with the rainfall intensity. Based on literature, there are also formulas for determining the time of concentration that clearly take into account the effect of rainfall intensity. The first formula was published in 1946 and is valid for American watersheds, while the last formula is from 1996. A total of 10 equations using rainfall intensity can be found in the international literature but since they were published between 1946 and 1996, their revision may be necessary. [25] It should also be noted that in Hungary these formulas could not be applied. In Hungarian literature, I did not find any formula during my research that takes into consideration the rainfall intensity when calculating the time of concentration. Overall, there is no publication in the international literature that has examined and explored this relationship in detail, especially concerning model simulations and their analysis.

In HEC-HMS version 4.7, the so-called variable parameter method is already available within the Clark Unit Hydrograph method which can deal with dynamic response characteristics. 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.

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, such as the probable maximum precipitation. When using the Clark Unit Hydrograph, tables relating time of concentration and storage coefficient to the excess precipitation can be used to vary the runoff response throughout the simulation. For the calculation method four parameters and two tables are needed. 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. The variable parameter relationships must be defined as percentage curves in the paired data manager. These curves must be monotonically increasing. 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). A method of time-area curve can also be applied.

The time-area curve is used to develop the translation hydrograph resulting from a burst of precipitation. For the study, I used the default option in which the curve represents the subbasin using an elliptical shape. This shape has been shown to approximate the timing of surface runoff very well for typical subbasins. However, there is also an option to provide a user-specified time-area curve. The independent axis of the percentage curve defines the percentage of the time of concentration, while the dependent axis of the curve defines the cumulative percentage of subbasin area contributing runoff. The curve must be monotonically increasing. [16] The starting values of the variable parameter method can be determined easily, however, the calibration of the curves need a lot of work.

The approach of the 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 (for those synthetic flood events that are larger than typical calibration data). The linearity assumption with UHs often leads modelers to arbitrarily adjust the UH parameters when applying models for simulating extreme floods. [16]

4.3. Model performance

The model performance was checked by three metrics. As a first step, I analyzed the runoff rates of the selected events. In chapter 3.1. it is explained that two different precipitation data sources were examined. With the help of runoff rates, I was able to assess the suitability of the events for modeling and I could also decide which precipitation data to use. Runoff rate can be calculated as the observed runoff volume divided by the precipitation volume. If a runoff rate is above 1, it means that the precipitation and/or runoff data is insufficient. The runoff rates of different catchments were analyzed and categorized by VITUKI. In *Table 3* the typical values of runoff rates can be seen according to seasons. [28]

Table 3. Typical values of runoff rates according to season.

0.01-0.2	Runoff rate values typical in summer
0.2-0.5	Runoff rate values typical in winter
0.5-1	Runoff rate values in case of frozen ground
1<	Incorrect value

The Nash-Sutcliffe efficiency coefficient (NSE) characterizes the model performance, it can be calculated with the following equation:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_m^t - Q_0^t)^2}{\sum_{t=1}^{T}(Q_0^t - \bar{Q}_0)^2}, \quad T = 1,2,\dots,n. \qquad (10)$$

where $\bar{Q}_0$ is the mean of observed discharges,
Q_m is modeled discharge,
Q_0^t is observed discharge at time *t*,
n number of observed discharges. [29]

Its value can vary between $-\infty$ and 1.0. If $\mathrm{NSE} < 0$, calculations with the average of the observed time-series gives a better approximation than the model, i.e., the model performance is unsatisfactory. If the value is between $0 < \mathrm{NSE} < 0.5$ the results are satisfactory, while between $0.5 < \mathrm{NSE} < 0.8$ the model simulation results are good. Above 0.8, the model performance is excellent. The perfect fit occurs when $\mathrm{NSE} = 1$, therefore the higher the value of NSE the better the model. [29]

Another way of checking the results of the simulations was noting the differences of observed and modeled time of peak discharges. If the difference is smaller than 3 hours, the model proves to be good. Values between 3 and 5 hours are satisfactory while differences above 5 hours are unsatisfactory. Perfect timing is considered excellent.

To help the understanding of the following chapters, I introduced categories and color codes which are presented in *Table 4*.

Table 4. Color codes applied for the results.

NSE [-]		**Difference in time of peak discharge [hr]**			
$\mathrm{NSE} < 0$	Unsatisfactory	$5 <$	Δt		Unsatisfactory
$0 \leq \mathrm{NSE} < 0.5$	Satisfactory	$3 <$	Δt	≤ 5	Satisfactory
$0.5 \leq \mathrm{NSE} < 0.8$	Good	$0 <$	Δt	≤ 3	Good
$0.8 \leq \mathrm{NSE} \leq 1.0$	Excellent	$0 =$	Δt		Excellent

5. Model description

As mentioned above, the catchments were modeled with the help of the HEC-HMS software. The concepts of the basin and meteorologic models are the same in both cases (characteristic and dynamic). However, two rainfall-runoff models had to be built for each catchment as these cases require different calculation methods.

5.1. Basin model

In Chapter 3.2., it was explained that the basis of the basin model is the geometric model which was built in ArcGIS. The geometric model was imported to the HEC-HMS software using the shape files exported from ArcGIS. According to the properties of delineated catchment areas, the basin model was created by the creation tools. For each catchment, I used the subbasin and the sink creation tools then I set up the connection between these elements. The last step was filling the elements with data such as the specification of the calculation methods, the size of the catchment area or the time-series data of the observed flow at the outlet point.

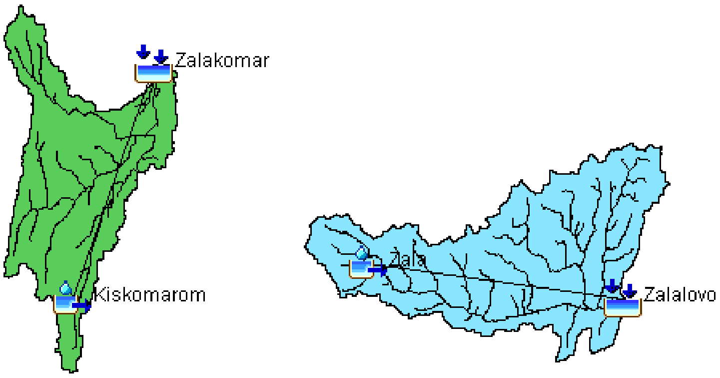

Figure 8. Basin models of Kiskomárom (left) and Zala (right) catchments

5.2. Meteorologic model

Meteorologic models are one of the main components in a project file. The principle purpose is to prepare meteorologic boundary conditions for subbasins. The meteorologic model contains the specification methods of the input data such as the precipitation. In the software, there are nine different precipitation methods available including an option for no precipitation. In my study, I used the specified hyetograph precipitation method. It allows the user to specify the exact time-series to use for the hyetograph at the subbasins. This method is useful when a single precipitation gage can be used to represent what happens over a subbasin. As I had the precipitation data pre-processed into one single time-series in case of both the ECMWF and gauging station data, this method was the most suitable. [16]

5.3. Calculation methods

The rainfall-runoff model applied in this study is deterministic, event-based and lumped. To create the model, I had to choose the calculation methods for each hydrological process, parameterize them and specify the input data. *Figure 9* is a flowchart of the calculation steps in HEC-HMS including the selected methods. *Surface, routing* and *loss/gain* calculations were not applied. Selecting a *surface* method is optional and generally only used for continuous simulation applications. For the *routing* calculation it is essential to know that a reach is an element with one or more inflow and only one outflow. Inflow comes from other elements in the basin model. If there is more than one inflow, all inflow is added together before computing the outflow. Outflow is computed using one of the several available methods for simulating open channel flow. [16] However, in this study I used simplified basin models. There were no subbasins which means that there was no need for adding the inflow of different elements before computing the outflow. By the *loss/gain* method, optional modeling of interactions with the subsurface is performed. A *loss/gain* method represents losses from the channel, additions to the channel from groundwater, or bi-directional water movements depending on the specific implementation of the applied method. [16] As the basin model was simplified and I performed event-based simulations, I did not use the *loss/gain* method. On the other hand, during my research I could not find proof stating that this process is significant regarding rainfall-runoff modeling.

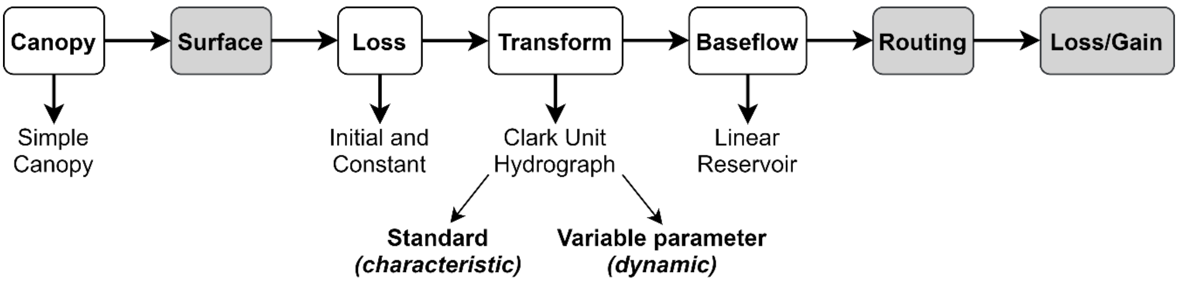

Figure 9. Scheme of the rainfall-runoff model created in HEC-HMS.

The *canopy* is one of the components that can be included in the subbasin element and can represent the presence of plants in the landscape. Plants intercept precipitation, reducing the amount of precipitation that arrives to the ground surface. Intercepted water evaporates between storm events. Plants also extract water from the soil in a process called transpiration. Evaporation and transpiration are often combined as evapo-transpiration. [16] I applied the simple canopy method, as both of the catchments showed high amount of vegetation. The necessary parameters for this method are the initial storage [%], max storage [mm] and crop coefficient [-]. The values were calibrated in both models and remained the same in case of all events. The reason for using constant values for every event is that all of them were selected from the summer season.

The *loss* method performs the actual infiltration calculation of the model. [16] Out of the twelve provided loss methods I applied the initial and constant loss method. This method conserves mass, meaning that the sum of precipitation infiltrating into the soil and the excess precipitation generating surface runoff will always be equal to the total incoming precipitation. It is important, that it can only be used for event simulation. [16] An advantage of this method is its simplicity. On the other hand, precise soil information and parameters usually cannot be obtained in Hungary but this method can be still appropriate for watersheds that lack detailed soil information. For the calculations initial loss [mm], constant rate [mm/hr] and impervious area [%] is needed. The initial loss was varied in case of the different events because the initial conditions at the catchment can be very different. For example, the soil saturation can be higher after a higher amount of antecedent precipitation which leads to a lower value of initial loss. [30] [31] The constant loss rate – which determines the rate of infiltration that will occur after the initial loss is satisfied – and the impervious area (all precipitation at this area contribute to direct runoff) are the same value for all events.

The *transform* method performs the actual surface runoff calculations contained within the subbasin. Out of the nine available transform methods I chose the Clark Unit Hydrograph method. The Clark Unit Hydrograph is a synthetic unit hydrograph method. This means that 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. [16] In Chapter 4.1. I introduced the basic concepts and equations of the Clark Unit Hydrograph used in HEC-HMS in detail. In practice, this is the method which can be used to perform simulations with a characteristic value of time of concentration (*standard method*) or with a dynamic approach (*variable parameter method*).

For the characteristic case I used the *standard* method. Time of concentration [hr] and storage coefficient [hr] is needed. In this case I calculated time of concentration using the Wisnovszky equation. The storage coefficient was calibrated.

To perform the dynamic case, I applied the *variable parameter* method. When using the Clark Unit Hydrograph, tables relating time of concentration and storage coefficient to the excess precipitation can be used to vary the runoff response throughout the simulation. [16] The possibilities and parameters of the method were described in Chapter 4.2 in more detail. The most important conclusion of applying this method is that the parameters and storage coefficient, time of concentration curves have to be calibrated carefully.

Subsurface flow calculation are performed by the *baseflow* method. I chose the linear reservoir baseflow method which, as its name implies, uses a linear reservoir to model the recession of baseflow after a storm event. In the HEC-HMS software, it is the only baseflow method that conserves mass within the subbasin. Infiltration (or percolation) computed by the loss method is interpreted as the inflow to the linear reservoirs. It can be used with one, two, or three reservoirs. Partition fractions are used to split the inflow to each of the reservoirs. The inflow is multiplied by the partition fraction to determine the amount of inflow going to each reservoir. The sum of the partition fractions must be less than or equal to one. If the sum of the fractions is less than one, the remaining percolated water is considered as aquifer recharge (i.e, it will not reach the outlet as subsurface flow). If the sum of the fractions is exactly equal to one, then all percolation will become baseflow and there will be no aquifer recharge. [16] The necessary parameters are the number of reservoirs, initial discharge [m^3/s], fraction [-], ground water storage coefficient [hr] and the number of ground water steps. The fraction determines how the percolation is split to the reservoirs. The groundwater storage coefficient is the time constant for each linear reservoir. Because it is measured in hours, it gives a sense of the response time of the subbasin regarding the groundwater percolation. The number of groundwater steps can be used to subdivide the routing through a reservoir and is related to the amount of attenuation during the routing. [16] Initial discharge was given from the measured data as an initial condition while the rest of the parameters were calculated.

6. Modeled events

In both cases, 7 events were selected for the model calibration, while 6 events were chosen to validate the model. The events were selected from the snow free (or summer) season to avoid the complex process of snowmelt modeling. This way, the amount 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 important to avoid possible measurement errors which could be seen from the analysis of runoff rates and the shapes of the hyeto- and hydrographs. The time windows, runoff rates and peak discharges of the calibration events can be seen in *Table 5*.

Table 5. Characteristics of the events used for calibration and validation.

		Number	Start date		End date		Runoff rate [-]		Peak discharge [m^3/s]
							ECMWF	Gauging station	
Zala	Calibration	**16**	02/06/2006	00:00	06/06/2006	00:00	0.23	-	9.9
		19	14/07/2011	00:00	17/07/2011	00:00	0.07	0.08	8.6
		22	17/07/2010	00:00	20/07/2010	00:00	0.07	-	7.5
		24	14/08/2005	00:00	17/08/2005	00:00	0.05	-	6.6
		28	01/06/2011	00:00	04/06/2011	00:00	0.08	0.24	5.6
		30	15/07/2010	00:00	17/07/2010	00:00	0.10	-	4.6
		36	27/07/2011	00:00	02/08/2011	00:00	0.07	-	4.0
	Validation	**1**	21/10/2014	00:00	25/10/2014	00:00	0.21	-	40.8
		5	18/09/2017	00:00	21/09/2017	00:00	0.09	0.09	21.2
		8	14/05/2006	00:00	17/05/2006	00:00	0.24	-	9.6
		11	27/08/2010	00:00	30/08/2010	00:00	0.18	-	12.2
		13	20/09/2014	00:00	25/09/2014	00:00	0.22	-	11.1
		14	26/09/2007	00:00	30/09/2007	00:00	0.13	-	10.8
Kiskomárom	Calibration	**17**	29/05/2006	00:00	02/06/2006	00:00	0.12	0.13	2.6
		18	18/09/2007	00:00	21/09/2007	00:00	0.15	-	2.4
		26	29/06/2006	00:00	02/07/2006	00:00	0.10	0.16	2.1
		28	26/05/2013	12:00	28/05/2013	00:00	0.13	2.63	2.0
		33	28/08/2010	00:00	30/08/2010	13:00	0.08	0.33	1.8
		39	21/09/2014	06:00	25/09/2014	00:00	0.17	-	1.5
		40	20/08/2014	22:00	23/08/2014	15:00	0.11	-	1.4
	Validation	**14**	09/06/2011	00:00	12/06/2011	00:00	0.23	-	2.6
		16	15/05/2010	00:00	19/05/2010	00:00	0.07	0.28	2.5
		25	19/07/2005	00:00	21/07/2005	00:00	0.14	0.16	2.2
		41	11/09/2010	00:00	14/09/2010	00:00	0.10	6.25	1.4
		42	14/08/2014	00:00	17/08/2014	00:00	0.06	-	1.4
		44	22/06/2009	00:00	26/06/2009	00:00	0.08	0.11	1.4

For the model, I chose to use the ECMWF precipitation data because gauging station data was not available for a lot of event's time window and if it was, it occurred that there was no precipitation measurement in the time-series despite the observed flow. It is also visible that summer events were chosen according to the values of runoff rates.

7. Calibration and validation

After creating the models, I calibrated the parameters to achieve the best possible results by a trial and error fashion. In all four cases, I chose the parameter combinations with the most appropriate results out of several simulations and performed the validation of the model. The following chapters describe the outcomes of the calibration and validation process. In all of the cases (both calibration and validation), hydrographs of the examined events are presented. These hydrographs were selected in pairs: the ones which were better simulated by the dynamic case and the ones with worse results than the characteristic case.

7.1. Characteristic case

7.1.1. Zala catchment

The results of the model calibration and validation at the Zala catchment can be seen in *Table 6*. The calculated value of time of concentration was 16 hours according to the Wisnovszky equation. The calibrated value of the storage coefficient is 20 hours. As *Table 6* shows, the results of the calibration are good or almost good in most cases. However, it is already visible that the calculated time of concentration value is not suitable for the catchment in case of these events. Following the calibration, I performed the validation. The results of the validation also show a good or in a few cases excellent model performance. All of the NSE values can be categorized as good or almost good. The difference of time of peak discharges shows bad model performance in only one case.

Table 6. Result of calibration (left) and validation (right) (Zala, characteristic case).

Event	NSE [-]	Δt [hr]
16	0.789	4
19	0.548	1
22	0.439	4
24	0.779	3
28	0.043	9
30	0.406	1
36	0.418	5
Mean	**0.489**	**4**

Event	NSE [-]	Δt [hr]
1	0.777	-3
5	0.749	0
8	0.437	-2
11	0.404	-7
13	0.775	2
14	0.808	2
Mean	**0.658**	**-1**

Figure 10 shows the calibration and validation events. These examples underline the varying performance of the model. It is also visible, that the measured peak discharge is rarely approximated well by the model.

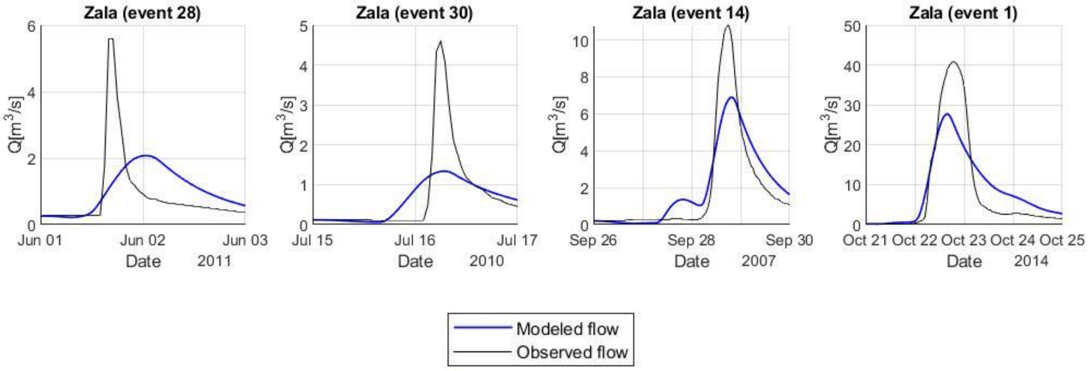

Figure 10. Zala, characteristic case: 28, 30 (calibration) and 14, 1 (validation).

7.1.2. Kiskomárom catchment

The model of Kiskomárom was also calibrated. The performance of the calibrated and validated model can be seen in *Table 7*. The calculated value of time of concentration was 11 hours according to the Wisnovszky equation. The calibrated value of the storage coefficient was also 20 hours. According to *Table 7*, the results of the calibration had wide range of categories. The NSE values are good or satisfactory in most cases. On the other hand, the differences between the observed and modeled time of peak discharges are not acceptable most cases. The model performance of the validation also varies between all categories but most of the cases it is unsatisfactory, especially reviewing the differences of time of peak discharges.

Table 7. Result of calibration (left) and validation (right) (Kiskomárom, characteristic case).

Event	NSE [-]	Δt [hr]
17	0.285	-4
18	0.765	-6
26	0.209	7
28	0.600	0
33	0.684	-6
39	-2.18	-2
40	0.123	-8
Mean	**0.069**	**-3**

Event	NSE [-]	Δt [hr]
14	0.449	-9
16	-0.34	7
25	-0.04	-9
41	-1.70	-3
42	0.295	-7
44	0.603	-13
Mean	**-0.12**	**-6**

Figure 11 shows simulations which were considered to be the best and the worst of the calibration and validation events. The model cannot estimate properly the hydrograph peaks, even though the hydrograph shapes appear to be acceptable.

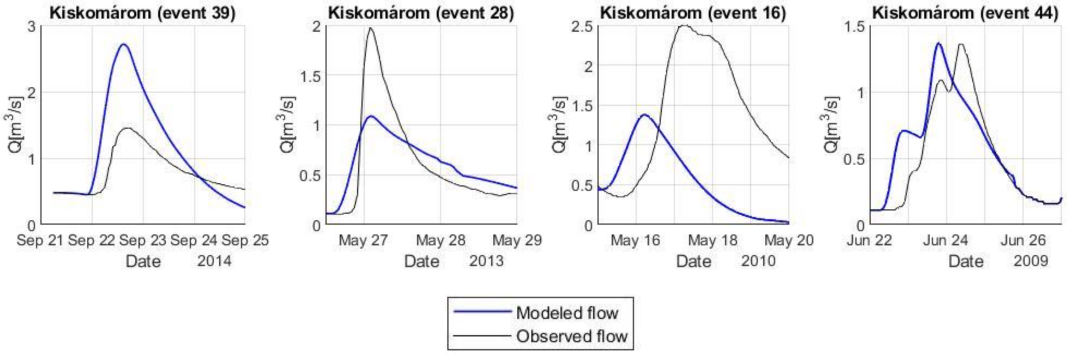

Figure 11. Kiskomárom, characteristic case: 39, 28 (calibration) and 16, 44 (validation).

7.2. Dynamic case

7.2.1. Zala catchment

The applied variable parameter method needed a value of time of concentration, storage coefficient and two curves as mentioned in Chapter 4.2. The calibrated values of time of concentration and storage coefficient are 7 and 15 hours, respectively. The calibrated curves can be seen in *Figure 12*.

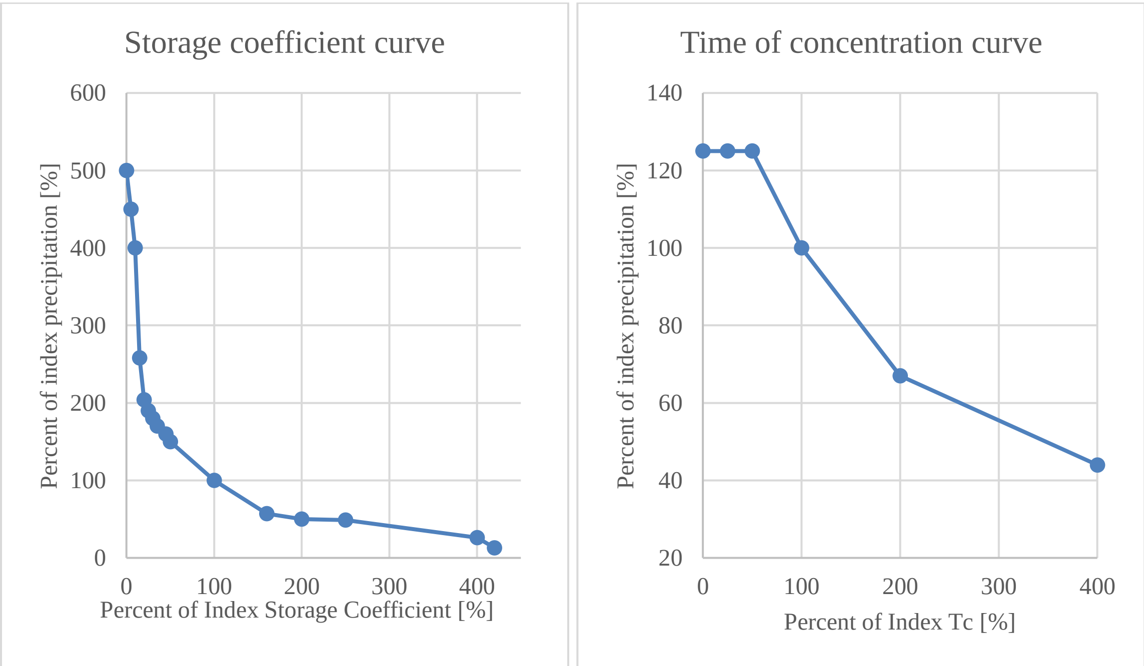

Figure 12. Storage coefficient and time of concentration curve (Zala).

The results of model calibration and validation at the Zala catchment can be seen in *Table **8***. The model performance was excellent or good both reviewing the NSE and the time difference of the peak discharge. The calibration of the model was also performed. As *Table **8*** shows, most of the values can be categorized as good or almost good. Regarding the difference of time of peak discharge, there is only one event with an unsatisfactory result.

Table 8. Result of calibration (left) and validation (right) (Zala, dynamic case).

Event	NSE [-]	Δt [hr]
16	0.848	1
19	0.447	-4
22	0.594	0
24	0.849	0
28	0.414	3
30	0.228	-5
36	0.742	0
Mean	**0.589**	**-1**

Event	NSE [-]	Δt [hr]
1	0.426	-11
5	0.554	3
8	0.454	4
11	0.38	4
13	0.765	-4
14	0.814	0
Mean	**0.566**	**-1**

As explained, *Figure 13* shows simulations which were considered to be the better and the worse in the dynamic case of Zala. Compared to the characteristic case (*Figure 11*) events 28 and 14 were simulated better in the dynamic case, while events 30 and 1 are more accurate in the characteristic case. It is clearly visible, that model requires further improvements to match the measured and modeled hydrographs with higher accuracy.

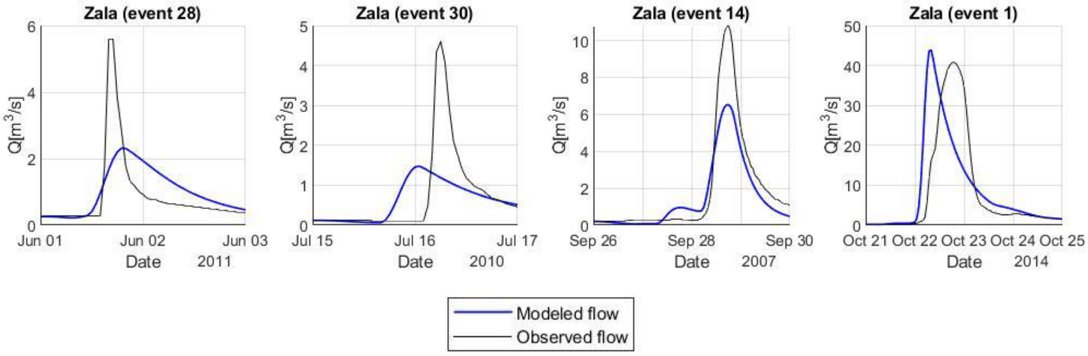

Figure 13. Zala, dynamic case: 28,30 (calibration) and 14,1 (validation).

7.2.2. Kiskomárom catchment

Regarding Kiskomárom, after calibration the value of time of concentration is 15 hours while the storage coefficient is 16 hours. The curves applied for the best results can be seen in *Figure 14*.

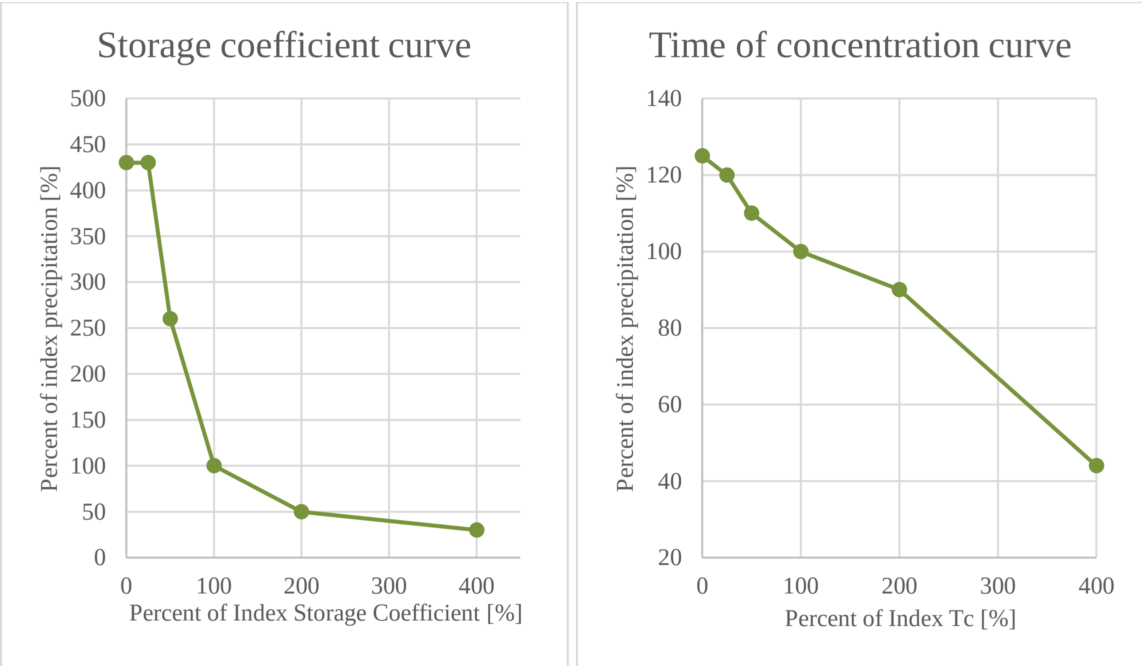

Figure 14. Storage coefficient and time of concentration curve (Kiskomárom).

Applying the curves, the results of calibrating the model of Kiskomárom can be seen in *Table 9*. The model performance was excellent or good in most cases of NSE while Δt was divided between good and unsatisfactory.

Table 9. Result of calibration (left) and validation (right) (Kiskomárom, dynamic case).

Event	NSE [-]	Δt [hr]
17	0.551	0
18	0.820	4
26	-0.14	11
28	-0.26	11
33	0.583	8
39	0.657	2
40	0.905	2
Mean	**0.446**	**5**

Event	NSE [-]	Δt [hr]
14	0.551	-6
16	0.883	7
25	0.418	4
41	0.141	0
42	0.753	5
44	0.623	-5
Mean	**0.561**	**1**

The results of validation are also visible in *Table 9*. The NSE values are good or almost good with only one exception. The difference of time of peak discharges is satisfactory in case of most of the events but it is unsatisfactory in two cases.

In *Figure 15*, following the previous concept, the better and worse simulations can be seen than the characteristic case of Kiskomárom. According to these figures, the model performance varies reviewing the estimation of hydrograph peaks. In general, the hydrographs appear to fit the measured values better than in case of Zala catchment and the improvement achieved by the dynamic model is more significant.

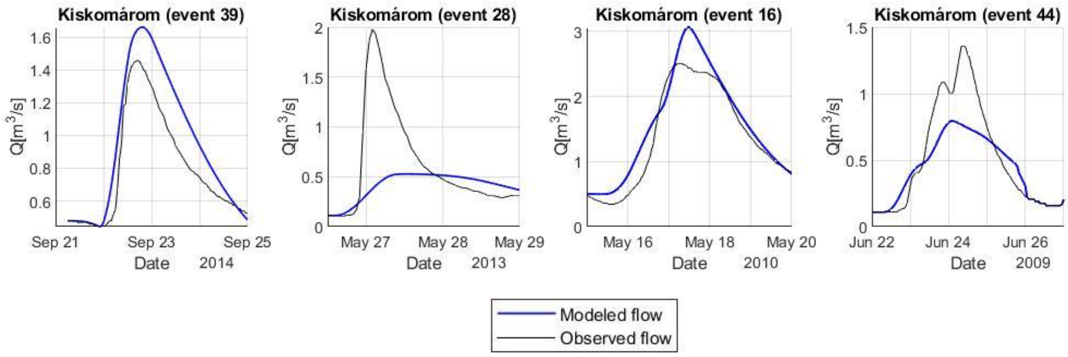

Figure 15. Kiskomárom, dynamic case: 39, 28 (calibration) and 16,44 (validation).

8. Summary and conclusions

In general, considering dynamic time of concentration led to better model performance. In *Figure 16*, the NSE values and the difference in time of peak discharge values are compared in case of the calibrated events. The NSE values of the dynamic case are significantly better at Kiskomárom, but the difference is less significant at Zala. Regarding |Δt|, the simulation of the dynamic case have more values below 3 hours at both catchments.

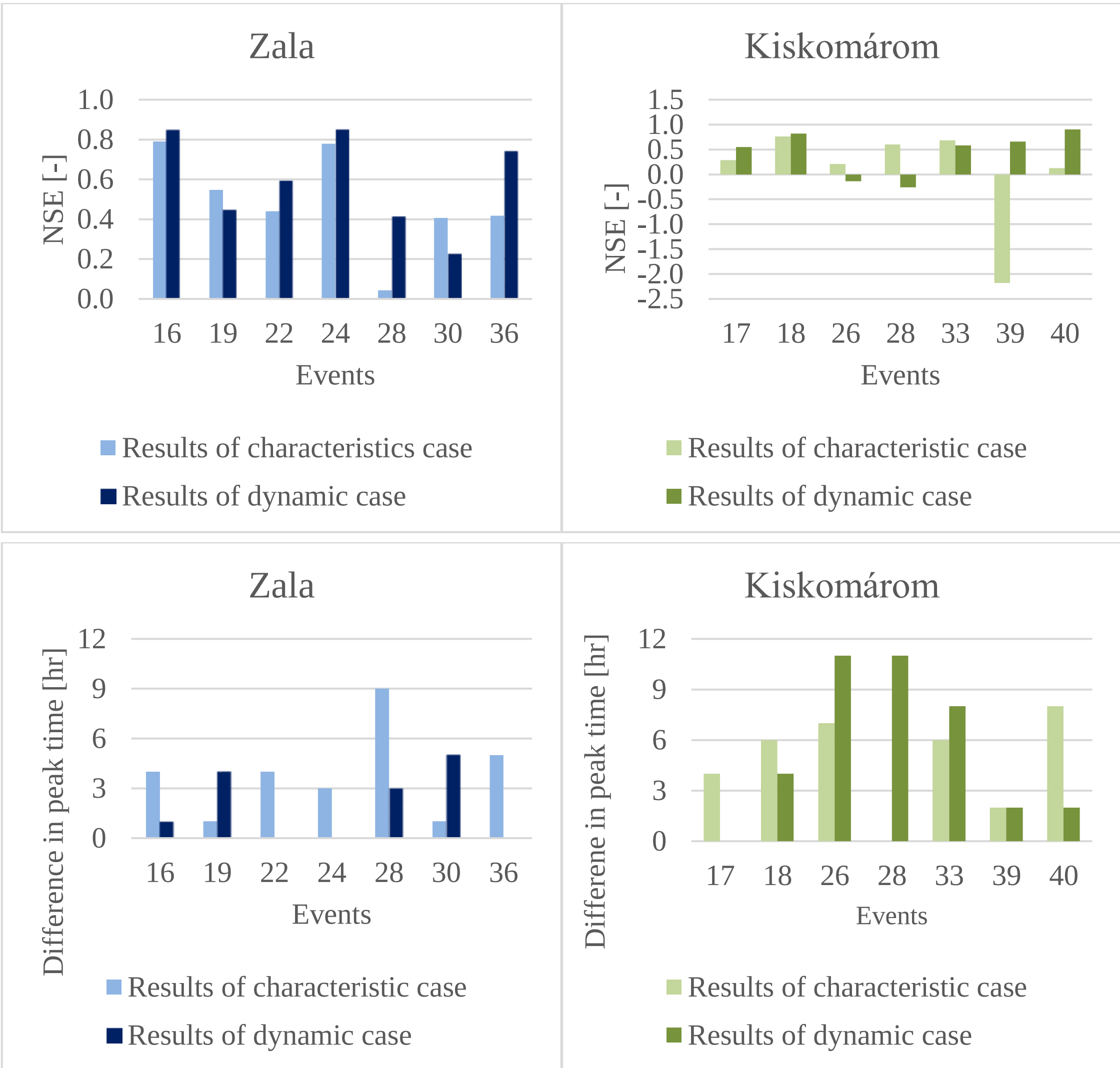

Figure 16. Results of calibration regarding NSE (top) and |Δt| (bottom).

The comparison of the two approaches in case of the validation of the models can be seen in *Figure 17*. Reviewing Kiskomárom, the results of the dynamic case are satisfactory. However, at the Zala catchment the results are not significantly better than the results of the characteristic case.

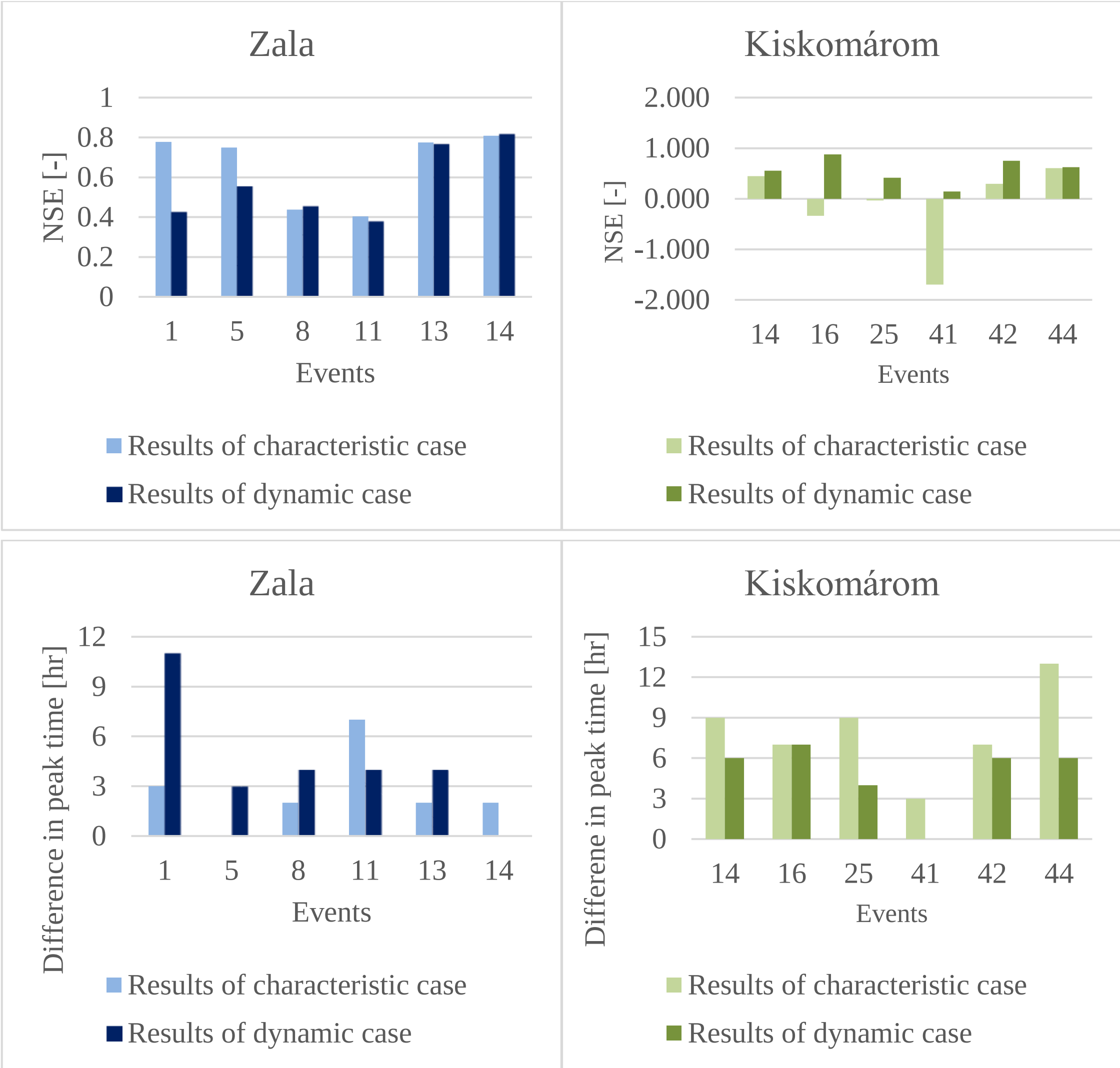

Figure 17. Results of validation regarding NSE (top) and |*Δt*| (bottom).

Overall, the model performance according to NSE and the time of peak discharges can be improved using the dynamic approach of time of concentration. The calibration itself is more difficult to perform than in the characteristic case but if the proper curves are applied, the simulations can give significantly better results. The suitable curves can be achieved if the calibration is performed on a larger variety of events with many different rainfall intensities. This way, the curves can be more accurate for simulating a variety of events, including extreme floods.

During this study, I performed the calibration and validation of two different rainfall-runoff models for two Hungarian catchments. The two models differed in terms of the adaptation of time of concentration in the Clark Unit Hydrograph method. The first approach applied a constant, characteristic value, while the second one used the novel, dynamic approach. The characteristic value of time of concentration was estimated using the empirical Wisnovszky equation, while the relationship between the excess rainfall intensity and time of concentration was calibrated in case of the dynamic approach. As assumed the dynamic time of concentration led to a better model performance at both catchments. The difference was more significant in case of the Kiskomárom catchment, which implies that the Wisnovszky equation gave worse estimation of the characteristic value for that catchment.

The results clearly showed that the dynamic time of concentration can improve the model performance, especially when the Wisnovszky equation yields an inadequate estimation of the time of concentration. Since the Wisnovszky equation proved to give inaccurate estimations in general, and the value of time of concentration is varying with rainfall intensity, using the dynamic approach is highly recommended in the Hungarian modeling practice, despite the complexity of the calibration.

This study was carried out as a first step of a more extensive analysis. The options to continue the study are involving more catchments (in Hungary and abroad), comparing the calibrated curves with measured time of concentration-rainfall intensity data, and providing a general methodology to estimate the curves required for the dynamic case using measured data.

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