

Development of the Synthetic Unit Hydrograph Tool – SUnHyT

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ABSTRACT

Unit hydrographs (UH) are widely used in scientific research and engineering projects to simulate rainfall-runoff processes. There are four main approaches for calculating UH: the traditional, the conceptual, the probabilistic, and the geomorphological approaches. Most software designed to facilitate the estimation of UH is usually based on only one UH approach, limiting its applicability for scientific hypotheses testing. This paper presents the Synthetic Unit Hydrograph Tool (SUnHyT), which provides nine different UH models from the four main approaches used in UH applications. SUnHyT is an open-source application that can be used intuitively through a graphical user interface. We tested the model in a case study that highlights the need for alternative approaches of UH when the traditional approach does not perform well. SUnHyT allows the estimation of design hydrographs in gauged and ungauged catchments and can be useful for hydrologists, water managers and decision-makers.

1. Introduction

Sherman (1932) theory for the unit hydrograph (UH), or instantaneous unit hydrograph, has become one of the most used theories for estimating storm runoff hydrographs (Todini, 1988). Even though more complex hydrological models are available, the UH is still used because it provides runoff estimates with few parameters that are easily determined using digital elevation models (Chavan and Srinivas, 2015; Lee et al., 2006). UH has been used as a model to estimate nonpoint pollution (Chen et al., 2017; Todeschini et al., 2014), sediment discharge (Singh et al., 2015), streamflow regionalization (de Lavenne et al., 2015; Littlewood and Croke, 2008; Razavi and Coulibaly, 2013; Seo et al., 2016; Yao et al., 2014), flood risk (de Gonzalo et al., 2012; Tsanakis et al., 2016), and flood prediction (Gad, 2013; Siqueira et al., 2016).

The different approaches used to calculate the UH shape are divided into four main classes (Singh et al., 2014, Fig. 1): (i) traditional or empirical; (ii) conceptual; (iii) probabilistic; and (iv) geomorphological. The traditional approach, also known as the synthetic unit hydrograph (SUH), uses physical characteristics related to the stream network and hydraulic properties to predict floods in ungauged catchments (Bernard, 1935; Mockus, 1957; Gottschalk and Weingartner, 1998; Mockus). The conceptual UH is based on a reservoir analogy (e.g. Clark, 1945; Dooge,

1973; Nash, 1959) or a linear cascade of reservoirs (Nash, 1957) that represents a complex hydrologic system. The probabilistic approach uses probability density functions (PDF), e.g. the two-parameter gamma distribution, to approximate the shape of the UH (e.g. Bhunya et al., 2009, 2008; Croley, 1980; Nadarajah, 2007; Singh, 2000).

The Geomorphological Instantaneous Unit Hydrograph (GIUH) integrates traditional and conceptual approaches by regarding catchments as hydrologic systems comprising segmented streams, with each segment displaying a unique response to rainfall inputs, referred to as a hydrologic response unit (HRU; Rigon et al., 2016; Azizian and Shokooi, 2015). The manner in which these segments connect or bifurcate can be described using Horton's laws (e.g. Rodríguez-Iturbe and Valdés, 1979; Rosso, 1984). Another perspective that incorporates geomorphological information from catchments stems from the concept of a width function (Kirkby, 1976), resulting in the Width Function Instantaneous Unit Hydrograph (WFIUH). This approach originates from the idea of maximizing information extraction from digital elevation models, where HRUs are groups of catchment pixels equidistant from the outlet (Rigon et al., 2016).

The applicability of one approach is often justified based on the limitations of others. For example, the most traditional model (i.e., Mockus, 1957) uses the time of concentration, which is a highly

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subjective parameter (Beven, 2020), and estimation of the time of concentration can differ by up to 500% (Grimaldi et al., 2012a). The conceptual and probability classes are black box models, their parameters cannot be directly related to catchment characteristics, and therefore, their application is limited to ungauged catchments. On the other hand, the GIUH has been widely applied in scientific research, but the velocity parameters used in those models are usually interpreted as velocities and travel times of the water in overland flow when they should be related to a constant wave celerity (Beven, 2020). The last developments offer a solution using WFIUH and estimate the hillslope velocities cell by cell through physical equations (e.g. Grimaldi et al., 2010; Grimaldi et al., 2012b; Grimaldi and Petroselli, 2014). However, the flow velocity of hillslopes tends to be overestimated using physical equations (e.g. Darcy–Weisbach formula, Manning’s formula) (Grimaldi et al., 2010).

HEC-HMS (USACE, 2001) is one of the most popular computer software applications based on UH theory, employing a traditional UH approach for hydrograph design. Other software options estimate UH using conceptual approach based on linear programming (e.g. Cavallini, 1993; Hromadka, 2000) and instrumental variables (Allen and Liu, 2011; Jakeman et al., 1990). There are also tools available to estimate UH using a geomorphological approach (e.g. Bhadra et al., 2008; Lee et al., 2006; Yang et al., 1998). However, the choice of the most suitable UH approach depends on the specific runoff generation processes within each catchment. Although the UH is indicated for catchments whose runoff generation process is Hortonian, the HU has been used in catchments with different runoff generation (Pedroso and Mannich, 2021). The uncertainty of UH is around 50% for ungauged catchments (Brunner et al., 2018), peak flow can be overestimated by up to 60 times in some catchments (Pedroso and Mannich, 2021), and errors can reach up to 137% using traditional and conceptual HU approaches (Steinmetz et al., 2019). There is a need to combine different classes of UH into an easy-to-use computational tool for scientific and engineering applications. These UH models in unified software encourage users to employ a joint method approach in order to verify the uncertainty inherent in rainfall-runoff models. In addition, the tool simplifies the process of identifying the UH model that is best suited for any specific application.

In this paper, we develop the Synthetic Unit Hydrograph Tool – SUNHyT. We implemented nine UH models in the tool: two traditional (Snyder, 1938; Mockus, 1957, known as SCS); two conceptual (Zoch, 1934; Nash, 1957); two probabilistic (two-parameter log-normal distribution - TwoParLn and two-parameter gamma distribution - TwoParGamma); and three geomorphologic (two based on Horton’s laws -

Rodríguez-Iturbe and Valdés, 1979; Rosso, 1984; and one based on width function - Kirkby, 1976). After presenting SUNHyT, we apply this tool to a case study in which we verify the performance of each UH model for rainfall-runoff simulation in a subtropical forest.

2. The unit hydrograph theory

Sherman (1932) developed the Unit Hydrograph (UH) based on the assumption that the catchment responds linearly to rainfall (Dooge, 1973). Considering surface runoff as a linear function of effective rainfall (Snyder, 1938), the resulting hydrograph is expressed by the convolution integral in Equation (1).

$$Q(t) = A \int_0^t q(t-\tau) * P_{ef}(\tau) d\tau \quad (1)$$

where $Q(t)$ is surface runoff per time unit [$L^3 T^{-1}$], A is drainage area, q is the unit hydrograph, P_{ef} [L] is the effective precipitation and τ [T] is travel time (Volpi et al., 2018).

Initially, HU was treated as a histogram whose ordinates were unknown parameters to be determined (Beven, 2012), and calibration was impossible with the available rainfall-runoff data at that time. Zoch (1934) proposed a conceptual UH (Fig. 1) with just one parameter, which describes catchment behavior as a reservoir and assumes that the river is dry when the rain began (Equation (2)).

$$q(t) = q_0 e^{-t/k} \quad (2)$$

where q_0 [$L T^{-1}$] represents the initial runoff and k [T^{-1}] is the linear storage coefficient. However, this situation does not occur very often in nature and Nash (1957) increased the complexity of the model to get closer to the real rainfall-runoff hydrograph. Nash (1957) assumed that a river system is equivalent to a series of linear reservoirs, where discharge is proportional to storage, with the downstream input corresponding to the upstream output (Equation (3)).

$$q(t) = \frac{1}{k\Gamma(n)} e^{-t/k} \left(\frac{t}{k}\right)^{n-1} \quad (3)$$

where n [-] is the number of reservoirs and Γ is the density gamma function. Thus, the form of the UH, controlled by the number of reservoirs (n) and linear storage coefficient (k), can be obtained by the convolution of upstream inflow with the downstream linear reservoir. This process, repeated n times, corresponds to a density gamma function

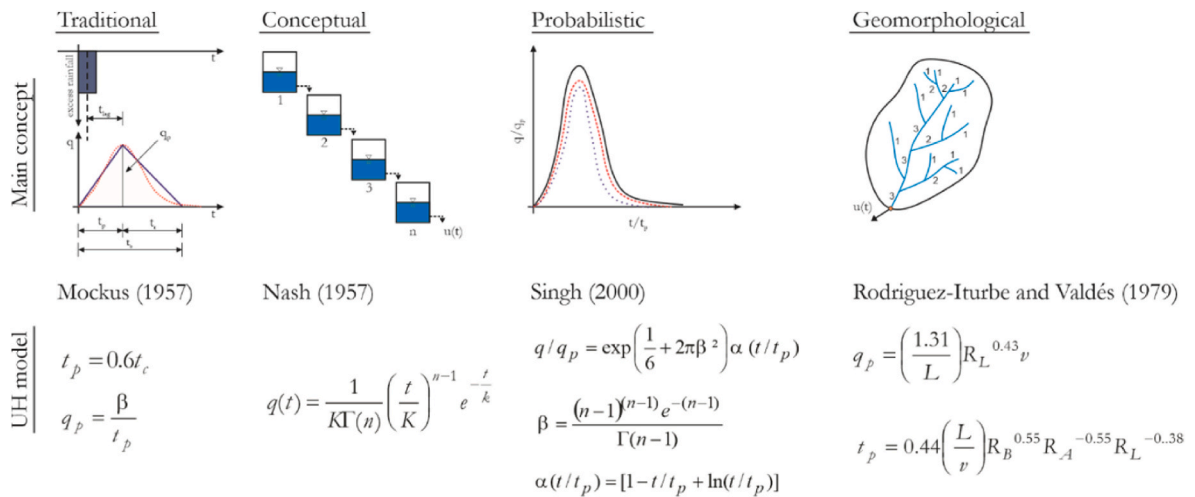


Fig. 1. Main UH models, where q_p is the peak flow, t_b is the base time, t_{lag} is the time between rainfall gravity center and the hydrograph peak, t_p is the peak time, t_r is the recession time, t_c is the concentration time, β is a product of peak rate flow, k is the storage coefficient, n is the number of reservoirs, α is a function of t/t_p , R_L is the stream lengths law, R_B is the bifurcation law, R_A is the law of stream areas, v is the average peak flow velocity or characteristic velocity.

(Γ). Nash (1957) reservoir system was further developed by Dooge (1959), who conceptualized the catchment response in terms of a succession of reservoirs and channels represented in a time-area curve, where each reservoir drained one catchment subdivision. Singh (1964) considered the catchment as a series of two reservoirs with different storage coefficients.

The major issue with conceptual models (Fig. 1) is that their parameters cannot be estimated without measured data. On the other hand, they consolidated the idea that UH could be described by the behavior of the composition of reservoirs, whose shape is similar to a probability density function (PDF). This conclusion led to new UH developments based on its association with PDF (Fig. 1). Nadarajah (2007) implemented nine PDFs to represent the UH. One example is the two-parameter lognormal distribution (Equation (4)).

$$q(t) = \frac{1}{\sqrt{2\pi}\sigma t} e^{-\left(\frac{(\ln t - \mu)^2}{2\sigma^2}\right)} \quad (4)$$

where σ [-] and μ [-] are parameters of the PDF function. Another example is the two parameters gamma distribution that results in the same mathematical formulation of Nash (1957) and has been widely adopted (e.g. Bhunya et al., 2007; Bhunya et al., 2008; Singh, 2000).

The conceptual and probabilistic UH models showed that it is possible to describe the rainfall-runoff process using UH. Nevertheless, it is only possible to establish the UH shape in catchments with rainfall-runoff data. The aim of going beyond this limitation has led to the so-called synthetic UH, which links the main components of UH to catchment characteristics, in order to make UH predictable based on catchment characteristics.

There are three main components of synthetic UH: (i) peak time, representing the moment when most of the catchment is generating outflow; (ii) peak flow, the outflow at the moment of peak time; and (iii) base time, the total duration of the UH (Singh, 1991). The traditional UH (as classified by Singh et al., 2014) determines the shape of the UH (i.e., base time, peak discharge, and peak time) on the basis of empirical relations derived from data on several catchment characteristics. Snyder (1938) derived a UH based on Equations (5)–(7).

$$t_p = C_t (LL_c)^{0.3} \quad (5)$$

$$q_p = 2.78 \left(\frac{A_w C_p}{t_p} \right) \quad (6)$$

$$t_b = 3 + 3 \left(\frac{t_p}{24} \right) \quad (7)$$

where t_p [T] is peak time, q_p [$L^3 T^{-1}$] is peak flow, t_b [T] is base time, C_t and C_p are dimensionless constants, A_w is the drainage area [L^2], L [L] is the mainstream length, L_c [L] is the distance from the catchment outlet to a point on the main stream nearest to the center of the catchment area [km].

Peak time and peak flow are closely related to the stream network, main stream length, slope, and catchment centroid (Snyder, 1938; Taylor and Schwarz, 1952). Moreover, Mockus (1957) stated that t_p and q_p are a function of the time of concentration (t_c), an attribute that can be calculated via empirical formulas (Grimaldi et al., 2012a) (Equations (8) and (9)).

$$t_p = 0.6 t_c \quad (8)$$

$$\frac{q(t)}{q_p} = e^m \left[\left(\frac{t}{t_p} \right)^m \right] \left[e^{-m \left(\frac{t}{t_p} \right)} \right] \quad (9)$$

where m is a dimensionless variable [-]; and t_c is the time of concentration [T].

These traditional UH can be described by a PDF using the gamma distribution (Equation (3)) (Singh, 2000), as shown in equations (Equations (10) and (11)).

$$n = \frac{7}{6} + 2\pi\beta^2 \quad (10)$$

$$k = \frac{t_p}{n-1} \quad (11)$$

where β [-] is a factor governing the shape of the dimensionless UH and varies for each model (e.g. β is 1.09 C_p for the Snyder model). Since the area under the PDF is guaranteed to be unity, it is not required to calculate t_b .

Motivated by the idea of predicting UH in ungauged catchments, Rodríguez-Iturbé and Valdés (1979) established a geomorphologic unit hydrograph (GIUH), in which only the parameters related to flow velocity need to be estimated. GIUH considers that rainfall randomly falling in a catchment follows a predetermined path according to the contribution area. Rodríguez-Iturbé and Valdés (1979) proposed the time for the water at each point of the catchment to reach the outlet where q_p , t_p and β depend on Horton's laws (Equations (12)–(14)).

$$q_p = \frac{1.31}{L} Rl^{0.43} v \quad (12)$$

$$t_p = \frac{0.44L}{v} \left(\frac{Rb}{Ra} \right)^{0.55} Rl^{-0.38} \quad (13)$$

$$\beta = 0.584 \left(\frac{Rb}{Ra} \right)^{0.55} Rl^{0.05} \quad (14)$$

where Rb [-] is the bifurcation ratio, Rl [-] is the length ratio, Ra [-] is the area ratio and L [L] is the length of the mainstream, v [$L T^{-1}$] is the hydrodynamic factor flow velocity.

Rosso (1984) unified aspects first introduced by Nash (1957) and Rodríguez-Iturbé and Valdés (1979) to create a UH model that estimates the number of reservoirs and linear storage coefficient using geomorphological data (Equation (18) and Equation (19)).

$$n = 3.29 \left(\frac{Rb}{Ra} \right)^{0.78} Rl^{0.07} \quad (15)$$

$$k = 0.70 \left(\frac{Ra}{RbRl} \right)^{0.48} \frac{L}{v} \quad (16)$$

Several other models have been derived since. Rodríguez-Iturbé et al. (1982) suggested a UH concept that varies depending on the intensity and duration of effective rainfall.

GIUH can be estimated using the Horton's laws (Rodríguez-Iturbé and Valdés, 1979) or using the width function (Kirkby, 1976), known as the width function instantaneous unit hydrograph (WFIUH). The width function represents the distribution of distances upstream from the outlet, which can be normalized by the total area to obtain a probability distribution function. The product of the distance and flow velocity corresponds to travel time. Flow velocity in the catchment can be divided into hillslope velocity and river velocity (Rigon et al., 2016). The WFIUH can be estimate using Equations (12)–(14).

$$T_{r \rightarrow o} = \sum_{i=r}^0 T_i = \sum_{i=r}^0 \frac{x_i}{v_r} \quad (17)$$

$$T_{h \rightarrow r} = \sum_{i=h}^0 T_i = \sum_{i=r}^0 \frac{x_i}{v_h} \quad (18)$$

$$q(t) = T_{r \rightarrow o} + T_{h \rightarrow r} \quad (19)$$

where $T_{r \rightarrow o}$ [T] is the travel time of the water in the river network to

outlet, $T_{h \rightarrow r}$ [T] is the travel time on the hillslope to the river, x is the position of the cell and v_r [L T⁻¹] is the median velocity of water in the river and v_h [L T⁻¹] is the median velocity of water on the hillslope. The latest developments of WFIUH reach a calibration-free configuration with one parameter (WFIUH-1par) (e.g. Grimaldi et al., 2010; Grimaldi et al., 2012b; Grimaldi and Petroselli, 2014) and estimate the hillslope velocities cell by cell using empirical equations and constraining the channel velocity to the time of concentration or to the lag time.

3. The synthetic unit hydrograph tool - SUNHyT

SUNHyT is a tool implemented in the MATLAB programming language and contains a graphical user interface (GUI) that facilitates UH determination by providing nine different methods: Snyder (1938), Mockus (1957), Zoch (1934), Nash (1957), two-parameter log-normal, two-parameter gamma distribution, Rodríguez-Iturbe and Valdés (1979), Rosso (1984), and width function-based geomorphological UH based on Kirkby (1976) approach. Snyder (1938) and Rodríguez-Iturbe and Valdés (1979) models are applied to the probabilistic theory introduced by Singh (2000).

Three modules are available for using the tool: (i) calibration; (ii) validation; and (iii) ungauged. In the calibration and validation modules, the user needs to input rainfall-runoff data. In the calibration module, different inputs are required for each model, as shown in Table 1. Flow accumulation (FAC) and flow direction (FDR) files in .txt format should be created by the user from the DEM.

To determine the hydrograph from the UH, it is necessary to determine the amount of rainfall that drains from the catchment through runoff. In this regard, SUNHyT is equipped with resources for separating baseflow and surface runoff in a hydrograph. Three numerical flow separation filters are provided within the tool: (i) Lyne and Hollick (1979), (ii) Chapman and Maxwell (1996), and (iii) Eckhardt (2005). Digital filters and mathematical formulations for numerical filters are presented in Carlotto and Chaffe (2019). The constant baseflow option can be used for the ungauged method. Alternatively, for the intermittent

stream, it is possible to use the tool without considering the baseflow.

Effective rainfall, a key parameter for estimating UH, is determined by Curve Number (e.g. Ajmal et al., 2015), which consists of two main components t : initial abstraction (I_a) [L] and curve number (CN) [-]. I_a is defined as the rainfall of an event that falls before the direct runoff starts. CN calibration is performed by conducting a mass balance, where all effective rainfall is converted into direct runoff. If there is no rainfall-runoff data, the tool supports the estimation of effective precipitation using the curve number method parameters, which are associated with soil type, soil cover, and saturation state. These parameters can be calibrated using data from neighboring gauged catchments (e.g. Cheng et al., 2006).

After defining the effective rainfall, a matrix with the effective rainfall is generated to perform the convolution operation, as explained by Cavallini (1993). To determine this matrix, it is necessary to determine the base time of the hydrograph. The base time is determined as the time interval between the beginning and end of the surface runoff in the calibration and validation module. In the ungauged module, the user must determine the base time.

The UH is calibrated using the D'Errico (2023) search algorithm based on Lagarias et al. (1998). The algorithm aims to find the lowest possible value for an operation. We employed an objective function (OF) inspired by the Nash-Sutcliffe equation. While Nash-Sutcliffe values range from one to minus infinite, our function varies from minus one to infinite (Equation (20)).

$$OF = - \frac{\sum_{t=1}^T (Q'_m - Q'_o)^2}{\sum_{t=1}^T (Q'_o - \overline{Q_o})^2} \quad (20)$$

where Q_0 is the mean of observed runoff, and Q_m is modeled runoff. Q'_o is observed discharge at time t . The output parameters are the ones that better respond to an objective function.

3.1. Graphical user interface

SUNHyT is composed of the main GUI that provides the choice of methods for separating hydrographs and creating unit hydrographs (UH). In the GUI, the three modules are available to perform the procedures. Each module includes features for viewing and saving results, with a GUI that allows the user to choose the visualization mode (graphs or spreadsheet), location, and format to save the data (.txt (text file) or .xlsx (Excel files)). The sub-windows that are part of the GUI are shown in Fig. 2.

A – General parameters: These are mandatory inputs used in all UH methods. The catchment area must be in square kilometers and the time interval (dt) must be given in seconds (e.g. if the data was monitored with a time interval of 1 h then dt is 3600 s).

B – Baseflow separation methods: It provides methods for baseflow hydrograph separation, and it is an optional procedure. When selected, the checkbox enables the Combobox to display the available options.

C – Unit hydrograph methods (UH): In this section, a Combobox displays all nine UH methods, and the user must choose one of them.

D – Selection of procedures to be performed: There are three procedures are available, and the user must select at least one of them: (i) calibration, (ii) validation, and (iii) ungauged.

E – Next button: Clicking this button registers the entered information and opens a new window where the user can input parameters based on the chosen methods and actions. If more than one action is selected, the window will open in the following order: calibration, validation and ungauged.

F – Data input: This panel contains buttons for entering precipitation and streamflow data, as well as information on flow accumulation

Table 1

The input and output for each UH model in the calibration module. Where TwoParLn is two-parameter log normal distribution, TwoParGamma is two-parameter gamma distribution, R-R is a rainfall-runoff event [mm – m³/s], A [km²] is drainage area, L is the mainstream length [km], Lc is the distance from the catchment outlet to a point on the main stream nearest to the center of the catchment area [km], t_c is the time of concentration [dt], Ct, Cp, σ , μ , β , α are dimensionless constants, n [-] is the number of reservoirs, a dimensionless parameter, and k [L T⁻¹] is the unit of time-related to reservoir decay, FAC is a raster of flow accumulation and FDR is a raster of flow direction, DEM is digital elevation model, tr is the threshold of cells to define drainage, v is the hydrodynamic factor flow velocity [m dt⁻¹], v_r is the median velocity of water in the river [m dt⁻¹] and v_h is the median velocity of water in the hillslope [m dt⁻¹]. dt is the temporal resolution of the input data.

UH model	Equation	Calibration- Input	Calibration- Output
Snyder (1938)	5, 6, 7, 10 and 11	R-R, A, L, Lc	C_b, C_p
Mockus (1957)	8 and 9	R-R, A	t_c
Zoch (1934)	3	R-R, A	k
Nash (1957)	4	R-R, A	n, k
TwoParLn	3	R-R, A	σ, μ
TwoParGamma	4	R-R, A	γ, α
Rodríguez-Iturbe and Valdés (1979)	10, 11, 12, 13 and 14	R-R, A, Rb, Rl, Ra and L	v
Rosso (1984)	15 and 16	R-R, A, Rb, Rl, Ra and L	v
Kirkby (1976)	17, 18 and 19	R-R, A, FAC and FDR derived from DEM and tr	v_r, v_h

Table 2

- Common values used or found in the literature for each parameter. Where TwoParLn is two-parameter log-normal distribution, TwoParGamma is two-parameter gamma distribution, t_c [T] is the time of concentration, C_t , C_p , σ , μ , γ , α are dimensionless constants, n [-] is the number of reservoirs, a dimensionless parameter, and k [T^{-1}] is the unit of time related to reservoir decay, v [$L T^{-1}$] is the hydrodynamic factor flow velocity, v_r [$L T^{-1}$] is the median velocity of water in the river and v_h [$L T^{-1}$] is the median velocity of water in the hillslope.

UH model	Parameters	Initial-Final	Literature-based	Catchment area [km ²]
Snyder (1938)	C_t	0.65–2.20	Silveira (2016); Singh et al. (2014); Snyder (1938).	0.25–25000
	C_p	0.31–1.22		
Mockus (1957)	t_c	Time of concentration (e.g. Fang et al., 2008; Kirpich, 1940)	NRCS (2007)	5.20–11.14
	m	0.50–6.00		
Zoch (1934)	k	1.0–10.00	–	<1
Nash (1957)	n	1.00–5.86	Bhunya et al. (2008)	114–350
	k	2.12–10.00 h ⁻¹		
TwoParLn	σ	$\sigma > 0$	Nadarajah (2007)	
	μ	$-\infty < \mu < +\infty$		
TwoParGamma	γ	$\gamma > 0$	Nadarajah (2007)	
	α	$\alpha > 0$		
Rodríguez-Iturbe and Valdés (1979)	v	1.0–5.0 m s ⁻¹	Rodríguez-Iturbe et al. (1979); Moussa (2008)	1–3024
Rosso (1984)	v	1.1–10.0 m s ⁻¹	Rosso (1984); Chen et al. (2019)	5–1719
Kirkby (1976)	v_r	1.27–2.42 m s ⁻¹	Di Lazzaro (2009); Rigon et al. (2016); Grimaldi et al. (2012b)	10–4116
	v_h	0.009–0.033 m s ⁻¹ (10–100 times smaller than v_r)		

and flow direction when needed. In the calibration and validation windows, the “Event data” button allows the user to locate and open the .txt file containing the event, with two columns consisting precipitation and streamflow data. In the “Ungauged” window, the “Event data” button allows to enter precipitation data for a period with no monitored streamflow data. The “Flow accumulation” and “Flow direction” buttons will only be visible when Kirkby’s method is selected. These buttons allow the user to locate and open the flow accumulation and flow direction data previously made by the user with a digital elevation model suitable for the study area. These files must be written in ASCII format in a .txt file. The structure of the data files can be verified in the test cases that are available with SUnHyT.

G – Baseflow parameters: the parameter entry will only be available if a hydrograph separation method has been selected. Otherwise, the parameter input panel will be identified as “not applicable”. For the Eckhardt method, the input boxes for parameters a and BFI will be enabled. For other methods, only the parameter a will be necessary.

H – Physical and geomorphological properties: This panel is related to physical and geomorphological properties of the catchment. When Snyder method is selected, the input values for the physical properties of the catchment will be enabled (2 inputs). In the case of Rodríguez-Iturbé and Rosso, the inputs for the geomorphological properties of the catchment are enabled (4 inputs). For the other methods, these properties are not required, and the parameter inputs will remain disabled and with the identification “not applicable”.

I – Parameters range: This section is for setting the parameters range calibration. In addition to defining the calibration range, the user must also specify an initial value for each parameter. Help texts are provided if the user hovers the mouse cursor over the parameter name. Table 2 displays the common values used or found in the literature for each parameter.

J – Start calibration: Clicking on this button initiates the calibration process. When the calibration is completed, the “View Results” and either “Next” or “Close” buttons will be enabled. For the Kirkby method, the user will be prompted to define a threshold corresponding to the minimum number of cells for the formation of the drainage network.

K – View results: This button opens the window for viewing and saving the results. The preview window and its features will be presented in items R, S, T, and U.

L – Next or close button: In the calibration and validation windows, the “Next” button appears when there are subsequent procedures (e.

g. it appears in the calibration window if both calibration and validation procedures are selected). The “Close” button appears when no further procedures are needed.

M – Validation parameters: Enter the validation parameters. If the calibration procedure has been completed, the validation parameters will be auto filled.

N – Start validation: This button will start the parameter validation process. When the calibration is finished, the “View Results” and “Next” buttons will be enabled.

O – Baseflow parameters: In the synthetic unit hydrograph estimation window for periods without streamflow monitoring (“Ungauged”). The baseflow parameters consist of: “Constant baseflow” and “Base time”. If the user does not have a value for the constant baseflow then enter the value zero to disregard the baseflow and obtain a unit hydrograph with streamflow starting at zero. The base time is around 1.6 times the time of concentration (USDA-NRCS, 2010). We recommend that the user chooses the base time greater than this value.

P – Parameters: In the “Ungauged” mode window, it is necessary to inform the Initial abstraction I_a (defined as the rainfall of an event that falls before the direct runoff starts) and Curve Number (CN). If the user wants to provide effective rainfall instead of using the CN method, the user should define CN equal to 100 and I_a equal to 0, this will define that all of the input rainfall will be effective rainfall. When the calibration process is applied for an event with the monitored streamflow to obtain parameters to estimate the unit hydrograph for a period without monitored streamflows, the parameters I_a , CN and others will be filled in automatically.

Q – Start button: This button starts the process of estimating the UH from a precipitation event in the “Ungauged” mode.

R – Visualization of calibration results: This is the window for viewing and saving the calibration results. To view the results (Unit Hydrographs), the user can choose between a graphical view (by checking the Figure option) and a spreadsheet (by checking the spreadsheet option). It is also possible to view basic statistics of the calibration of the parameters in the form of graphs that show the evolution of the objective function values. To save the results, the user must check which data to save (Unit hydrograph, Calibrated parameters, and others). During the saving process, messages will appear to inform the user which results are being saved, allowing confirmation or cancellation of the save process. To proceed with

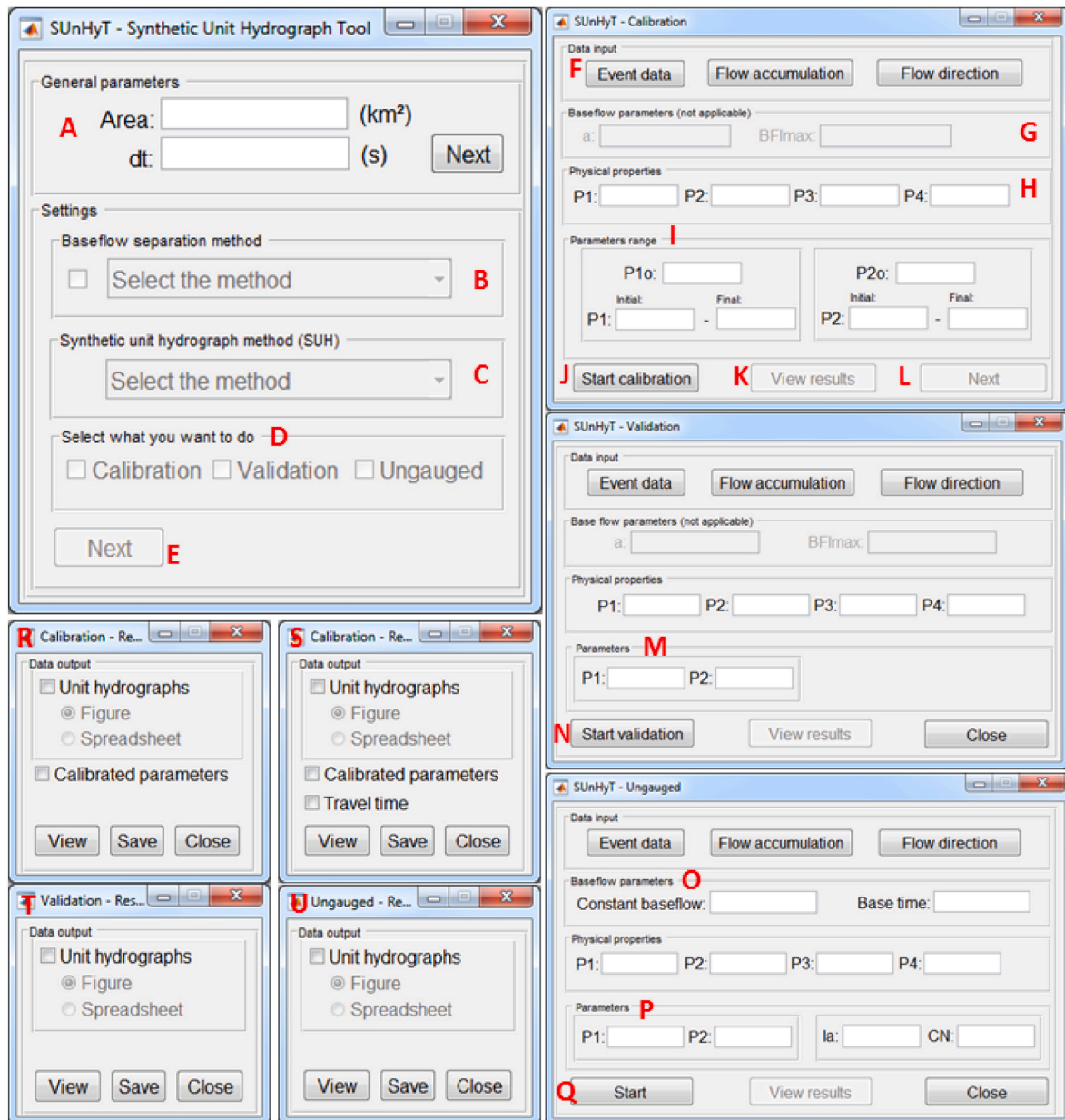


Fig. 2. The graphical user interface of the calibration, validation, ungauged, and data visualization and saving modules available at SUNHyT. Identified with letters are the components of the GUI.

saving the results, the user must confirm and specify the location and filename for the saved files.

S – Visualization of calibration results (Kirkby’s method): The results display window of the Kirkby method offers the same viewing and saving options as other methods, with an additional feature that allows users to view water travel times in the river and on the hillslopes. The procedures for saving the calibration results and statistics are the same as those for other methods.

T – Visualization of validation results: The resources for viewing and saving validation results, as well as the procedures for these tasks, are the same as those described in sections R and S.

U – Visualization of ungauged results: The resources and procedures for viewing and saving results in ‘Ungauged’ mode are the same as those presented in topics R and S above.

4. SUNHyT case study: Ribeirão Grande Catchment

We used SUNHyT to determine the Unit Hydrograph (UH) of the Ribeirão Grande Catchment (RGC). RGC is in southern Brazil (Fig. 3a) and it is the largest catchment that flows into the Peri Lake (Fig. 3b), with 5.3 km². Peri Lake is the largest source used for water supply on the Island of Florianópolis. RGC is located in the transition between tropical and temperate climates, with hot summers, no dry season, and the average annual precipitation of 1500 mm. RGC is covered by Atlantic Rainforest in two different stages, advanced and initial. The average elevation of RGC is 195 m, which ranges from 32 to 374 m. At the RGC outlet there is a water level sensor with a 1-h time discretization (Fig. 3).

The physical characteristics of RGC, as detailed in Table 3, were calculated using the digital elevation model provided by the Santa Catarina Department for Sustainable Development (SDS/SC) with 1-m spatial resolution (SDS, 2013).

In this case, all three modules of the tool, “Calibration”, “Validation”,

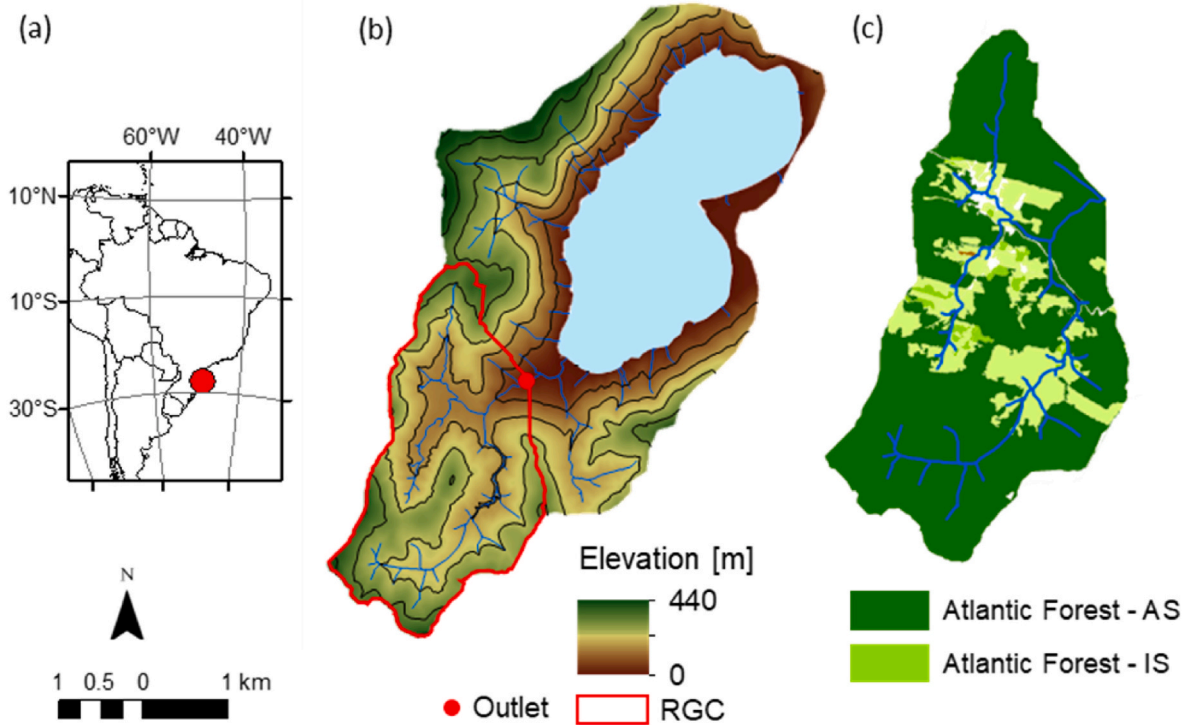


Fig. 3. Ribeirão Grande Catchment. (a) Location of Ribeirão Grande Catchment in South Brazil; (b) digital elevation map of Peri Lake Experimental Catchment, contours are shown at 70 m intervals, where RGC is Ribeirão Grande Catchment; and (c) land cover, where AS is advanced stage and IS is initial stage.

Table 3

Ribeirão Grande catchment physical parameters. Where A [km²] is the area, L [km] is the main stream length, L_c [km] is the distance from the catchment outlet to a point on the main stream nearest to the center of the catchment area, R_b [-] is Horton law of stream number, R_l [-] is the law of stream length, R_a [-] is the law of stream areas.

A	L	L_c	R_l	R_b	R_a
5.30	3.15	2.11	2.14	3.98	4.17

and “Ungauged”, were used. Two events were selected as input data (the events are available with the program). All UH models were used for this analysis. Two events were selected, ‘event_calibration.txt’ was used for calibration, and ‘event_validation.txt’ was used for validation. Hypothetical precipitation was utilized to estimate the hydrograph in the “Ungauged” module.

The digital baseflow filter by Eckhardt (2005) was selected with the following parameters: $\alpha = 0.995$ and $BFI = 0.80$. For UH calibration, the initial, maximum and minimum values chosen for the parameters were respectively: 1000, 10 and 10000 m h⁻¹ for v_r , and 10, 100 and 1000 m h⁻¹ for v_h . The optimal value was 6108 m h⁻¹ or 1.69 m s⁻¹ (v_r) and 48 m h⁻¹ or 0.01 m s⁻¹ (v_h) (Fig. 4c). The water travel time is longer on the hillslope than on the river (Fig. 4c).

Fig. 4 shows that calibration and validation processes resulted in a good fit with the observed data. When calibrating and validating all models, it is evident that no class (traditional, conceptual, probabilistic, or geomorphological) outperformed the others in either calibration or validation, as indicated in Table 4.

The poorest calibration results were obtained for the conceptual model proposed by Zoch (1934). This was expected because Zoch (1934) considers that the catchment is just one reservoir, whereas Nash (1957) views it as a collection of reservoirs. This catchment can be represented as 1.28 reservoirs and decay of 2.63 h (Table 4). Despite sharing the same theoretical foundation, the calibration of the velocity parameter ‘ v ’ varied between Rosso (1984) and Rodríguez-Iturbé (1979) (Table 4).

We measured discharge and velocity 43 times in 21 cross-sections of PLEC (Innocente dos Santos et al., 2021). Velocities ranged from 0.01 to 1.33 m s⁻¹ and discharges from 0.12 to 337.5 L s⁻¹. With these discharge measurements, we were able to establish the relationship between stream velocity and discharge as Bergstrom et al. (2016). Based on this relationship, the median velocity during the peak (Fig. 4a) was 0.64 m s⁻¹. Kirkby (1976) model overestimated the velocity of the river (1.69 m s⁻¹), while hillslope velocity was very low (0.01 m s⁻¹). It is possible that the velocity of the river is overestimated to compensate for the velocity in the hillslope. Rosso (1984) and Rodríguez-Iturbé and Valdes (1979) didn’t perform well, even though Rosso (1984) estimated a coherent hydrodynamic factor flow velocity (0.77 m s⁻¹).

In traditional models the values were not consistent with what was expected. The parameters of the Snyder (1938) model are out of the literature references (Table 2). While the time of concentration of Mockus (1957) is longer than that calculated by time of concentrations formulas: Kirpich (1940): 0.35 h; Chow (1962): 0.68 h; Johnsntone and Cross (1949): 1.35 h; and Dooge (1973): 0.95 h.

Nash (1957), TwoParLn and TwoParGamma have performed well, as these models are conceptual or probabilistic, there is no parameter related to the physical characteristics of the catchment.

When using the tool in the “Ungauged” module, it is possible to verify the impact that the parameters cause on the design hydrograph. For example, a design hydrograph is shown using the parameters calibrated for the case study (Fig. 5a) with Mockus (1957). The calibrated time of concentration is 3.6 h, the peak flow is 0.32 m³ s⁻¹, and the duration of the event is 26 h (Fig. 5b). If the time of concentration were 10 h, the peak flow would be lower, 0.25 m³ s⁻¹, and the event duration would be larger, 41 h (Fig. 5c). Conversely, if the time of concentration is reduced to 1 h, the peak flow would increase to 0.43 m³ s⁻¹, and the event duration would be shorter, at 16 h (Fig. 5d).

5. Conclusions

The Synthetic Unit Hydrograph Tool – SUNHyT implements nine

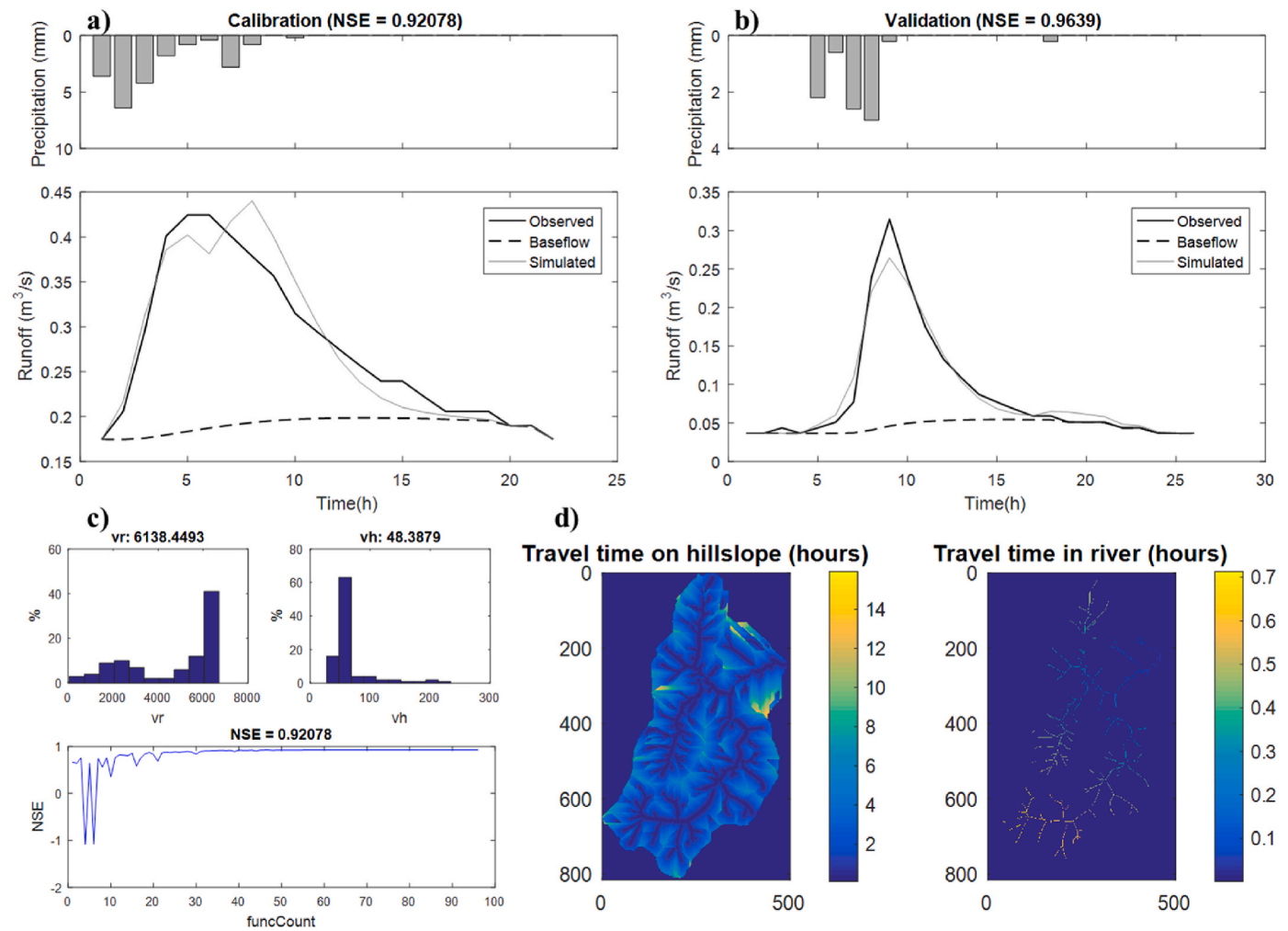


Fig. 4. Calibration and validation of the UH. a) Rainfall-runoff event calibrated using UH based in width function. b) Calibration parameters of UH based in width function. c) Rainfall-runoff event validated using UH based in width function. d) Travel time simulated by using UH based in width function.

Table 4

– Calibration (Cal) and validation (Val) results. Where TwoParLn is two-parameter log normal distribution, TwoParGamma is two parameter gamma distribution, t_c is the time of concentration, C_t , C_p , σ , μ , γ , α are dimensionless constants, n is the number of reservoirs, a dimensionless parameter, and k is the unit of time related to reservoir decay, v is the hydrodynamic factor flow velocity, v_r is the median velocity of water in the river and v_h is the median velocity of water in the hillslope.

UH	Parameters	Cal	Val
		Nash	Nash
Snyder (1938)	$C_p = 0.43$ $C_t = 0.13$	0.95	0.92
Mockus (1957)	$t_c = 3.59$ h $m = 1.74$ $k = 3.31$ h ⁻¹	0.92	0.96
Zoch (1934)		0.83	0.80
Nash (1957)	$n = 1.28$ $k = 2.63$ h ⁻¹	0.92	0.95
TwoParLn	$\sigma = 0.65$ $\mu = 1.11$	0.92	0.96
TwoParGamma	$\gamma = 2.63$ $\alpha = 1.28$ $v = 0.10$ m s ⁻¹	0.92	0.96
Rodriguez-Iturbé and Valdes (1979)		0.85	0.82
Rosso (1984)	$v = 0.77$ m s ⁻¹	0.85	0.82
Kirkby (1976)	$v_r = 1.69$ m s ⁻¹ $v_h = 0.01$ m s ⁻¹	0.95	0.96

different UH models from four different classes: traditional, conceptual, probabilistic, and geomorphological. SUNHyT can be used intuitively through a graphical user interface, developed in the MATLAB. This tool combines a wide range of UH methods into one user-friendly tool, with the potential to enhance the use of various UH theories and models within the academic, research, and engineering communities. The ungauged module, in addition to estimating hydrographs in ungauged catchments, also provides the user with the experience of being able to visually check the impact of each parameter of UH on the storm hydrograph.

In the case study, we tested the most robust synthetic unit hydrograph for rainfall-runoff simulation in a subtropical forest. All UH performed well, but the advantage of the GIUH and WFIUH is that the parameters have a clear interpretation with respect to flow velocity. A suitable WFIUH approach for understanding and application in ungauged catchments, could certainly be employed, and SUNHyT, as an open tool, provides the foundation for exploring this issue. We highlight the importance of testing the performance of multiple UH models to ensure adequate performance in rainfall-runoff modeling.

SUNHyT is a valuable tool for hydrologists, engineers, researchers, and decision-makers in water management. It integrates multiple UH approaches, promoting the adoption of ensemble methods to address the inherent uncertainty in rainfall-runoff models. Additionally, the calibration tool simplifies the process of identifying the most suitable UH model for a specific application.

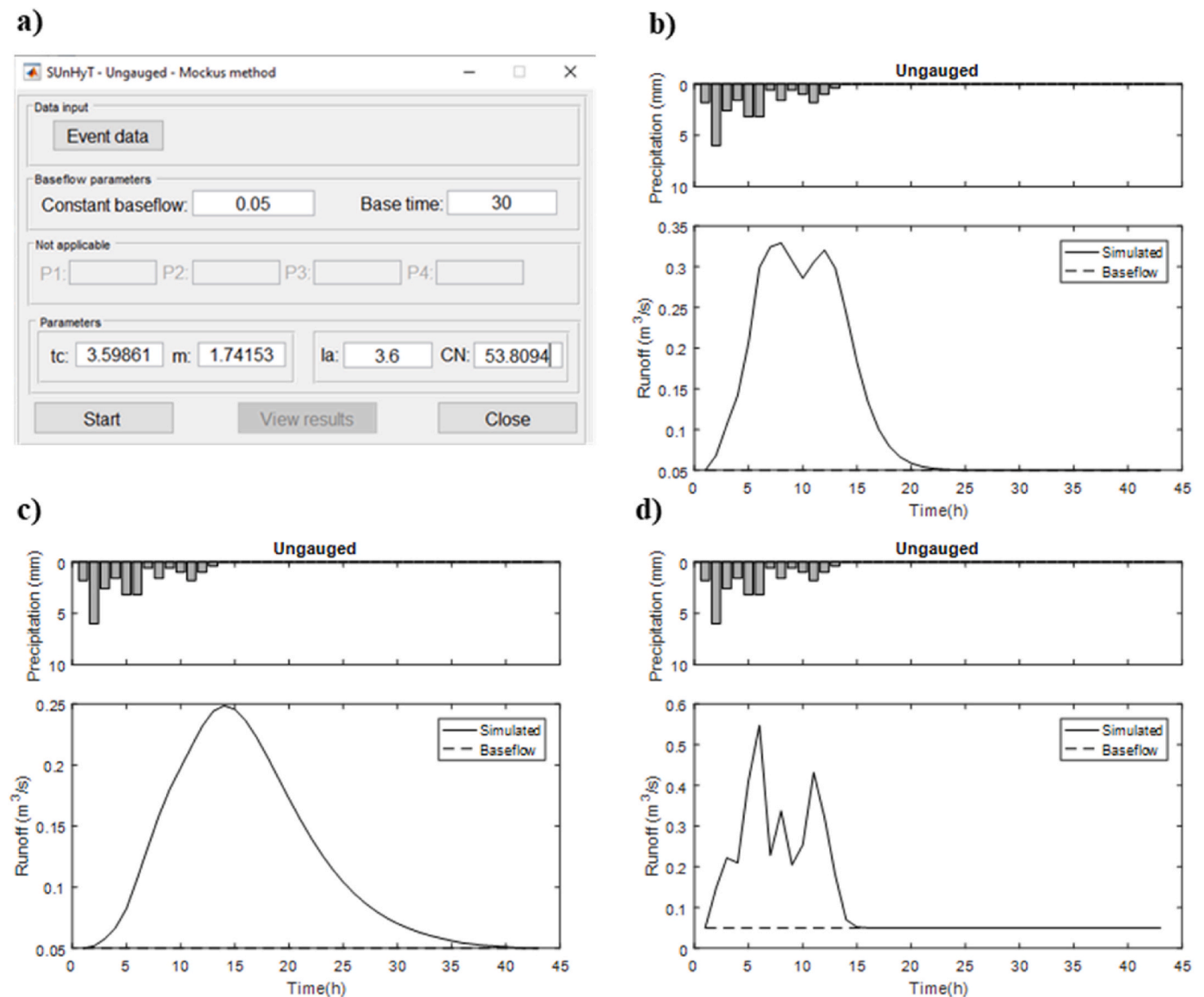


Fig. 5. Simulation of designed hydrographs: a) The interface of the Ungauged module with the calibrated parameters of the Mockus model. b) Design hydrograph to calibrated parameters in a). c) Design hydrograph to calibrated parameters but with the time of concentration (t_c) set to 10 h. d) Design hydrograph to calibrated parameters but with a time of concentration (t_c) as 1 h.

Computer code availability

- Name of code: SUNHyT
- Developers: Camyla Innocente dos Santos and Tomas Carlotto
- Contact address: camylainnocente@gmail.com
- Year first available: 2023
- Software required: MATLAB® version 2014b or later
- Program language: MATLAB®
- Program size: 672 KB
- Details on how to access the source code: The proposed tool is available on <https://github.com/LabHidro/SUNHyT>

CRediT authorship contribution statement

Camyla Innocente dos Santos: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tomas Carlotto:** Writing – original draft, Software. **Leonardo Vilela Steiner:** Validation, Conceptualization. **Pedro Luiz Borges Chaffe:** Writing – review & editing,

Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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