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A parsimonious geomorphological unit hydrograph for rainfall-runoff modelling in small ungauged basins

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A parsimonious geomorphological unit hydrograph for rainfall–runoff modelling in small ungauged basins

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Abstract In this study, a parsimonious hydrological modelling algorithm is proposed based on the automated DEM-based geomorphic characterization of runoff dynamics in scarcely monitored river basins. The proposed approach implements the instantaneous unit hydrograph (IUH) concept, estimated using the width function (WF), for characterizing the travel time distribution using just one parameter, the river network flow velocity. Hillslope velocities are defined using spatially-distributed empirical formulas based on slope and soil-use information extrapolated from digital topographic data. Case studies are presented for testing model performance and comparing simulated and observed hydrographs of 25 selected flood events, as well as investigating the differences with the geomorphological instantaneous unit hydrograph (GIUH) model results. The calibration of the WFIUH channel flow velocity parameter using the concentration time is investigated providing interesting insights for the use of such a method for hydrological prediction in ungauged basins.

Key words rainfall–runoff models; GIS; GIUH; WFIUH; DEM; terrain analysis; unit hydrograph; ungauged basin; small basin

Un hydrogramme unitaire géomorphologique parcimonieux pour la modélisation pluie-débit dans les petits bassins non jaugés

Résumé Dans cette étude, nous proposons un algorithme de modélisation hydrologique parcimonieux de la dynamique des eaux de ruissellement dans les bassins fluviaux peu jaugés, basé sur la caractérisation géomorphologique automatisée à partir d'un modèle numérique de terrain (MNT). L'approche proposée met en oeuvre l'hydrogramme unitaire instantané (HUI), estimé à partir du concept de la fonction largeur (FL), pour caractériser la distribution des temps de parcours en utilisant un seul paramètre, la vitesse des rivières du réseau, alors que les vitesses sur les versants sont définies en utilisant des formules empiriques distribuées dépendant de la pente et de l'utilisation du sol extrapolés à partir de données topographiques numériques. Des études de cas permettent de tester les performances du modèle et de comparer les hydrogrammes simulés et observés de 25 crues sélectionnées, ainsi que d'étudier les différences avec les résultats de l'hydrogramme unitaire géomorphologique instantané (HUGI). On a étudié le calage du paramétre de vitesse d'écoulement utilisant le temps de concentration, et fourni un aperçu intéressant de l'utilisation de cette méthode pour la prévision hydrologique dans les bassins non jaugés.

Mots clefs modèle pluie-débit; SIG; HUGI, MNT; analyse de terrain; hydrogramme unitaire; bassin non jaugé; petit bassin

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INTRODUCTION

Rainfall–runoff modelling in small ungauged basins (SUB) is a relevant topic in hydrology, with specific regard to the estimation of the synthetic design hydrograph (SDH) that plays the major role in flood mapping projects for SUB. The *a priori* floodplain identification is, in fact, the main non-structural flood protection system for SUBs given the limited time that occurs between the rainfall impulse and the flooding, making the use of real-time alert and evacuation systems impossible. Among the different rainfall–runoff models, the instantaneous unit hydrograph (IUH) is particularly efficient for SUBs that respect well the physics of the impulsive response and the spatial homogeneity of the rainfall forcing—mandatory conditions for the application of the IUH method in contrast with widely-used, spatially-distributed hydrological models that are more suited for large data-rich basins.

In this study, the term *small* refers to basins with drainage areas less than 150–200 km^2, for which it is reasonable to accept the linear theory of the IUH (Dooge 1973), and the term *ungauged* means that runoff observations are lacking. However, nowadays digital elevation models (DEM) and land-use data (i.e. CORINE 2000) are always available at high resolution and precision and hydrological modelling approaches that optimize their use, such as the GIUH (Rodriguez-Iturbe and Valdes 1979, Gupta *et al.* 1980, Rodriguez-Iturbe *et al.* 1982) and the WFIUH (Mesa and Mifflin 1986, Rinaldo *et al.* 1991, 1995, Naden 1992, Rodríguez-Iturbe and Rinaldo 1997, Giannoni *et al.* 2005, Kumar *et al.* 2007, Noto and La Loggia 2007), are able to provide an accurate and reliable representation of the hydrological forcing and dynamics for SUBs.

This paper is organized as follows: in the following section, the background and objectives of this work are presented, introducing the methodology descriptions. Then, selected study areas and data are described, followed by the presentation of test results, comments and concluding remarks.

Background and objectives

The geomorphological IUH (GIUH) and the width-funtion IUH (WFIUH) are rainfall–runoff models based on the geomorphically-based representation of the IUH function. The GIUH characterizes the IUH function by interpreting the hydrological behaviour of the stream network by means of Horton ratios and by lumping the complex properties of the runoff production kinematic mechanism using an averaged channel velocity that is generally demonstrated to be treated as a non-physical calibration parameter (Franchini and O'Connel 1996). The WFIUF incorporates the spatial distribution of the hillslope and channel runoff dynamics at the basin scale into the IUH by means of the fully distributed residency time function or width function (Rodríguez-Iturbe and Rinaldo 1997) that is calibrated using physically-based surface flow velocity parameters. As a result, in both approaches the automated estimation and calibration of the runoff travel velocity distributed field at the hillslope, floodplain and channel scales controls the SDH results.

In this study, we extend the results of a recent contribution (Grimaldi *et al.* 2010) that demonstrated the potential for the automatic definition of the hillslope flow velocity based on empirical schemes by investigating the implementation of an experimental parsimonious geomorphic IUH for which the only physical calibration parameter is the river channel velocity, introducing the so-called one-parameter WFIUH, namely WFIUH-1par.

This work also investigates the use of the basin concentration time for automatically estimating the river channel velocity, paving the way to the potential automatic calibration of the rainfall–runoff WFIUH-1par model.

METHODOLOGY

The proposed methodology is based on two main steps: (1) implementation of advanced terrain analysis techniques for DEM pre- and post-processing to estimate river basin main hydrological and geomorphic features with specific regard to the river network and the width function (WF) as well the Horton ratios needed for the application of both the GIUH and WFIUH-1par; and (2) GIUH and WFIUH-1par implementation at the flood event scale convolving the space-invariant rainfall and the WF for estimating the corresponding hydrograph, and tuning (i.e. calibrating) the river flow velocity parameter to match the observed time of concentration estimated from rainfall–runoff measurements. While the general schematic of the methodology is represented in the flow chart of Fig. 1, the two main steps and related sub-steps are hereafter also described in detail.

1. The first step includes the use of advanced DEM pre-processing techniques for the identification of the drainage network. Terrain analysis procedures

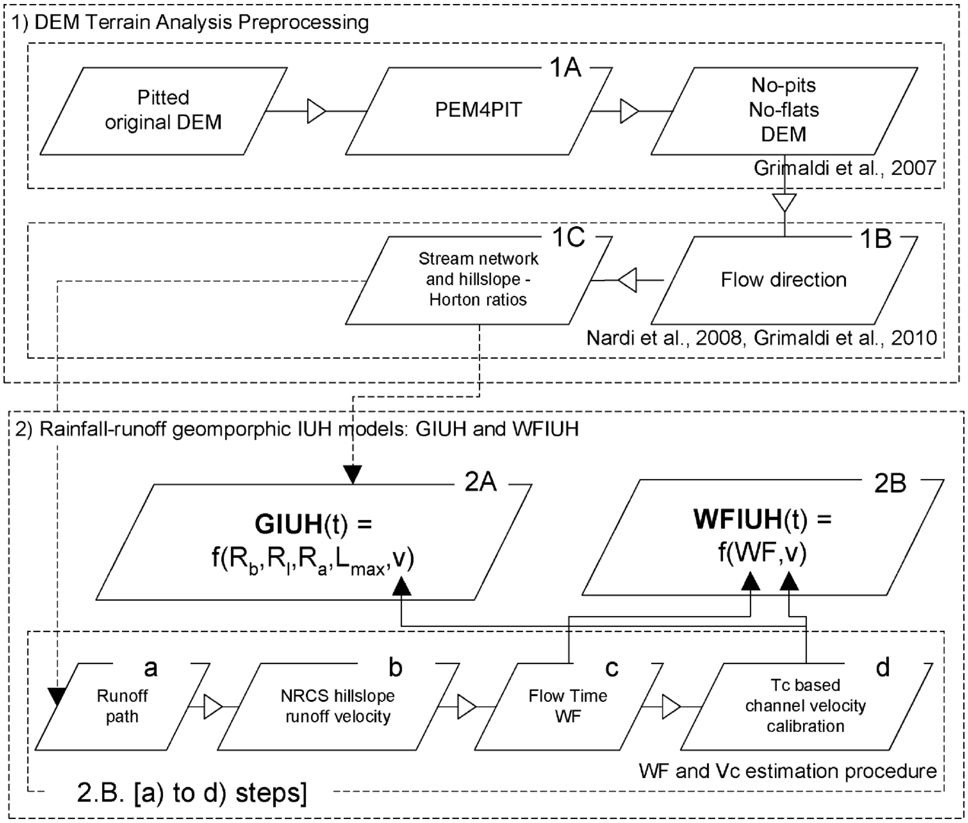

Fig. 1 Flow chart of the proposed methodology for the DEM-based estimation of the GIUH and WFIUH models based on the automated calibration of the channel flow velocity parameter using the time of concentration.

are particularly important when automating the extraction of river basin geomorphic parameters using digital topography. There is extensive literature regarding this step (Rulli and Rosso 2002, 2005, 2007, Grimaldi *et al.* 2007, 2010, Nardi *et al.* 2008, Santini *et al.* 2009). The selected methods for pit and flat areas removal, flow direction definition and automatic blue line extraction are extensively described in Nardi *et al.* (2008) and include in particular:

(a) pit and flat area removal using the PEM4PIT method (Grimaldi *et al.* 2007, Santini *et al.* 2009);
(b) flow direction definition using an optimized single flow direction method (Nardi *et al.* 2008);
(c) drainage network extraction using the drop analysis approach (Tarboton *et al.* 1991, Tarboton and Ames 2001), hillslope identification and estimation of Horton ratios R_b, R_l, and R_a (bifurcation, length and area ratios) and $L_{\max}$ (that is the maximum order river link length).

2. The second step includes the application of the GIUH or WFIUH-1par approaches based on the following steps:

   (a) Estimation of the GIUH by applying the Rosso (1984) scheme as follows:

$$\mathrm{GIUH}(t) = \frac{1}{k\Gamma(n)}\left(\frac{t}{k}\right)^{n-1} \mathrm{e}^{-t/k} \tag{1}$$

$$n = 3.29{R_b}^{0.78}{R_a}^{-0.78}{R_l}^{0.07} \tag{2}$$

$$k = 0.70\frac{L_{\max}}{v}{R_b}^{-0.48}{R_a}^{0.48}{R_l}^{-0.48} \tag{3}$$

where v is the channel velocity that is quantified constraining the T_c value to the 99% cumulative GIUH, as suggested by Franchini and O'Connell (1996) that also found that v is generally not defined representing the physics of channelized runoff, but it is rather a calibration parameter.

(b) Estimation of the WFIUH-1par based on the following equation:

$$\mathrm{WFIUH}(t) = \mathrm{FT} = \frac{L_c(x)}{v_c(x)} + \frac{L_h(x)}{v_h(x)} \quad (4)$$

where FT is the flow time, L_c and L_h are respectively, the channel and hillslope flow path for the generic cell *x,* with $x = 1$ to *n* which is the number of basin cells, and v_c and v_h are channel and hillslope flow velocities estimated as explained below.

While the estimation of the residency time distribution generally requires two time-invariant values for the hillslope and channel velocities (Franchini and O'Connell 1996, Botter and Rinaldo 2003, Saco and Kumar 2004, Giannoni *et al.* 2005), the WFIUH is here defined by automating the hillslope velocity estimation and consequently calibrating the channel flow component implementing the following four steps:

(i) Runoff paths (also known as flow length, FL) are measured for each location of the basin along the pre-defined topography-controlled flow direction that is based on a single flow approach for channels and on a multiple flow algorithm for hillslopes (Nardi *et al.* 2008);

(ii) The hillslope runoff velocity component is defined as in Grimaldi *et al.* (2010), where the NRCS (NRCS 1997) and Maidment *et al.* (1996) approaches were tested and compared, demonstrating the validity of the NRCS approach that is applied here. The NRCS scheme defines the hillslope flow velocity using the formula:

$$v_h = a\sqrt{S} \quad (5)$$

where v_h is the flow velocity in the single hillslope cell, *S* is the cell slope, and *a* is a coefficient related to soil use (Haan *et al*. 1994, McCuen 1998). To reduce potential overestimation, for $S > 0.04$, the formula (5) is applied with (UDFCD 1990):

$$S' = 0.05247 + 0.06363S - 0.182\mathrm{e}^{-62.38S} \quad (6)$$

To avoid unrealistic values and biased results due to a particular combination of slope and soil use, a further reasonable condition is applied, restricting the resulting velocity values within the 0.02–2 m/s range (Grimaldi *et al.* 2010).

(iii) Rescaling the FL by associating to each single runoff path its corresponding flow velocity to obtain the so-called flow time (FT) that is the probability distribution of the time required for rainfall drops, not infiltrated or intercepted, to reach the basin outlet. Hillslopes are associated to the flow velocity defined as in (ii), while the channels are treated as explained in the following sub-step.

(iv) Calibrating the channel flow velocity using the time of concentration (T_c). As a result, the WFIUH-1par channel velocity is estimated so that the abscissa of the maximum FT is equal to T_c for a given flood event. In SUB applications the T_c is estimated using empirical formulas or more detailed approaches (see for instance McCuen 2009). In this study, to better evaluate the model performances excluding the bias of relying on further empirical modelling techniques we estimated T_c using observed data.

Study areas and flood event data

Five study areas were selected pertaining to different climatic regions, and with drainage areas varying from 13 to 150 km^2 and including a significant number of observed flood events: four SUBs in Texas (USA): the Cow Bayou SUB 4, near Bruceville (five rainfall–runoff events observed from 1965 to 1975); the Escondido Creek SUB 11, near Kennedy pertaining to the San Antonio basin (five rainfall–runoff events observed from 1962 to 1970); the North Creek near Jacksboro within the Trinity basin (seven rainfall–runoff events observed from 1962 to 1974); and the North Elm Creek near Cameron (five rainfall–runoff events observed from 1965 to 1970) pertaining to the Brazos basin; and one in northern Italy, the Mastallone basin near Ponte Folle of the Sesia–Po river system (three rainfall–runoff events observed from 1964 to 1981). Digital elevation models and ancillary data (i.e. land use) for the four US basins, classified as small rural watersheds with limited human activity, were gathered from the US Geological Survey (USGS) National Map Seamless Server (http://seamless.usgs.gov/) at a spatial resolution of 30 m and floating point precision. Further information on these basins is available within the Synthesis of Rainfall and Runoff Data publication for the Texas Department of Transportation Research Projects 0–4193 and 0–4194 (Asquith *et al.* 2004). The Italian basin DEM was provided by the Italian

Table 1 Morphometric properties of the five selected basins. Statistics for elevation and slope are calculated considering a sample of all the basin single cell elevation values and the local downslope is estimated by considering the elevation difference along the flow direction.

	Cow Bayou	Escondido Creek	North Creek	North Elm Creek	Mastallone
Outlet	Sub. 4 near Bruceville	Sub. 11 near Kennedy	Jacksboro	Cameron	Ponte Folle
Basin	Brazos	San Antonio	Trinity	Brazos	Sesia-Po
Country	Texas, USA	Texas, USA	Texas, USA	Texas, USA	Piedmont, Italy
Latitude	31°19′59″N	28°51′39″N	33°16′57″N	30°55′52″	46°01′40″N
Longitude	97°16′02″W	97°50′39″W	98°17′53″W	97°01′13″W	8°41′16″E
Area (km^2)	13.08	22.8	58.96	119.46	148.47
Min elevation (m)	180.3	92.1	312.4	100.9	489.0
Max elevation (m)	266.3	138.4	439.7	188.0	2478.0
Mean elevation (m)	223.5	114.6	373.6	144.5	1318.3
Max slope (°)	21.4	13.7	23.7	12.2	80.9
Mean slope (°)	3.4	1.7	3.0	0.8	36.1
Main channel length (km)	7.09	8.00	18.02	33.34	27.47
Maximum divide–outlet distance (km)	7.35	8.63	18.47	35.55	28.83
Max order (-)	4	4	6	3	4

Geographic Military Institute (IGMI 2003) at a spatial resolution of 20 m and integer precision, while the land cover was extracted from the European CORINE database (CORINE 2000). Table 1 summarizes the main geographic and morphometric properties of the five selected basins.

The available 25 flood event data are processed to estimate the direct runoff, the rainfall excess and the concentration time by implementing the following three steps:

1. Recursive filter application for total runoff estimation (Lyne and Hollick 1979, Nathan and McMahon 1990):

$$Q_d(t) = \beta Q_d(t-1) + \frac{1+\beta}{2}\left[Q(t) - Q(t-1)\right] \tag{7}$$

   where $Q(t)$ and $Q(t-1)$ are the total runoff at time t and $t-1$, $Q_d(t)$ and $Q_d(t-1)$ are the direct runoff at time t and $t-1$ (for $t = 0$ the runoff equals zero) and β is the recursive filter parameter, calibrated to match the observed hydrograph recession curve. The recursive filter is passed three times (forward–backward–forward) to minimize the phase distortion effect on the peak (Nathan and McMahon 1990, Serinaldi and Grimaldi 2011).
2. From the direct runoff total volume, the rainfall excess is estimated using the Soil Conservation Service Curve Number (SCS-CN) method (USDA-SDS 1986, Chow *et al.* 1988); the CN parameter is estimated by comparing the total excess rainfall volume to the total direct runoff volume.
3. The concentration time T_c is estimated using flood rainfall and runoff by applying the theoretical definition (McCuen 2009; Grimaldi *et al.* 2012) and, thus, measuring the time lapse from the end of rainfall excess to the inflection point of the total storm hydrograph.

The selected rainfall–runoff events are listed with their corresponding properties in Table 2.

RESULTS AND COMMENTS

Case studies show performances of the WFIUH-1par and the GIUH models calibrated estimating T_c using observed data. The North Creek near Jacksboro case study is selected to represent comparative results. Figure 2 shows the simulated 6th-order (Strahler 1957) drainage network, defined using the proposed experimental procedure (Steps 1(a)–(c)), characterized by $L_{\max}$ of 4.68 km, and R_b, R_l, R_a ratios of 3.3, 1.81 and 3.53, respectively. The velocity distribution related to the flood event of May 1964, calibrated using the proposed method (Step 2(b)(iii)) with an observed concentration time of 365 minutes, is shown in Fig. 3. For this event, the non-significant portion (0.13%) of hillslope cell velocity values that were

Table 2 Data set of 25 rainfall–runoff observations for the four selected basins. CGRF: cumulated gross rainfall; CGRU: cumulated gross runoff; β: recursive filter parameter of formula (7); CNRU: cumulated net runoff; Gross *Q*max: maximum gross runoff; Net *Q*max: maximum direct runoff.

Event	Date (m/dd/yyyy)	CGRF (mm)	CGRU (mm)	β (-)	CNRU (mm)	Gross *Q*max (m^3/s)	Net *Q*max (m^3/s)
Cow Bayou							
1	03/29/1965	109.5	26.5	0.995	16.1	30.8	28.9
2	02/08/1966	60.7	18.9	0.988	9.1	37.9	35.8
3	04/24/1966	50.0	9.3	0.991	5.2	19.6	18.6
4	14/12/1969	55.4	13.9	0.993	8.2	8.9	7.6
5	02/01/1975	67.6	21.4	0.996	12.0	11.7	10.3
Escondido Creek							
1	12/02/1962	46.7	4.2	0.989	2.0	9.1	8.2
2	02/04/1965	74.2	7.5	0.998	5.9	9.1	8.5
3	09/19/1967	489.2	425.8	0.998	285.9	530.5	510.3
4	05/11/1968	119.4	30.2	0.997	20.7	22.2	20.4
5	05/31/1970	40.39	11.4	0.988	5.6	20.9	18.1
North Creek							
1	06/09/1962	108.7	58.9	0.996	44.1	234.8	220.9
2	09/07/1962	34.0	12.4	0.996	8.5	31.7	27.9
3	05/29/1964	114.8	22.8	0.997	16.8	48.6	45.8
4	11/18/1964	30.2	11.3	0.995	7.7	48.2	44.0
5	05/29/1967	63.5	13.8	0.998	10.5	34.3	32.0
6	05/11/1972	89.7	28.0	0.993	13.8	118.1	109.7
7	10/30/1974	69.9	25.9	0.994	11.2	58.8	57.7
North Elm Creek							
1	05/28/1965	74.42	47.3	0.999	40.6	158.6	152.9
2	11/30/1968	34.54	15.1	0.998	12.2	45.1	41.5
3	04/11/1969	56.64	52.0	0.998	36.8	200.9	187.7
4	02/06/1970	35.31	17.5	0.999	14.1	63.4	60.3
5	09/26/1970	36.32	8.3	0.999	6.7	20.2	18.6
Mastallone							
1	06/01/1964	130.5	102.5	0.996	32.6	234.9	181.6
2	08/01/1978	67.0	32.4	0.999	20.1	139.8	131.3
3	03/26/1981	344.0	295.2	0.999	193.4	377.9	355.3

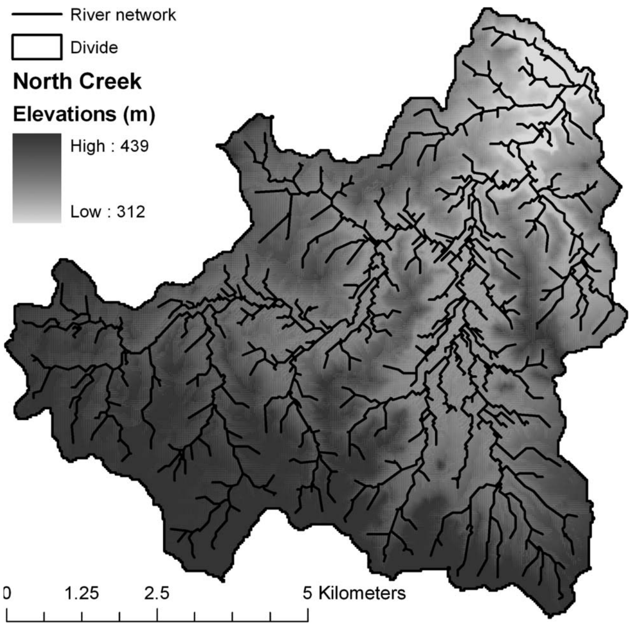

Fig. 2 Trinity River basin, North Creek near Jacksboro: DEM and drainage network.

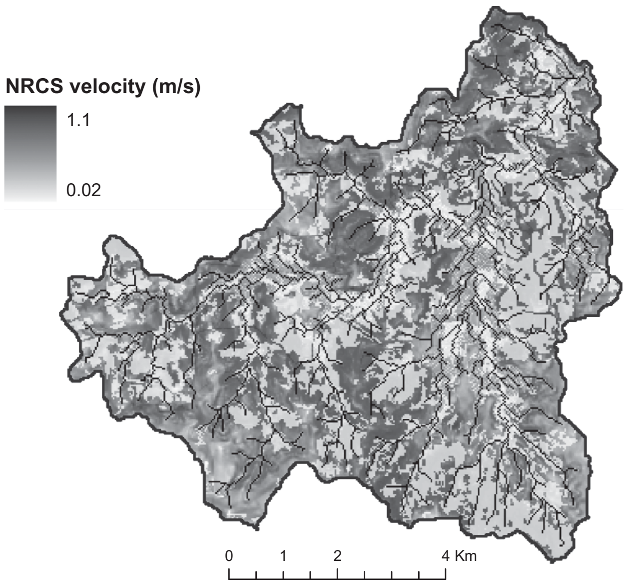

Fig. 3 Trinity River basin, North Creek near Jacksboro. Flow velocity spatial distribution estimated using the NRCS method related to the flood event of 05-29-1964.

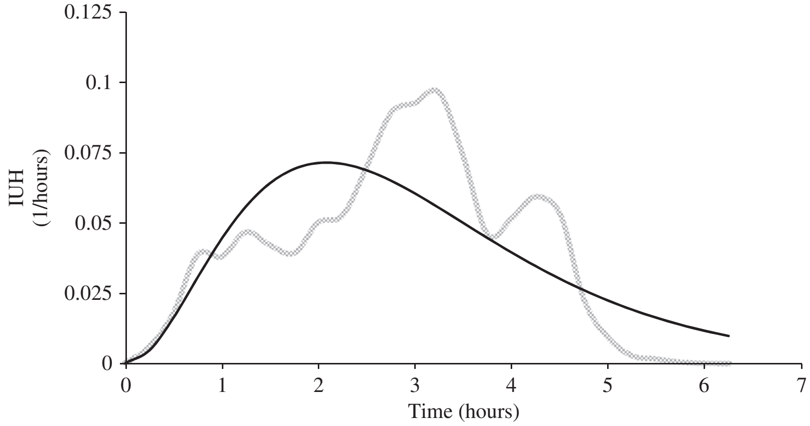

Fig. 4 Trinity River basin, North Creek near Jacksboro. WFIUH-1par (grey line) and GIUH (black line) hydrographs calibrated using observed flood event of 05-29-1964.

less than 0.02 m/s were filtered out. Figure 4 compares the two resulting IUHs for the same flood event, confirming the expected behaviour of a smoothed function for the GIUH and a more variable hydrograph for the WFIUH-1par that is better representing the heterogeneous runoff response strictly related to the topographic and hydrogeomorphic (e.g. stream network and hillslopes) properties.

Figure 5 shows comparative results for seven different events of the North Creek case study showing the simulated and observed hydrographs. It seems that the WFIUH-1par together with a more realistic shape is also better catching the runoff peak timing and intensity. It is interesting to note that, while both approaches provided comparable values for the simulated hydrograph properties in terms of peak discharge and base time, the shape of the curves are significantly different, determining a completely different dynamic of the flood volume distribution over time.

A summary of the model tests conducted for the five basins and the available observed flood events are given in Table 3, which includes the estimated calibration channel velocities, the percentage difference between observed and estimated peak flow, and the peak flow values for both approaches. The mean and the coefficient of variation (CV) related to the flood events of each basin are also included.

Figure 6 shows on a log–log plot the distribution of the differences between simulated (dots) and observed peak discharges (black curve). Simulated and observed values are placed on the *y*-and *x*-axis, respectively. The interpolated curve of observation separates the chart into two zones: overestimated and underestimated values are respectively on the left and right. Although the majority of the simulated values tend to underestimate, we believe this behaviour is not general, but probably linked with the direct runoff estimation methodology.

As a general comment on the results, it is noted that the distributed geomorphological information of the WFIUH-1par approach seems a good compromise between simplicity and accuracy, providing a better representation of the runoff dynamics than the GIUH approach in terms of a more detailed characterization of the timing of the flood hydrograph parameters, and in particular the base time and peak. The proposed approach, developed to optimize the estimation of the one and only WFIUH-1par calibration parameter, demonstrates that it could be particularly efficient for the SDH estimation in SUBs. Nevertheless, it is also noted that the time of concentration, on which the method heavily relies, still has an unpredictable and crucial role. See, for example, Fig. 7, representing the significant variability of the WFIUH-1par results with varying T_c values. Indeed, for the selected event it seems that the right T_c value is approximately 100 min, compared to the estimated 255 min value. This simple example clearly confirms the prominent role of T_c, which, especially in a SUB, and regardless of the rainfall–runoff scheme implemented, neglects the significant differences that in any case would occur between detailed or simplified schemes (e.g. WFIUH, GIUH *versus* the rational method for example).

CONCLUSIONS

In this study, an improved version of the geomorphological instantaneous unit hydrograph based on width function (WFIUH) is described. The innovative part of the proposed methodology

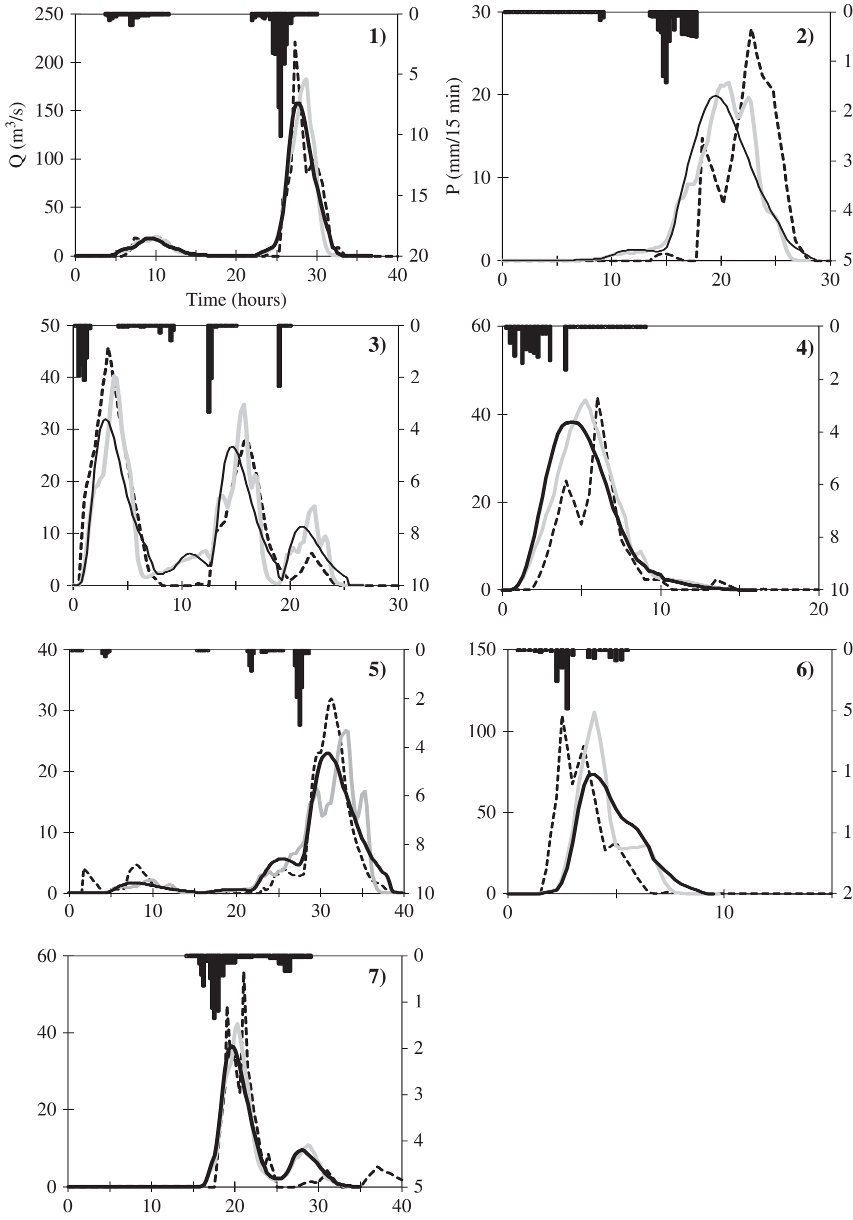

Fig. 5 Trinity River basin, North Creek near Jacksboro: comparison of observed (dotted line) with simulated hydrographs with the WFIUH-1par (grey line) and GIUH (black line).

pertains to the investigation of a parsimonious WFIUH, based on one physically-based parameter, the channel flow velocity. This gives birth to the so-called WFIUH-1par, while the other parameters are automatically estimated using DEM-based GIS algorithms and empirical formulas. This approach seems to be particularly useful for synthetic design hydrograph estimation in small and ungauged basins (SUB), where the lack of observations prompts the need for a simple procedure. The WFIUH-1par is tested and compared with the GIUH model for 25 rainfall–runoff flood events observed in five watersheds. The results provide interesting insights concerning the better performance of the WFIUH-1par model in determining a more realistic shape of the simulated hydrograph as well as in catching the multi-modal behaviour (e.g. multiple flow peaks), which are usually lumped in the GIUH. Case study applications are developed for estimating the channel flow velocity by using the basin concentration time

Table 3 Summary of results of selected flood events (ΔQmax represents the differences with observed data, v_c is channel flow, CV: coefficient of variation).

Event (-)	Date (mm/dd/yyyy)	Qmax (m^3/s): Observed	WFIUH-1par	GIUH	ΔQmax (%): WFIUH-1par	GIUH	v_c (m/s): WFIUH-1par	GIUH
Cow Bayou								
1	03/29/1965	28.9	13.7	14.4	−52.7	−50.2	0.51	0.78
2	02/08/1966	35.8	22.0	19.2	−38.5	−46.3	1.22	1.62
3	04/24/1966	18.6	12.8	11.8	−31.3	−36.7	1.45	1.84
4	04/12/1969	7.6	6.0	5.9	−21.4	−22.5	0.68	1.02
5	02/01/1975	10.3	6.5	6.9	−37.2	−33.2	0.45	0.70
Mean					−36.2	−37.8	0.9	1.2
CV					0.3	0.3	0.5	0.4
Escondido Creek								
1	12/02/1962	8.2	5.6	4.1	−32.2	−50.8	0.97	1.61
2	02/04/1965	8.5	6.9	6.2	−19.7	−27.0	0.62	1.32
3	09/19/1967	510.3	338.8	251.1	−33.6	−50.8	1.19	1.70
4	05/11/1968	20.4	14.4	14.6	−29.4	−28.3	0.43	1.08
5	05/31/1970	18.1	16.3	13.6	−9.9	−24.8	0.68	1.38
Mean					−25.0	−36.3	0.8	1.4
CV					0.4	0.4	0.4	0.2
North Creek								
1	06/09/1962	220.9	181.6	157.4	−17.8	−28.7	1.10	0.79
2	09/07/1962	27.9	21.4	19.9	−23.3	−28.7	0.60	0.48
3	05/29/1964	45.8	40.2	32.0	−12.2	−30.1	1.10	0.79
4	11/18/1964	44.0	43.2	38.2	−1.8	−13.2	1.00	0.73
5	05/29/1967	32.0	26.7	23.0	−16.6	−28.1	0.60	0.48
6	05/11/1972	109.7	111.6	73.4	1.7	−33.1	2.80	1.33
7	10/30/1974	57.7	42.2	36.3	−26.9	−37.1	1.25	0.90
Mean					−13.8	−28.4	1.2	0.8
CV					0.8	0.3	0.6	0.4
North Elm Creek								
1	05/28/1965	152.9	177.4	150.6	16.0	−1.5	1.96	1.18
2	11/30/1968	41.5	33.8	29.9	−18.5	−27.9	0.90	0.84
3	04/11/1969	187.7	166.8	153.4	−11.1	−18.3	2.98	1.27
4	02/06/1970	60.3	49.4	42.6	−18.1	−29.5	1.05	0.91
5	09/26/1970	18.6	15.3	13.2	−17.8	−29.1	0.47	0.57
Mean					−9.9	−21.2	1.5	1.0
CV					1.5	0.6	0.7	0.3
Mastallone								
1	06/01/1964	181.6	108.1	109.1	−40.5	−39.9	0.86	1.57
2	08/01/1978	131.3	122.3	100.3	−6.8	−23.6	1.30	2.28
3	03/26/1981	355.3	285.6	274.6	−19.6	−22.7	0.78	1.43
Mean					−22.3	−28.7	1.0	1.8
CV					0.8	0.3	0.3	0.3

T_c extrapolated from observed data, posing the basis for the development of a completely automated procedure for automatically calibrating the WFIUH-1par. Nevertheless, it is important to note that T_c is particularly difficult to quantify, and results are significantly sensitive to the T_c uncertainty. As a result, future studies shall focus on an innovative unbiased procedure for the estimation of T_c.

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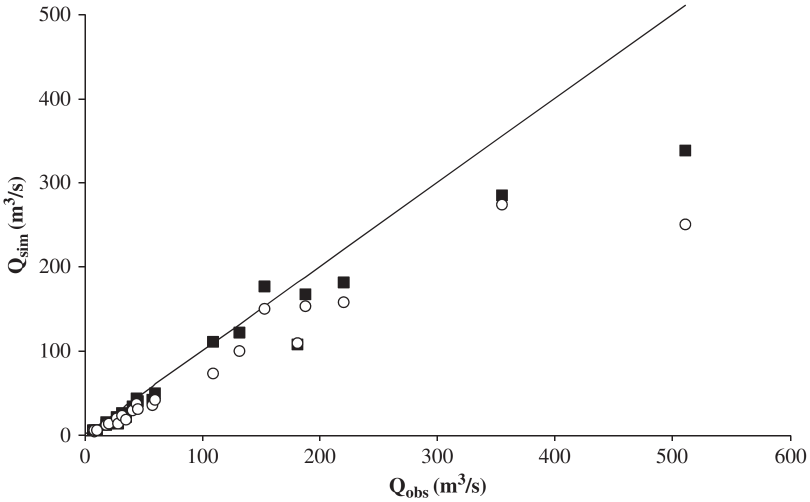

Fig. 6 Simulations *vs* observations plot: Comparison of WFIUH-1par (black squares) and GIUH (white points) discharges. The black line represents observed data.

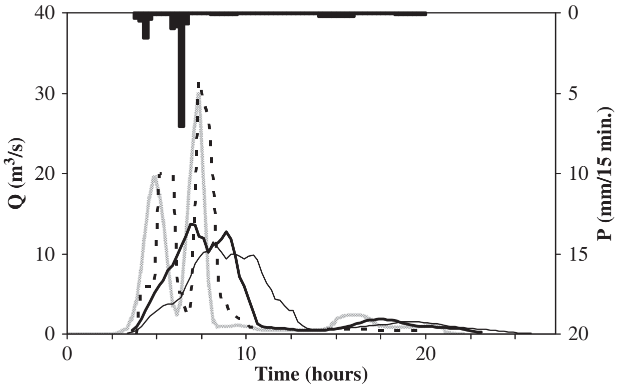

Fig. 7 Cow Bayou basin, 03/29/1965 flood event; comparison of observed hydrographs (dotted line) with WFIUH-1par results (dark grey: $T_c = 100$ min; heavy black: $T_c = 255$ min; light black: $T_c = 400$ min).

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