JOURNAL OF
ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 18 2010

IMPROVED HORTON-STRAHLER SCHEME FOR STREAM NETWORK CLASSIFICATION AND ITS IMPLEMENTATION IN THE METHOD OF GEOMORPHOLOGIC INSTANTANEOUS UNIT HYDROGRAPH

Gordan Prskalo

Faculty of Civil Engineering
University of Mostar
Mostar, Bosnia and Herzegovina

The Horton-Strahler scheme for stream network classification was introduced into hydrological practice in the middle of the last century. It found a significant application in the process of defining the Geomorphologic Instantaneous Unit Hydrograph (GIUH) as the method aiming to relate geomorphological characteristics of a basin to basin response in the form of unit hydrograph, or direct runoff hydrograph. The paper analyzes the problems related to its implementation in the GIUH method, i.e. to determination of initial and transition probabilities, which, in turn, are used to define the probability distribution function for water flow paths in the basin. Many authors have agreed that this classification is rather rough and in some cases leads to certain irregularities, i.e. inaccuracies. The particular problem is that negative values may also result when calculating initial and transition probabilities at higher stream orders. In this regard, the so-called Improved Horton-Strahler Scheme (IHSS) for classification of the hydrographic network has been proposed in the paper. The basic idea is that streams and hillslopes are classified in groups or orders according to flow paths. Thus, we avoided the averaging or uniform distribution of numbers and lengths of streams and hillslope areas to a number of flow paths, as is the case with the original Horton-Strahler scheme. The improved Horton-Strahler Scheme was applied to the catchment of the Brijesnica River in Bosnia and Herzegovina and the relevant unit hydrographs were calculated using the GIUH method.

INTRODUCTION

Assessment of characteristic values of flood, or defining of the response of a water basin to rainfall in an ungauged basin, is a complex hydrological problem. It is often very difficult to carry out such measurements, for the procedure is time-consuming and the lives of the people carrying them out may be at risk (Bonacci, 1983). For its solution, various theories and methods have been developed in hydrology. The purpose of rainfall-runoff modelling is the conversion of rainfall into runoff at the river basin outlet (Fleurant et al., 2006). One of certainly the most significant methods is the unit hydrograph theory proposed by Sherman in 1932 (Sherman, 1932). Although more than 75 years have passed since then, it has not lost its topicality to date. Introduction of new methods in analysis and synthesis of systems in hydrology in 1960s, methods for calculation and change of unit hydrograph theory have been supplemented and improved, but the underlying principles of Sherman's theory have practically remained unchanged (Hrelja, 2007).

The unit hydrograph and hence the direct runoff hydrograph is usually defined on the basis of rainfall and runoff data. However, since such data are not available for many basins requiring floodwater assessment (the case of Bosnia and Herzegovina), various alternative methods are used in trying to define unit hydrographs. A continuing problem in hydrology is the estimation of peak discharges for design purposes on catchments with only limited available data (Blazkov and Beven, 1986). In this respect, hydrological research was focused on establishing the connection between the geomorphologic characteristics of basin and the hydrological response of basin to rainfall. The idea of identifying a basin-scale transfer function from some geomorphological characteristics emerged in order to give physical basis to the UH (Cudennec et al., 2004).

In different ways, geomorphological basin characteristics were incorporated into appropriate unit hydrograph - or direct runoff hydrograph - calculation methods, e.g. by defining different geomorphological basin parameters (basin slope, basin shape factors, drainage density, stream frequency, etc.), relevant hydrographic network classifications (Scheidegger, 1968, 1968b; Tokunada, 1978; Knighton, 1984; Kirchner, 1993; Tarboton, 1996; Britton, 2002; Xiong and Li, 2004; Li et al., 2006; Zhang et al., 2007; Vogt and Foisneau, 2007;) or by the width function (Marani et al., 1994; Veneziano et al., 2000; Veitzer and Gupta, 2001; Puente and Sivakumar, 2003; Moussa, 2008).

A major step forward to that direction was made by Rodríguez-Iturbe and Valdes (1979) who introduced the concept of geomorphologic instantaneous unit hydrograph (GIUH), which was later generalized by Gupta et al. (1980), Rodríguez-Iturbe et al. (1982) and Gupta and Waymire (1983). Introduction of geomorphologic characteristics of basin into calculation was performed through analysis of stream network and basin, i.e. analysis of relevant parameters resulting from that analysis. From a number of hydrographic network classifications, Rodriguez-Iturbe and Valdes selected the Horton-Strahler scheme. For this scheme, Horton developed relevant expressions, the so-called Horton's morphometric parameters, which are used for the definition of GIUH (Rodríguez-Iturbe and Valdes, 1979; Gupta et al., 1980; Rosso, 1984; Beven, 1986; Gupta et al., 1986; Allam and Balkhair, 1987; Gupta and Mesa, 1988; Jin, 1992; Beven and Wood, 1993; E.F Rinaldo et al., 1995; Rodríguez-Iturbe and Rinaldo, 1997; Gupta and Waymire, 1998; Hall et al., 2001; Saco and Kumar, 2002; Bhunya et al., 2008; Rodriguez et al., 2005; Kumar et al., 2007; Singh et al., 2007; Lee et al., 2008).

Horton-Strahler's laws were extensively used in geomorphological applications to classify river systems to establish relations with the fractal nature of the channel network and to characterize scale properties (Moussa, 2009). Horton-Strahler's ordering scheme were also applied in other domains, such as coding binary trees, or establishing hierarchical structures of cities (Moussa, 2009).

This paper deals with improvement of the Horton-Strahler scheme of classification of the hydrographic network, or with influence of such network on characteristic values of the GIUH.

PROBLEMS RELATED TO IMPLEMENTATION HORTON-STRAHLER SCHEME IN GIUH METHOD

The GIUH method is based on the assumption that probability distribution of the travel time required for a raindrop to reach the basin outlet profile depends on the geomorphologic structure of stream network and hillslopes. In other words, the GIUH is interpreted as the probability distribution density function of the travel time for random raindrops h(t), uniformly distributed over the river basin, to reach the basin outlet profile and can be expressed as in Equation (1):

$$h(t)=\frac{d}{dt}P(T_B\le t)=\frac{d}{dt}\left[\sum_{s_n\in S}P\left(T_{s_n}\le t\right)\cdot P(s_n)\right] \tag{1}$$

where P(.) denotes the probability for the series in parentheses, T_B raindrop travel time to basin outlet, T_{s_n} raindrop travel time on the individual path s_n, $P(s_n)$ probability that raindrops will flow on the path s_n, $S=\{s_n\}$, n=1,2,3,... is the set of all possible paths by which raindrops can flow.

According to original Horton-Strahler scheme (OHSS) of hydrographic network, a raindrop travels on the basin surface making transitions from streams of lower order to streams of higher order. That transition can be comprehended as a change of state where the state is the order of the stream in which the raindrop currently travels. Progress states are defined as the position of a raindrop in a small part of the basin hillslope a_ω or stream r_ω of order ω in which the raindrop is found at time *t*.

To define the GIUH, it is necessary to know the probability distribution of flow paths $P(s_n)$,which is evident from Equations (1). If the stream network is to be classified according to the OHSS, then probabilities of flow paths are calculated according to Equation (2).

$$P(s_n)=\theta_i\cdot p_{ij}\cdot p_{jk}\cdots p_{l\Omega} \tag{2}$$

where θ_i is the probability that the raindrop will start its travel on the part of hillslope and drain toward i-order stream, p_{ij} is the probability of transition from stream of order i to stream of order j.

Rodriguez-Iturbe and Valdes (1979) demonstrated that probabilities of initial states θ_i and transition values p_{ij} are only functions of geomorphologic and geometrical properties of hillslope. The physical interpretation of these probabilities can be expressed as:

$$\theta_i=\frac{(total\ area\ draining\ into\ stream\ of\ order\ i)}{(total\ basin\ area)} \tag{3}$$

$$p_{ij} = \frac{(number\ of\ stream\ of\ order\ i\ draining\ into\ stream\ of\ order\ j)}{(total\ number\ of\ stream\ of\ order\ i)} \quad (4)$$

The number of possible flow paths $S=\{s_n\}$, depending on the highest order of the hydrographic network Ω can be calculated according to the Equation 5:

$$n = 2^{\Omega - 1} \quad (5)$$

The probability of a certain path actually represents the initial probability of order which is, for the purpose of its uniform distribution to various flow paths, corrected by multiplication with transition probabilities. Transition probabilities are also calculated assuming the uniform distribution of stream numbers to various flow paths. So, for example, in a highest-order stream $\Omega = 4$ there are eight flow paths. The probability forming method for these paths is shown in Figure 1.

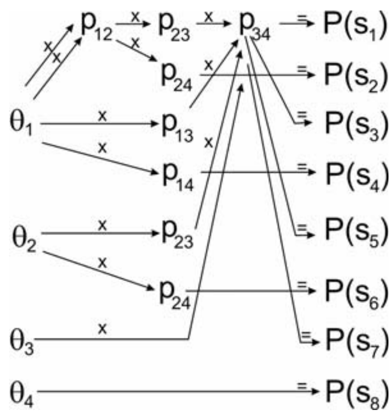

Figure 1. Example of forming of probabilities of flow paths according to the OHSS for Ω=4.

On the basis of such classification of hydrographic network, Gupta et al. (1980) offered equations for assessment of initial probabilities θ_i and for transition probabilities p_{ij} which are necessary for the calculation of flow path probability distribution and further for calculation of the GIUH ordinates.

Assuming the uniform distribution of rainfalls in a basin, initial probabilities are defined as the ratio of total area directly draining to stream of order i to total basin area:

$$\theta_i = \frac{N_i \overline{DA_i}}{A_\Omega} \quad (6)$$

where i is stream order; $\overline{DA_i}$ is mean area directly draining to stream of order i; A_Ω is the total area of basin; N_i is the number of streams of order i.

Thus, based on the previous equation, Gupta et al. (1980) gave the following equations:

$$\theta_1 = \frac{N_1 \overline{A}_1}{A_\Omega} \quad (7)$$

$$\theta_i = \frac{N_i}{A_\Omega}\left[\overline{A}_i - \sum_{\omega=1}^{i-1} \overline{A}_\omega \left(\frac{N_\omega p_{\omega i}}{N_i}\right)\right] \quad 1 \leq \omega \leq i \leq \Omega \quad (8)$$

or this is the mean value of the area directly draining to the stream of order i as well as its tributaries. In Equation (7), there is nothing unclear for a first-order stream in relation to the physical definition of initial probability, but Equation (8) for streams of order from 2 to Ω shows certain inaccuracies, i.e. it can yield negative values for higher orders (van der Tak, 1990).

Reasons for that are easier to understand if Equation (8) is written in the following form:

$$\theta_i = \frac{1}{A_\Omega}\left[N_i \overline{A_i} - \sum_{\omega=1}^{i-1} N_\omega \overline{A_\omega}\, p_{\omega i} \right] \tag{9}$$

For accurate value of initial probability, it is necessary to have precise values of the area directly draining to streams of order i.

The value $N_i \overline{A_i}$ is the cumulative value of the area, i.e. the value of the area draining to i-order stream and all its tributaries of order ω ($\omega < i$). In other words, to obtain the exact value of the area directly draining into i-order stream, it is necessary to deduce the area draining into tributaries of stream order ω ($\omega < i$). That is resolved in Equations (8) or (9) by using the transition probability $p_{\omega i}$ defined as the number of ω-order streams flowing into i-order streams divided by the total number of ω-order streams. Inaccuracy of Equations (8) or (9) is due to the assumption that the area draining into stream ω is uniformly distributed between different flow paths $S=\{s_n\}$, n=1,2,3,....

Gupta et al. (1980) also gave equations for the defining of transition probabilities that have physical meaning as in Equation (4)

$$p_{\omega i} = \frac{\left(N_\omega - 2N_{\omega+1}\right)E\left(i,\Omega\right)}{N_\omega \sum\limits_{k=\omega+1}^{\Omega} E\left(k,\Omega\right)} + 2\frac{N_{\omega+1}}{N_\omega}\delta_{\omega+1,i} \qquad 1 \le \omega \le i \le \Omega \tag{10}$$

where $d_{\omega+1,i}$ = 1 if $i = \omega+1$, $d_{\omega+1,i}$ = 0 if $i \neq \omega+1$.

$$E\left(i,\Omega\right) = N_i \prod_{\omega=2}^{i} \frac{N_{\omega-1}-1}{2N_\omega - 1} \quad i = 2,\ldots,\Omega \tag{11}$$

Also, Equations (10) and (11) are based on assumptions that result in certain inaccuracies. The other term in Equation (10) is unambiguous and applies to streams forming a higher order stream by their combining for $i = \omega+1$. Let us remember the original Horton-Strahler scheme (OHSS) or the case of two same-order streams connecting with each other and then forming a stream of a higher order, or of order higher by one. Thus in Equation (10) the portion of ω-order streams that do not create higher-order streams in the previously described way is N_ω-$2N_{\omega+1}/N_\omega$. So, the transition probability $p_{\omega i}$ is estimated as a product of this portion of stream number N_ω and assessed relative numbers of streams of order i in streams downstream from the ω-order stream, which is given by the part of Equation (10) $E\left(i,\Omega\right) / \sum\limits_{k=\omega+1}^{\Omega} E\left(k,\Omega\right)$. This assumption leads to error, and the basic reason is in the assumption that, like in initial probabilities, transitions from ω-order streams to a higher-order stream are uniformly distributed among different flow paths $S=\{s_n\}$, n=1,2,3,....

This problem can be overcome by appropriate hydrographic network classification method that allows grouping of streams and hillslopes according to flow paths that a raindrop will follow to basin outlet.

IMPROVED HORTON-STRAHLER SCHEME FOR CLASSIFICATION OF STREAM NETWORKS

According to the original Horton-Strahler scheme (OHSS) of hydrographic network classification, streams and hillslopes are separated into corresponding orders according to clearly established rules. However, the classification according to the OHSS does not provide data on numbers, lengths and areas of hillslopes of a single order for various flow paths. For that reason, in addition to defining initial probabilities, transition probabilities and corresponding equations based on stream numbers and lengths and hillslope areas in certain orders are also introduced, and all for the purpose of defining the flow path probability.

To this effect, an improvement to the OHSS is made in this paper in those streams and hillslopes that are assigned to groups according to flow paths. Namely, if analyzing a hydrographic network, it can be affirmed that a raindrop currently located on a hillslope or in a certain stream has a unique flow path to the outlet from the basin. Consequently, every hillslope or stream can be marked according to the path that raindrop will follow toward the outlet (Figure 2). This new classification is called the improved Horton-Strahler scheme (IHSS) of hydrographic network classification because it is based on the OHSS classification of streams into corresponding orders.

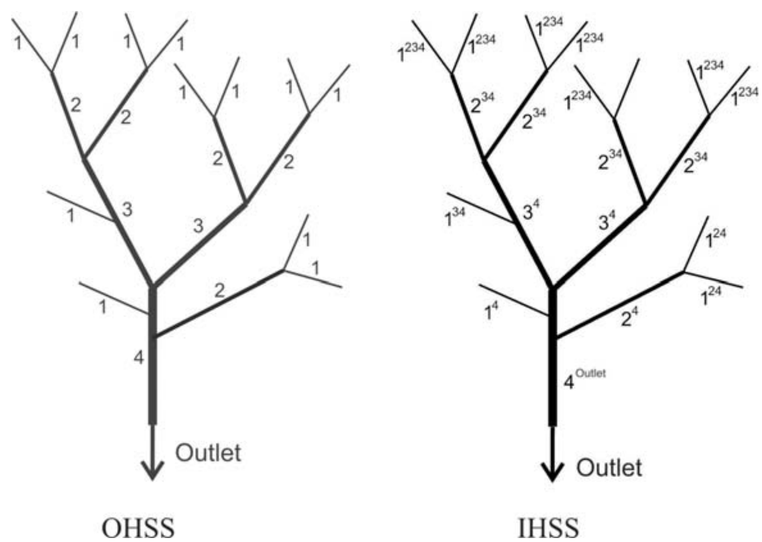

Figure 2. Example of the OHSS and IHSS of hydrographic network classification

The larger number in the stream mark indicates the stream number according to the OHSS, while the numbers in superscript denote orders of streams in which raindrop will travel to the outlet from the basin. In this manner, streams are grouped according to flow paths, i.e. every stream group according to the OHSS is divided into new groups according to the IHSS. Thus e.g. a stream group of first order according to the OHSS is now divided into four new stream groups according to the IHSS, specifically into streams of orders 1^{234}, 1^{24}, 1^{34} and 1^{4}. In a general case, the number of new groups according to the IHSS of a certain group of streams ω according to OHSS depends on the group order ω and highest order of basin Ω, and can be determined as:

$$\left(n_{NG}\right)_{\omega} = 2^{\Omega-\omega-1} \tag{12}$$

where $\left(n_{NG}\right)_{\omega}$ is the number of new groups of ω-order stream. It is clear that the total number of groups according to the IHSS is equal to the number of flow paths n and is defined by Equation (5).

Marking of hillslopes according to the IHSS is performed in the same manner (Figure 3). Individual hillslopes are assigned to groups according to marks of streams into which rainfall flows from them. In this manner we obtain groups of hillslopes from which rainfall flows to the basin outlet over particular drainage paths.

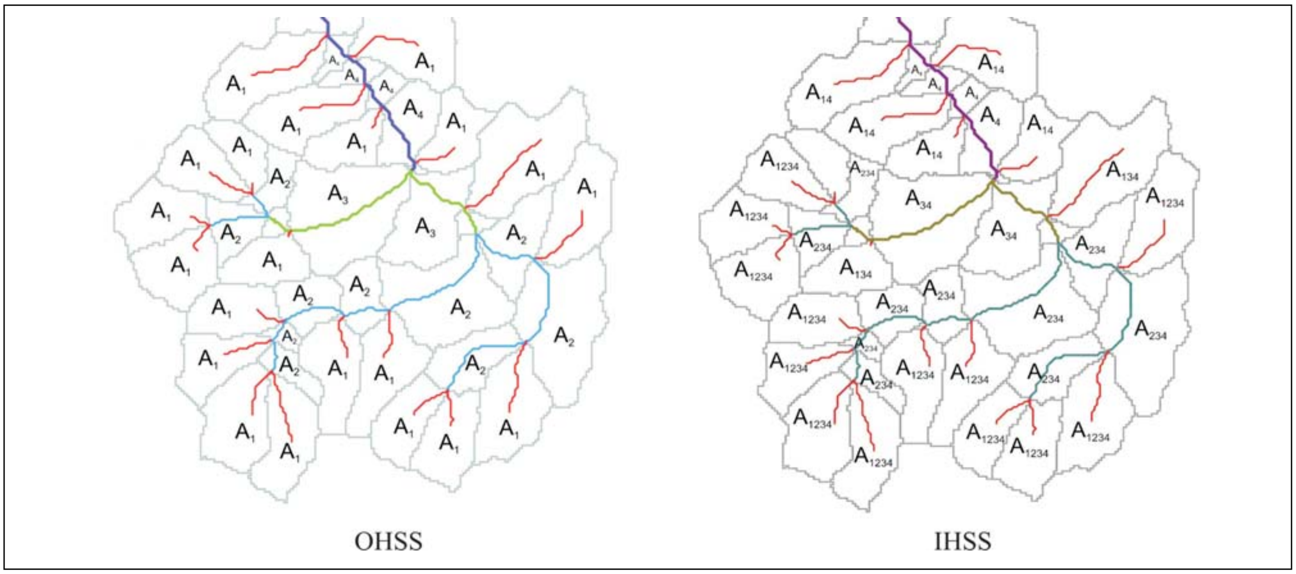

Figure 3. Example of hillslope marking according to the OHSS and the IHSS.

Determination of flow path probability based on the IHSS

In Figure 1, it is obvious that individual initial or transition probabilities are uniformly distributed to several flow paths. It can also be observed that the probability for the last flow path $P(s_8)$ is equal to the initial probability for the highest order of basin Ω. If the hydrographic network is classified according to the IHSS, such method of probability forming for flow paths can be applied to all paths because the IHSS precisely defines areas that follow certain flow paths, i.e. the probability forming scheme will be as in Figure 4.

$$\theta_1 \longrightarrow P(s_1)$$
$$\theta_2 \longrightarrow P(s_2)$$
$$\theta_3 \longrightarrow P(s_3)$$
$$\theta_4 \longrightarrow P(s_4)$$
$$\theta_5 \longrightarrow P(s_5)$$
$$\theta_6 \longrightarrow P(s_6)$$
$$\theta_7 \longrightarrow P(s_7)$$
$$\theta_8 \longrightarrow P(s_8)$$

Figure 4. Forming of probabilities of flow paths according to the IHSS.

According to that, flow path probability can be defined as:

$$P(s_n) = \theta_n = \frac{\sum_{k=1}^{N_{A_n}} A_{nk}}{A_\Omega} = \frac{A_n}{A_\Omega} \tag{13}$$

where n is number of flow paths, s_n is flow path; θ_n is the initial probability according to the IHSS for corresponding flow path n; A_ω is the total basin area; A_n is the area of hillslope that corresponds to flow path s_n; N_{A_n} is the number of sub-hillslopes for corresponding flow path s_n.

Average travel time in stream and hillslope

For defining a GIUH, it is necessary to calculate average time in hillslope ($1/\alpha_i$) and stream ($1/\beta_i$) using the parameters α_i and β_i.

$$\alpha_i = \frac{v_0}{L_0} \tag{14}$$

$$\beta_i = \frac{v_s}{\overline{L_i}} \tag{15}$$

where $L_0 = \frac{1}{2D}$ is average path of water flow in the basin area (hillslopes), v_0 is velocity in hillslopes, D is stream network density, v_S is velocity along streams, $\overline{L_i}$ is the average length of i-order stream.

Figure 5 illustrates a detail of a hydrographic network which is divided into appropriate paths with corresponding hillslopes. The calculation of average travel time according to the OHSS includes the mean value of lengths of streams of corresponding orders. In Figure 5, it is possible to observe a high difference in length of arrow-marked streams of the same order according to the OHSS. However, in the definition of the average flow time along the first-order stream, both streams participate with the same weight of influence. Also, marked streams do not belong to the same flow path. Namely, the shorter stream of first order flows into the stream of second order and then into the stream of third order etc., while the longer stream of first order flows into the stream of third order etc., which means that they do not belong to same flow paths.

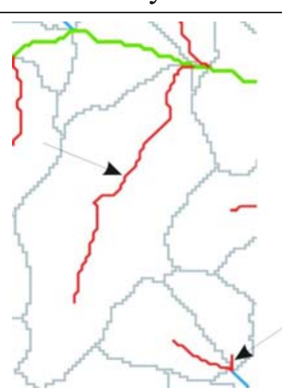

Figure 5. A detail of hydrographic network.

Obviously, if accuracies of values determined by the GIUH method need to be increased, it is also necessary somehow to include differences in lengths of streams of individual orders into the calculation of average travel time. By introducing the IHSS stream classification (Figure 6), all streams of one order that follow the same flow path are assigned to one group, where the length L_i^n or the mean length $\overline{L_i^n}$ are defined specifically for them, and thus the average travel time $1/\beta_i^n$ is defined for every stream group, i.e. the parameter β_i^n is defined as:

$$\beta_i^n = \frac{v_s}{\overline{L_i^n}} \tag{16}$$

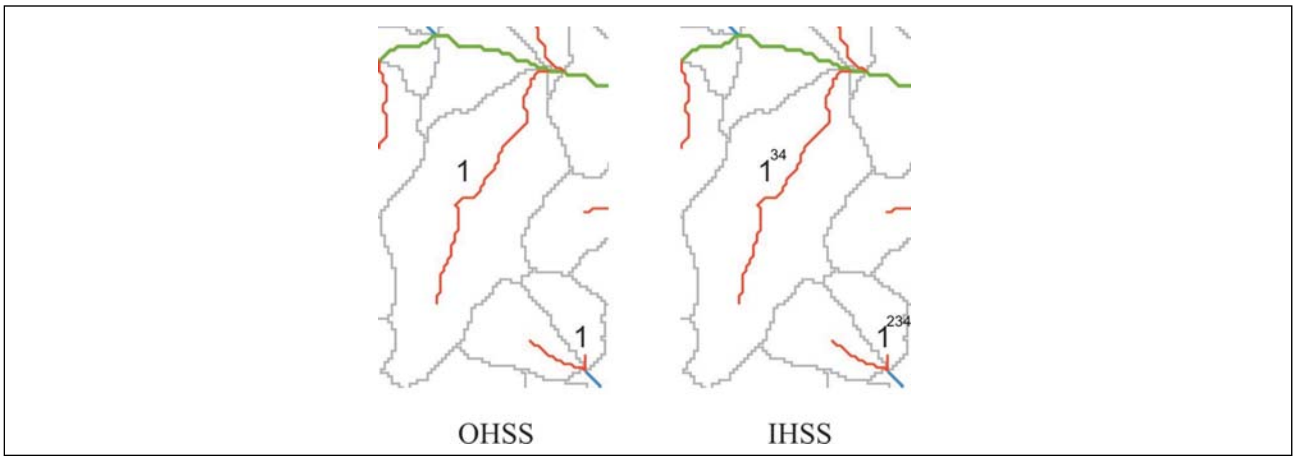

Figure 6. Details of hydrographic network according to the OHSS and the IHSS.

Van der Tak (1990) introduced and provided the expression for calculation of the local density of stream network:

$$D_i = \frac{1}{N_i}\sum_{k=1}^{N_i}\frac{L_\omega^k}{DA_i^k} \tag{17}$$

where D_i is local density of stream network for order $_i$; D is the stream network density for the entire basin; N_i is the number of i-order streams; A_i is the area of *i*-order hillslope.

Consequently, the stream network density can be calculated not only for the entire basin but also locally for individual orders according to the OHSS. However, this expression was also obtained on the basis of averaged stream areas, lengths and numbers for individual orders. If the basin is classified according to the IHSS, it is possible to define local stream network densities as well as local average path length per hillslope for every flow path separately and thus obtain average travel time per hillslope for every flow path, and not, as was done according OHSS, the same average travel time for all hillslopes.

$$D_i^n = \frac{L_i^n}{A_i^n} \tag{18}$$

where D_i^n is the local stream network density for flow path *n*; L_i^n are lengths of *i*-order streams for flow path n; A_i^n is the area of i-order hillslope for flow path n.

Thus, local average path length per hillslope can be obtained as:

$$\left(L_0\right)_i^n = \frac{1}{2D_i^n} \tag{19}$$

and the parameters for defining travel time per i-order hillslope which corresponds to path n as:

$$\alpha_i^n = \frac{v_0}{\left(L_0\right)_i^n} . \tag{20}$$

Theoretical basis for defining the GIUH based on IHSS

The advantage of the IHSS over OHSS is in that it clearly defines the present position of raindrop as well as subsequent positions over which the raindrop travels to the basin outlet. Such classification of stream network allows the distribution of probabilities of flow paths, and hence the GIUH ordinates, to be defined more accurately.

Thus, for example, for a basin with the highest order $\Omega = 4$, flow paths are the following:

$$S = \{s_1, s_2, s_3, s_4, s_5, s_6, s_7, s_8\}$$
$$s_1 : a_1 \rightarrow r_1^{234} \rightarrow r_2^{34} \rightarrow r_3^{4} \rightarrow r_4^{outlet} \rightarrow outlet$$
$$s_2 : a_2 \rightarrow r_1^{24} \rightarrow r_2^{4} \rightarrow r_4^{outlet} \rightarrow outlet$$
$$s_3 : a_3 \rightarrow r_1^{34} \rightarrow r_3^{4} \rightarrow r_4^{outlet} \rightarrow outlet$$
$$s_4 : a_4 \rightarrow r_1^{4} \rightarrow r_4^{outlet} \rightarrow outlet$$
$$s_5 : a_5 \rightarrow r_2^{34} \rightarrow r_3^{4} \rightarrow r_4^{outlet} \rightarrow outlet$$
$$s_6 : a_6 \rightarrow r_2^{4} \rightarrow r_4^{outlet} \rightarrow outlet$$
$$s_7 : a_7 \rightarrow r_3^{4} \rightarrow r_4^{outlet} \rightarrow outlet$$
$$s_8 : a_8 \rightarrow r_4^{outlet} \rightarrow outlet$$

Travel time T_{s_n} over a certain path $a_n \rightarrow r_i^{jkm...\Omega} \rightarrow r_j^{km...\Omega} \rightarrow r_k^{m...\Omega}, ..., \rightarrow r_\Omega^{outlet} \rightarrow outlet$ is equal to the sum of travel times in sub-sections of that path:

$$T_{s_n} = T_{a_n} + T_{r_i^{jkm...\Omega}} + T_{r_j^{km...\Omega}} + T_{r_k^{m...\Omega}}, ..., + T_{r_\Omega^{outlet}} \tag{21}$$

where T_{a_n} is the travel time of rainfall in a certain part of hillslope of the corresponding flow path s_n; $T_{r_i^{jkm...\Omega}}, i \in (1, 2, ..., j, k, m, ..., \Omega)$ is rainfall travel time in a group of streams of the corresponding path. In accordance with previously introduced designations, the probability distribution density function of total travel time of raindrops T_{s_n} is then the convolution of probability distribution density functions $f_{T_{a_n}}(t)$ and $f_{T_{r_i}^{jkm...\Omega}}(t)$ that correspond to path elements (s_n).

$$f_{T_{s_n}}(t) = f_{Ta_n}(t) * f_{Tr_i^{jkm...\Omega}}(t) * f_{Tr_j^{km...\Omega}}(t) * f_{Tr_k^{m...\Omega}}(t) * ... * f_{Tr_\Omega^{outlet}}(t) \tag{22}$$

The GIUH ordinates defined through the IHSS can be calculated as:

$$u(0,t) = \sum_{s_n \in S} f_{T_{a_n}}(t) * f_{T_{r_i}^{jkm...\Omega}}(t) * f_{T_{r_j}^{km...\Omega}}(t) * f_{T_{r_k}^{m...\Omega}}(t) * ... * f_{T_{r_\Omega}^{outlet}}(t) \cdot P(s_n) \tag{23}$$

EXAMPLE OF DEFINING THE GIUH BASED ON IHSS

Study area: Brijesnica River Basin

The Brijesnica River Basin is part of the larger Bosna River Basin that is situated in Bosnia and Herzegovina (Figure 7). In geomorphologic terms, the basin belongs to the mountainous area. In geologic terms, the basin is situated in the border area between the central ophiolitic zone and the neogene basin of the town of Tuzla, i.e. the southernmost area with aquatic sedimentation up to Quaternary age. The average annual precipitation is about 900 mm. The main physical-geographical properties of the Brijesnica River basin are given in Table 1.

This basin has a rather inhomogeneous hydrographic network structure, which is evident in Figure 8 where it is possible to observe a high number of first-order streams directly flowing into fourth-order streams. According to the new IHSS classification, streams and hillslopes should be grouped according to flow paths which raindrop will follow on the way to the basin outlet, i.e. according to the water gauging station that measures the flow. The full marking of all hillslopes and streams is presented in Figure 9.

Figure 7. Geographical position of the Brijesnica River Basin.

Table 1. Main physical-geomorphologic characteristics of the Brijesnica River basin.

Stream	Flow gauge station	Basin area (km^2)	Average basin height (m a.s.l.)	Basin perimeter (km)	Concentration coefficient	Average basin head (m/m)
Brijesnica	Rosulja	27	434	25	0.62	0.035

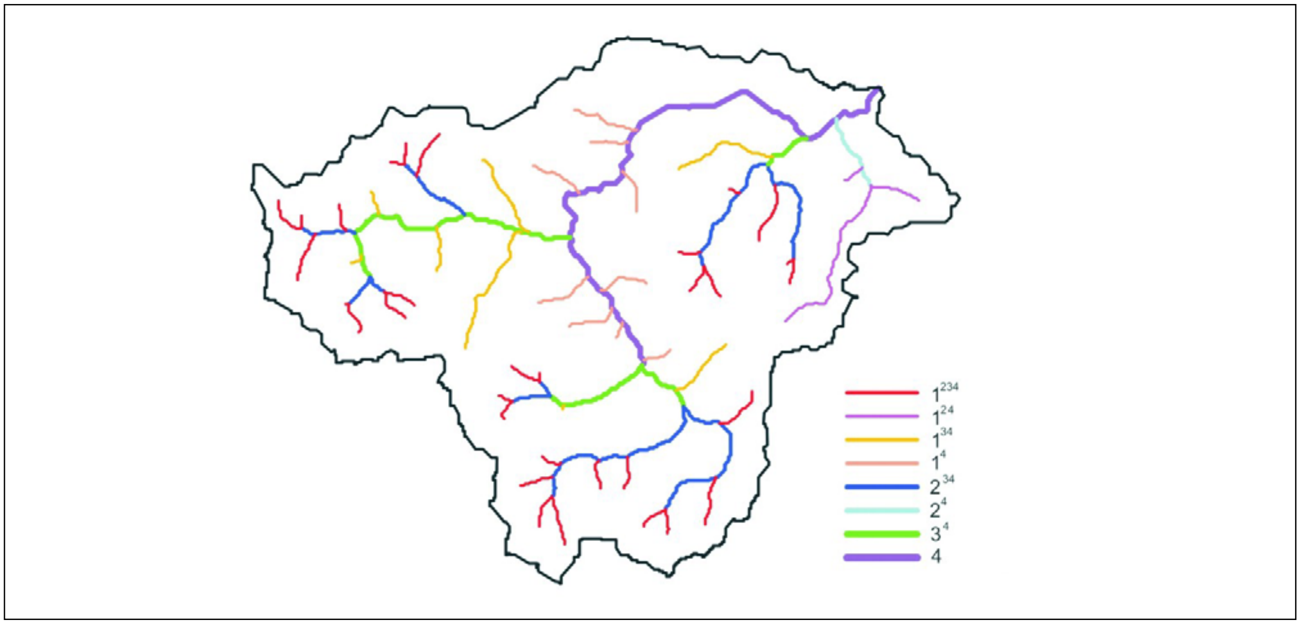

Figure 8. The Brijesnica River basin: streams assigned to groups depending on flow path (IHSS).

Figure 10 shows the contribution of individual hillslopes grouped according to individual flow paths. Parameters required for definition of GIUH through the IHSS are given in Table 2.

The GIUH was defined first on the basis of the OHSS hydrographic network, and a unit one-hour hydrograph was calculated. The flow velocity was used as a calibration parameter for the GIUH models (Al-Wagdany and Rao, 1997). Model calibration was performed by using an averaged unit hydrograph obtained on the basis of observed data (Figure 11) for the purpose of determining characteristic flow velocities. The best agreement (Figure 12) of the UH was achieved for the velocities v_o = 0.015 m/s and v_s = 1.2 m/s.

The GIUH calculation according to new IHSS was performed with previously obtained characteristic velocities of flow on hillslopes and along streams with the purpose of comparing hydrographs depending on the hydrographic network classification.

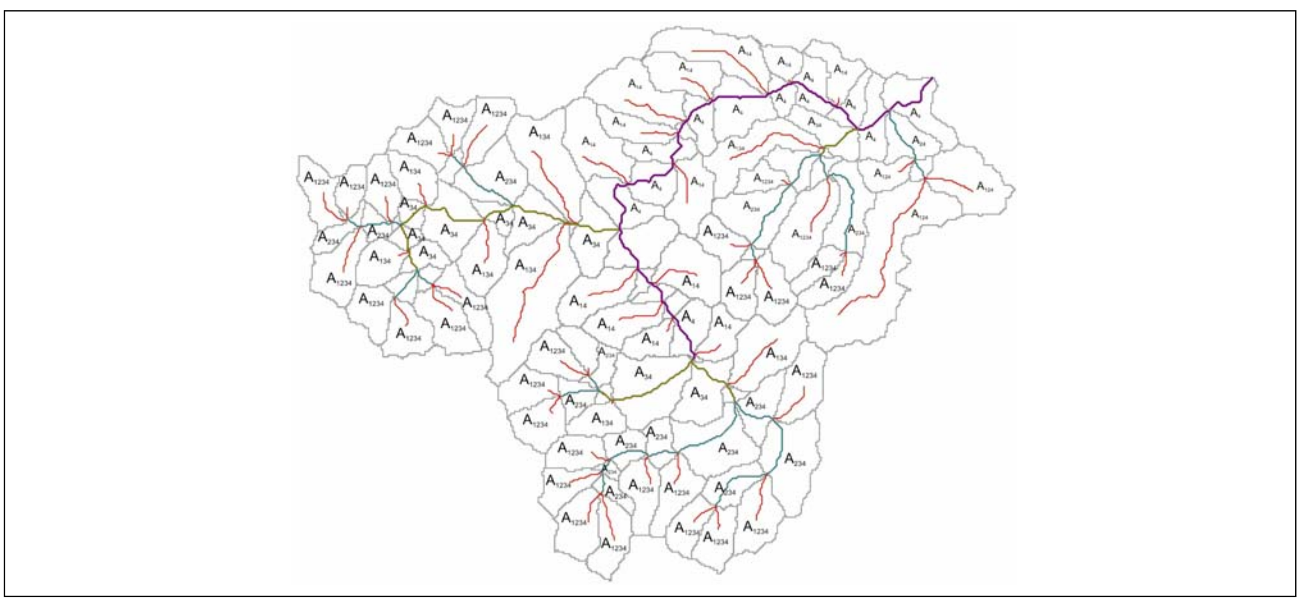

Figure 9. Hydrographic network classification according to the IHSS, Brijesnica River basin up to GS Rosulja.

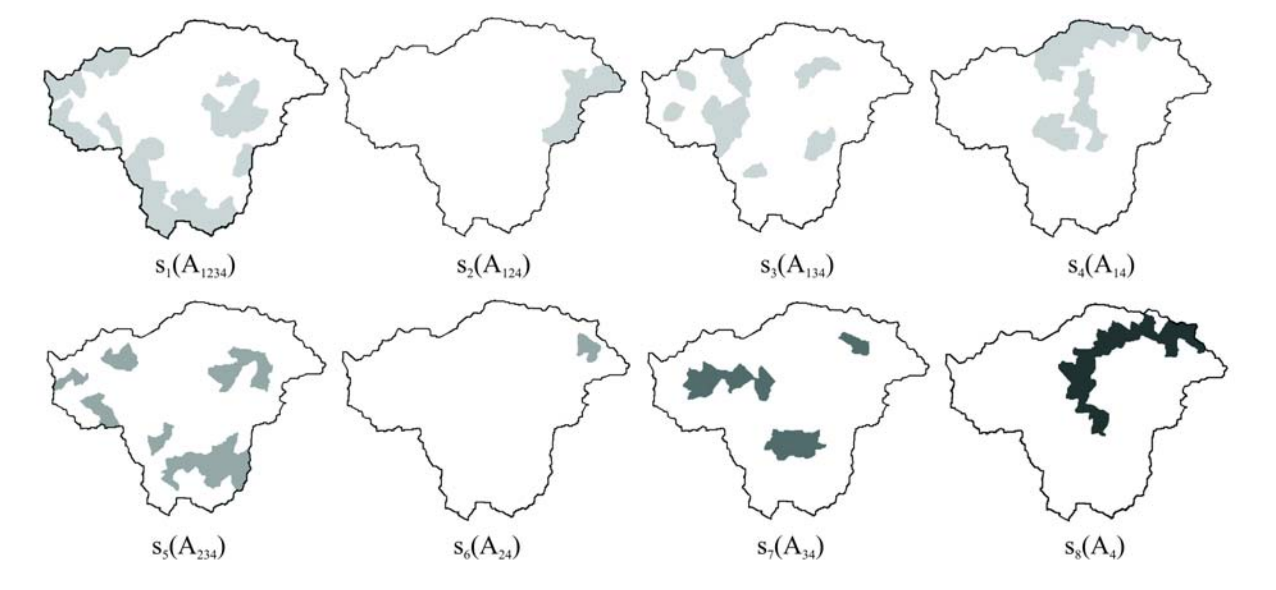

Figure 10. Contribution of areas of individual hillslopes pertaining to flow paths in relation to the total basin area.

Table 2. Parameters required for definition of GIUH through IHSS.

Flow path n (stream orders)	Pertaining area $A_n\left(km^2\right)$	Initial probability θ_n	Length of streams L_n(km)	Number of streams N_n	Mean length of streams $\overline{L_n}$(km)	Local hydrographic network density $D_n\left(\frac{1}{km}\right)$	Average local path length per hillslope $\left(L_0\right)_n = \frac{1}{2 \cdot D_n}$(km)
1 (1234)	7.695	0.278	10.547	32	0.330	1.371	0.365
2 (124)	1.942	0.070	3.006	3	1.002	1.548	0.323
3 (134)	3.657	0.132	5.880	8	0.735	1.608	0.311
4 (14)	4.123	0.149	6.661	13	0.512	1.616	0.309
5 (234)	4.401	0.159	10.316	10	1.032	2.344	0.213
6 (24)	0.286	0.010	0.931	1	0.931	3.255	0.154
7 (34)	2.561	0.093	6.010	4	1.503	2.347	0.213
8 (4)	3.015	0.109	7.256	1	7.256	2.407	0.208

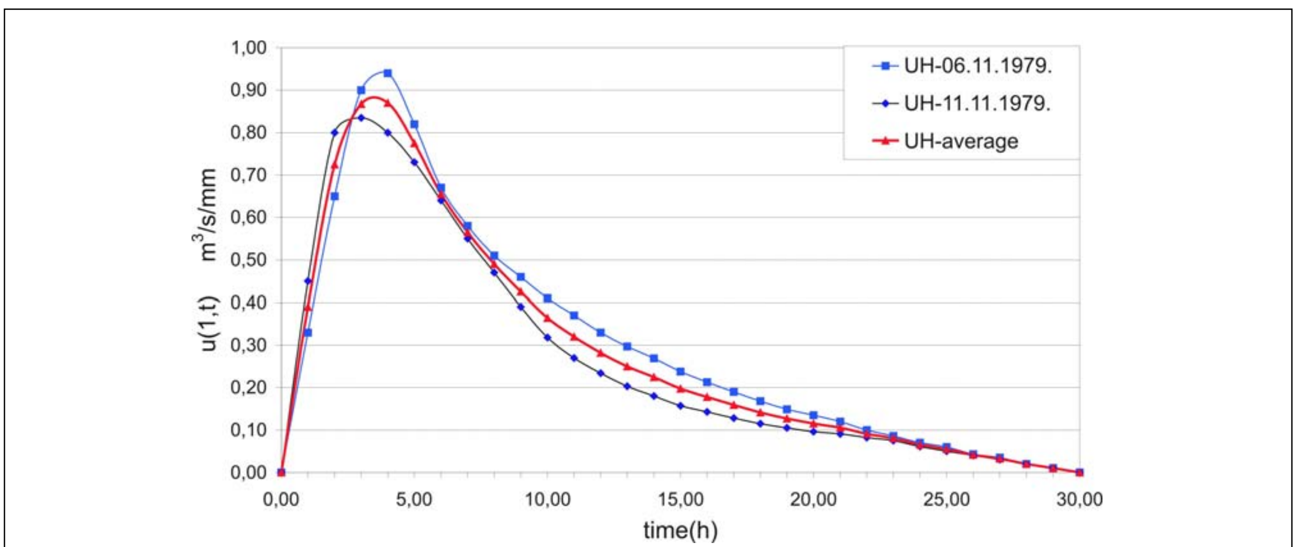

Figure 11. Unit hydrographs determined on the basis of observed data.

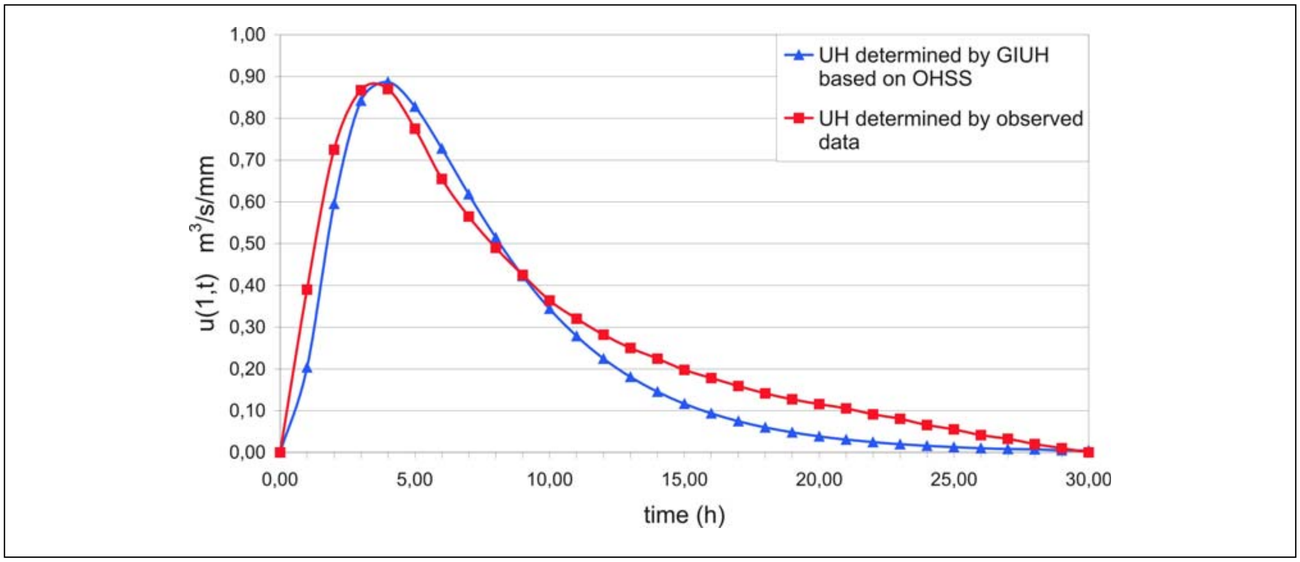

Figure 12. UH (OHSS) model calibration with the UH obtained through observed data.

Figure 13 presents two unit hydrographs:

- unit hydrograph obtained by the GIUH method on the basis of OHSS; and

- unit hydrograph obtained by the GIUH method on the basis of IHSS.

It is noticeable that, at the same characteristic flow velocities, the hydrograph obtained by the IHSS has lower values of the maximum ordinate and somewhat higher descending branch.

If the new UH is calibrated according to the UH obtained on the basis of observed data, a better agreement of the descending hydrograph branch will be noticed (Figure 14). In this case, characteristic flow velocities are certainly slightly higher, and they are v_0=0.015 m/s, v_S=1.6 m/s. An exceptionally good agreement of the ascending branch and peak of the diagram and the beginning of the descending branch is also noticeable.

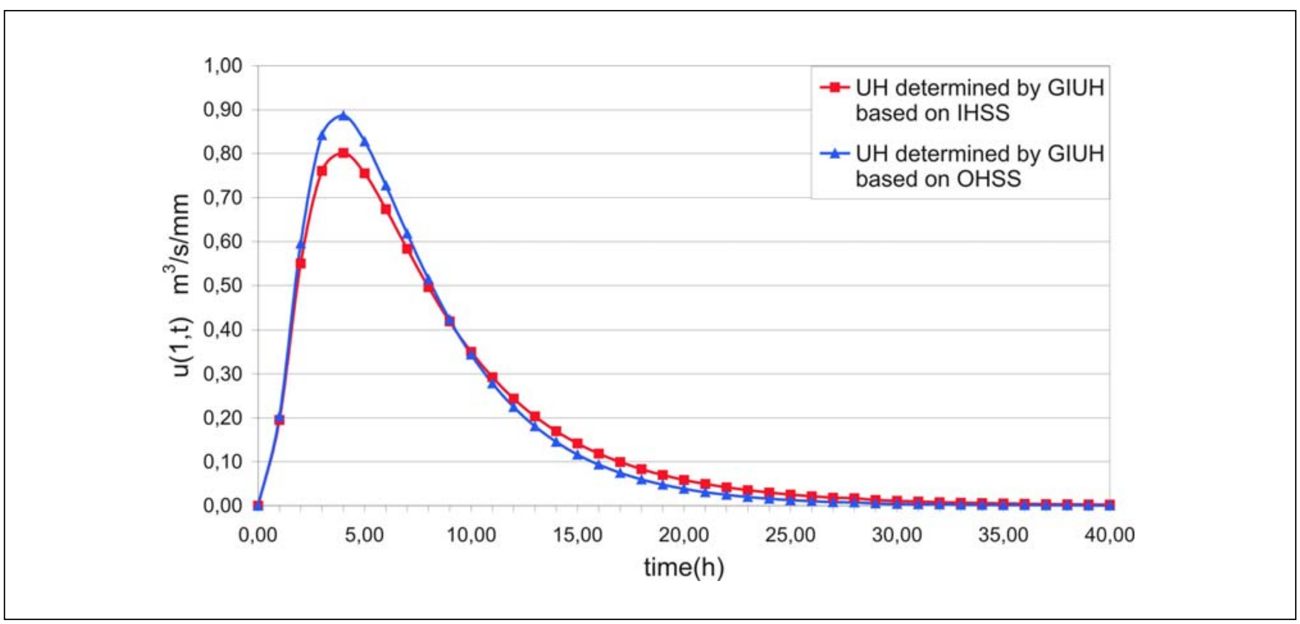

Figure 13. The Brijesnica River basin: comparison of $u(1,t)_{GUIH}^{OHSS}$ and $u(1,t)_{GUIH}^{IHSS}$; v_0=0.015 m/s, v_S=1.2 m/s.

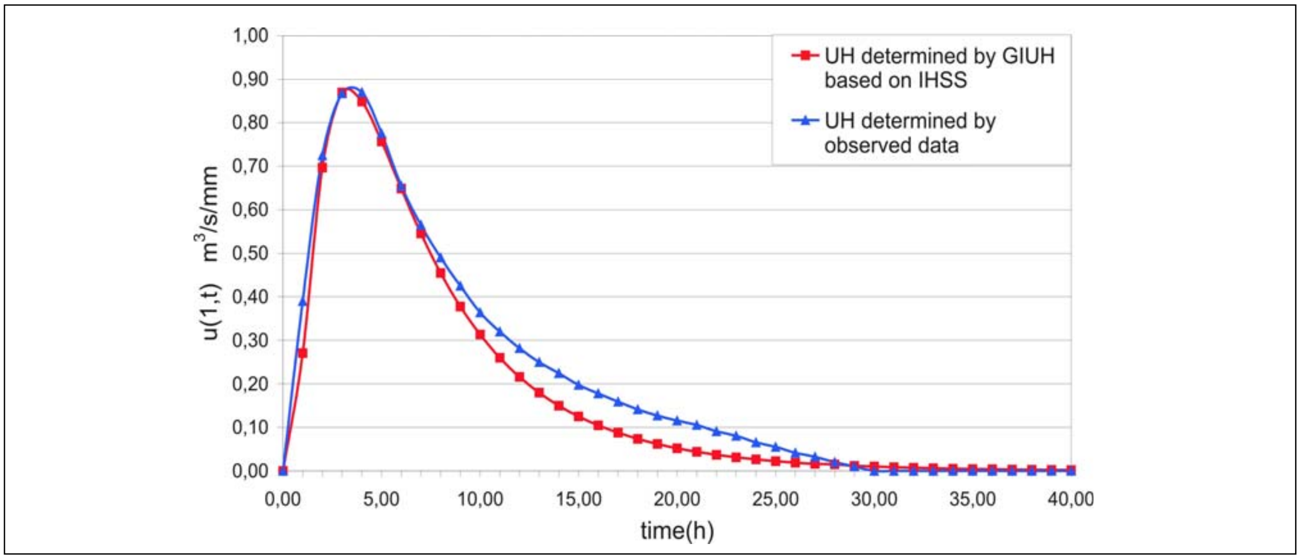

Figure 14. Brijesnica River basin: comparison of the observed $u(1,t)_{OBS}$ and $u(1,t)_{GUIH}^{IHSS}$; v_0=0.015 m/s, v_S=1.6 m/s.

CONCLUSION

As is known, the GIUH method is the method aimed to define the response of a basin to rainfall using information on the river basin geomorphology. However, this method also requires appropriate data that are not only of a geomorphological character such as water velocities in streams and in catchment areas, rainfall intensity, and so on. Nevertheless, the GIUH method has been the subject of many studies that obtained unit hydrographs using the method mainly by calibration of the relevant parameters. In this paper, emphasis is laid on the very character of information about basin geomorphology. This information has been implemented in the method in different ways, most often by the Horton-Strahler scheme of hydrographic network classification, and by the width function, and appropriate procedures have been developed for obtaining unit hydrographs and direct runoff hydrographs.

In the standard procedure for determining the direct runoff hydrograph by the GIUH method using the Horton-Strahler scheme, where relevant expressions are used to define initial and transition probabilities and hence also runoff path probabilities, problems in calculation were observed. Specifically there were problems determining these probabilities, especially for higher stream orders according to the original Horton-Strahler scheme (OHSS), and negative values were obtained by using relevant equations. The problem was identified already by van der Tak (1990), and according to him, it was caused by a uniform distribution of lengths and areas of hillslopes to different flow paths. This, in turn, is the consequence of the method of hydrographic network classification according to the OHSS, which was chosen as the basis for the development of the GIUH model. According to this scheme, streams and hillslopes are assigned to orders regardless of flow path to which they belong. The problem can be overcome by using physical equations for initial and transition probabilities, however Gupta and Waymire (1983) agree that the original Horton-Strahler scheme is too rough to adequately describe the hydrographic network that will be used to define basin response to rainfall. In this connection, in this paper, the so-called improved Horton-Strahler scheme (IHSS) of hydrographic network classification was developed, for which the underlying idea was to assign streams and hillslopes to groups according to flow paths. In this way, it is possible to obtain precisely defined basin parts that directly participate in the forming of flow for each path separately, i.e. the uniform distribution of basin parts to several flow paths was avoided. That drawback in the OHSS was handled by using transition probabilities, which were also, like in initial probabilities, obtained by uniform distribution to several flow paths.

In addition, the hydrographic network classification according to the IHSS allows calculation of local densities of stream network that are included in calculation of average lengths of hillslopes, but now for each flow path separately. Also, it is possible to calculate average travel times along streams and over hillslopes through parameters α and β for each flow path differently, which is certainly more accurate in relation to the OHSS.

The GIUH model according to the IHSS was applied in the Brijesnica River Basin in Bosnia and Herzegovina. The results indicated that maximum values of unit hydrographs and direct runoff hydrographs according to the IHSS are to some extent lower than corresponding hydrographs according to the OHSS, i.e. the new model calibration yields higher values of characteristic flow velocities. Better agreement of descending branches in the hydrograph was also reported, which was one of the shortcomings of the previous calibration with the model according to OHSS.

However, in any case, the intention here was not to show possible improvements of using the IHSS over OHSS because that is self-evident. The IHSS is a more detailed presentation of a hydrographic network and thereby its results can be considered as more accurate. The problem of determining characteristic velocities, which is considered essential in defining the GIUH, for which many authors offered various solutions, still remains. By introducing the new hydrographic network scheme (IHSS), it is expected that solutions given for various GIUH-related problems will get a new dimension.

ACKNOWLEDGMENTS

This paper was reviewed by Professor Ognjen Bonacci, Faculty of Civil Engineering and Architecture, University of Split, Croatia, by Professor Husno Hrelja, Faculty of Civil Engineering, University of Sarajevo, Bosnia and Herzegovina, and by Professor Vesna Denic-Jukic, Faculty of Civil Engineering and Architecture, University of Split, Croatia

REFERENCES

Allam, M.N., K.S. Balkhair. 1987. Case study evaluation of geomorphologic instantaneous unit hydrograph. Water Resources Management, Vol. 1, 267–297.

Al-Wagdany, A.S., and A.R. Rao. 1997. Estimation of the Velocity Parameter of the Geomorphologic Instantaneous Unit Hydrograph. Water Resources Management, Vol. 11, 1-16.

Beven, K.J. 1986. Runoff production and flood frequency in catchments of order n: an alternative approach, In: V.K. Gupta, I. Rodríguez-Iturbe and E.F. Wood (Eds.), Scale Problems in Hydrology. Reidel, Dordrecht, 107-131.

Beven, K.J., and E.F. Wood. 1993. Flow routing and the hydrological response of channel networks, in K.J. Beven and M.J.Kirkby (eds), Channel Network Hydrology, Wiley: 99-128.

Bhunya, P.K., R. Berndtsson, P.K. Singh, P. Hubert. 2008. Comparison between Weibull and gamma distribution to derive synthetic unit hydrograph using Horton order ratios. Water Resour. Res., Vol. 44, W04421, doi:10.1029/2007WR006031.

Bonacci, O. 1983. Several methods for discharge measurements of floods. Hydrological Sciences Journal, Vol. 28, 513-524.

Bras, R.L. 1990. Hydrology: An introduction to hydrologic science. Addison-Wesley Publishing Company, New York, USA, ISBN 0-201-05922-3.

Britton, P. 2002. Review of Existing River Coding Systems for River Basin Management and Reporting. WFD GIS Working Group: European Coding Systems Task Group. Available at: http://193.178.1.168/River_Coding_Review.htm.

Cudennec, C., Y. Fouad, G. Sumarjo, J. Duchesne. 2004. A geomorphological explanation of the unit hydrograph concept. Hydrological Processes, Vol. 18, 603-621.

Fleurant, C., B. Kartiwa, B. Roland. 2006. Analytical model for a Geomorphologic Instantaneous Unit Hydrograph (AGIUH). Hydrological Processes, Vol. 20(18) p, 3879-3895.

Gupta, V.K., and O.J. Mesa. 1988. Runoff generation and hydrologic response via channel network geomorphology-Recent progress and open problems. J. Hydrol., Vol. 102, 3-28.

Gupta, V.K., E. Waymire, C.T. Wang. 1980. Representation of an Instantaneous Unit Hydrograph from Geomorphology. Water Resources Research, Vol. 16(5), 855-862.

Gupta, V.K., E. Waymire. 1983. On the formulation of an analytical approach to hydrologic response and similarity at the basin scale. Journal of Hydrology, Vol. 65, 95-123.

Gupta, V.K., E. Waymire, I. Rodríguez-Iturbe. 1986. On scales, gravity and network structure in basin runoff, in Scale Problems in Hydrology, chap. 8, edited by V. Gupta, I. Rodriguez-Iturbe, and E. Wood, pp. 159-184, D. Reidel, Dordrecht.

Gupta, V.K., and E. Waymire. 1998. Spatial variability and scale invariance in hydrologic regionalization, in Scale Dependence and Scale Invariance in Hydrology, edited by G. Sposito, pp. 88-135, Cambridge Univ. Press, Cambridge, Mass.

Hall, M.J., A.F. Zaki, M.M.A. Shahin. 2001. Regional analysis using Geomorphoclimatic Instantaneous Unit Hydrograph. Hydrology and Earth System Sciences, 5(1), 93-102.

Hrelja, H. 2007. Engineering hydrology. Faculty of Civil Engineering, University of Sarajevo, Bosnia and Herzegovina, ISBN 978-9958-638-14-5.

Jin, C. 1992. A deterministic gamma-type Geomorphologic Instantaneous Unit Hydrograph based on path type. Water resources Res., 28(2), 479-486.

Kirchner, J.W. 1993. Statistical inevitability of Horton's laws and the apparent randomness of stream channel networks. Geology, Vol. 21, 591-594.

Knighton, D. 1984. Fluvial Forms and Processes. Edward Arnold, London.

Kumar, R., C. Chatterjee, R.D. Singh, A.K. Lohani, S. Kumar. 2007. Runoff estimation for an ungauged catchment using geomorphological instantaneous unit hydrograph (GIUH) models. Hydrol. Process., Vol. 21, 1829-1840, doi:10.1002/hyp.6318.

Lee, K.T., N.C. Chen, Y.R. Chung. 2008. Derivation of variable IUH corresponding to time-varying rainfall intensity during storms. Hydrol. Sci. J., Vol. 53(2), 323–337.

Li, T.J., J.H. Liu, G.Q Wang. 2006. Drainage network codification method for digital watershed model. Advances in Water Science, Vol. 17, 658-664.

Marani, A., A. Rinaldo, R. Rigon, I. Rodríguez-Iturbe. 1994. Geomorphological width functions and the random cascade, Geophysical Research Letter, 21(9), 2123-2126.

Moussa, R. 2008. What controls the width function shape, and can it be used for channel network comparison and regionalization?. Water Resources Research, 44, 20 p., W08456, doi:10.1029/2007WR006118.

Moussa, R. 2009. Definition of new equivalent indices of Horton-Strahler ratios for the derivation of the Geomorphological Instantaneous Unit Hydrograph. Water Resources Research, 45, 24 p., W09406, doi:10.1029/2008WR007330.

Puente, C.E., B. Sivakumar. 2003. A deterministic width function model. Nonlinear Processes in Geophysics, Vol. 10, 525-529.

Rinaldo, A., G.K. Vogel, R. Rigon, I. Rodriguez-Iturbe. 1995. Can one gauge the shape of a basin?. Water Resour. Res., Vol. 31(4), 1119-1127.

Rodriguez, F., C. Cudennec, and H. Andrieu. 2005. Application of morphological approaches to determine unit hydrographs of urban catchments. Hydrol. Process., Vol. 19, 1021–1035.

Rodriguez-Iturbe, I., M. González Sanabria, and R.L. Bras. 1982. A Geomorphoclimatic Theory of the Instantaneous Unit Hydrograph. Water Resour. Res., Vol. 18(4), 877-886.

Rodriguez-Iturbe, I., and A. Rinaldo. 1997. Fractal River Basins. Chance and Self-Organization, 547 pp., Cambridge Univ. Press, New York.

Rodriguez-Iturbe, I., J.B. Valdes. 1979. The geomorphologic structure of hydrologic Response. Water Resour. Res., Vol. 15, 1409-1420.

Rosso, R. 1984. Nash model relation to Horton order ratios, Water Resour. Res., Vol. 20(7), 914– 921.

Saco, P.M., and P. Kumar. 2002. Kinematic dispersion in stream networks: 1. Coupling hydraulic and network geometry. Water Resour. Res., Vol. 38(11), 1244, doi:10.1029/2001WR000695.

Scheidegger, A.E. 1968a. Horton's law of stream numbers. Water Resour. Res., Vol. 4(3), 655– 658.

Scheidegger, A.E. 1968b. Horton's laws of stream lengths and drainage areas. Water Resour. Res., Vol. 4(5), 1015–1021.

Sherman, L.K. 1932. Streamflow from rainfall by the unit hydrograph method. English News Record, Vol. 108, 501-505.

Singh, P.K., P.K. Bhunya, S.K. Mishraa, and U.C. Chaube. 2007. An extended hybrid model for synthetic unit hydrograph derivation. J. Hydrol., Vol. 336, 347–360, doi:10.1016/j.jhydrol.2007.01.006.

Tarboton, D.G. 1996. Fractal river networks, Horton's laws and Tokunada cyclicity. Journal of Hydrology, Vol. 187, 105-117.

Tokunada, E. 1978. Consideration on the Composition of Drainage Networks and Their Evolution. Geographical Report No. 13, Tokyo Metropolitan University.

van der Tak, L., R.L. Bras. 1990. Incorporating hillslope effect into the geomorphologic instantaneous unit hydrograph. Water Resources Res., Vol. 26(10), 2393-2400.

Veitzer, S., V. Gupta. 2001. Statistical self-similarity of width function maxima with implications to floods, Adv. Water Res., Vol. 24, 955–965.

Veneziano, D., G.E. Molgen, P. Furcolo, and V. Iacobellis. 2000. Stochastic model of the width Function. Water Resour. Res., Vol. 36(4), 1143-157.

Vogt, J., S. Foisneau. 2007. European River and Catchment Datebase Version 2.0, Analysis Tools. EUR-Scientific and Technical Research series ISSN 1018-5593.

Zhang, L., G.Q. Wang, B.X. Dai, T.J. Li. 2007. Classification and Codification Methods of Stream Network in a River Basin: A Review. Environmental Informatics Archives, Vol. 5, 364-372.

Xiong, D.W., C. Li, G.H. Ni. 2004. Application of a distributed hydrological model to the Yellow River basin, Acta Geographica Sinica, Vol. 59, 143-154.

ADDRESS FOR CORRESPONDENCE
Gordan Prskalo
Faculty of Civil Engineering
University of Mostar,
Matice Hrvtaske bb
Mostar, Bosnia and Herzegovina

Email:gordan.prskalo@tel.net.ba