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Some Remarks on the Use of GIUH in the Hydrological Practice

C. Corradini
Dept. of Civil Engrg., Perugia University, Perugia, Italy

F. Melone
National Research Council – IRPI, Perugia, Italy

V. P. Singh
Louisiana State University, Baton Rouge, La 70803-6405, USA

The geomorphologic instantaneous unit hydrograph (GIUH) as a component of rainfall-runoff models directed to the determination of design hydrographs in ungaged basins is investigated. Specifically, we first performed a sensitivity analysis of the GIUH to errors in the basin lag estimated by commonly used empirical relationships involving basin area. Then, the details required in representing the geomorphologic features in the GIUH estimate for fixed basin lag, L, were examined. Real basins located in Central Italy were selected; they range in area from 12 km^2 to 4,147 km^2 and are characterized by a significant variability in the drainage channel density, D. It was found that given L a minimum detail was necessary in representing basin geomorphology. Further, the estimate of L through basin area led to large errors in computing design hydrographs for a few small basins. An explicit consideration of D is suggested in order to eliminate this shortcoming.

Introduction

An estimate of the magnitude of the flood to be considered in designing a given structure is a crucial problem in hydraulic engineering practice. In the past a common method used for designing urban structures was the rational method which considered only the peak discharge. However, more appropriately, recently developed design methods rely on the use of flow hydrographs frequently obtained, in ungaged basins, through rainfall-runoff models. The instantaneous unit hydrograph (IUH) synthesized by the geomorphological technique (Rodríguez-Iturbe and Valdés 1979; Gupta *et al.* 1980), which requires only one parameter to be determined empirically, is considered effective in this framework. According to Gupta *et al.* (1980) this parameter may be assumed equal to the basin lag, *L*, whose estimate should be very accurate.

Real basins are nonlinear in their behaviour, so in a given basin *L* should be variable with values decreasing from small to high-sized floods depending on physiographic, channel, and basin factors (Singh 1990). Relationships between L and flood magnitude have been proposed, for example, by Laurenson (1964) and Askew (1970). However, for floods of appreciable magnitude the variability of *L* is relatively small (Boyd 1982; Rossi 1974). Therefore, for design purposes, *L* is usually taken as a constant in a given basin, while its variability from one basin to another is commonly expressed through a nonlinear relation with basin area (Nash 1960; Bell and Omkar 1969; Boyd 1978; Panu and Singh 1981).

Many relationships have been proposed for estimating the lag time (see Singh (1988) for a summary), but only those developed by Hickok *et al.* (1959) for small basins with area up to 3.2 km^2 explicitly allow for drainage channel network characteristics. Conversely, channel network characteristics have a primary role in the formulation of the GIUH (Gupta *et al.* 1980), even though in a preliminary analysis limited to large basins Corradini *et al.* (1986) showed that a great detail was not required in representing them if the basin lag was correctly assessed. For a reliable application of the geomorphological approach further analyses of the role of channel network in determining *L* and, in turn, in computing the GIUH and design hydrographs are needed.

The objective of this paper is to investigate the role the above issues play on a variety of Italian basins ranging in area from 12 km^2 to 4,147 km^2. The maximum detail in the representation of the geomorphologic features was that obtained by the scale map 1:100,000. The influence of errors in the GIUH determination on design hydrographs was examined by adopting design hyetographs developed by the alternating block method.

Basin Lag and its Relation with Basin Area and Drainage Channel Network

The basin lag was obtained by averaging the lags for a few available rainfall-runoff events each »observed« as the time interval between the centroids of effective rainfall and direct runoff. The effective rainfall as a function of time was estimated considering the infiltration as the major loss represented through the two-stage form of the Philip infiltration equation.

A relationship commonly used in order to express the basin lag for flood events of significant magnitude is in the form

$$L^* = \beta A^{\alpha} \tag{1}$$

where L^* is the theoretical basin lag and A is the basin area. In Eq. (1) α and β are usually considered to be constant for basins in the same geographic area. More specifically, with L in hours and A in km^2, α is frequently taken as 0.33 or 0.38 (Singh 1988). In principle, a relationship involving explicitly the flood magnitude should be preferred, but usually adequate series of experimental data are not available for its calibration. Typically very long periods of observations of discharge may be found only at the outlet of large basins, while design hydrographs are frequently needed for small basins. Therefore, an approximate relationship independent of flood magnitude and developed through the more significant flood events observed in a few years must be used also for events with much longer return periods. Various other relationships have been proposed which, in addition to A, link the basin lag with physiographic features. Only the relationships proposed by Hickok *et al.* (1959) involve an explicit dependence on the general characteristics of the drainage channel network, but they were developed in the limits of very small basins. The last type of dependence can be investigated in a larger range of basin area by examining the differences between L and L^* in terms of drainage channel density D, and channel frequency F, expressed as

$$D = \frac{1}{A}\sum_{1}^{W}{}_i\, \overline{l_i}\, N_i \tag{2}$$

$$F = \frac{1}{A}\sum_{1}^{W}{}_i\, N_i \tag{3}$$

where according to the Horton-Strahler ordering scheme W is the basin order, $\overline{l_i}$ is the average length of the ith order channels and N_i is the number of the ith order channels.

GIUH Formulation

Rodríguez-Iturbe and Valdés (1979) developed a linear geomorphologic approach to specify the IUH of a given basin, which was later reformulated by Gupta *et al.* (1980). This approach substantially involves: a) Ordering of a basin according to the Horton-Strahler scheme which leads to define channels c, and overland regions r, of different orders. We design each element of a given order, c_i or r_i, as a state x_i. b) Averaging geometric and hydrologic features of each state. c) Identifying all the different paths followed by rainwater to reach the outlet, by considering that two different paths contain at least a different state. The formulation of the GIUH is probabilistic in character, however, a deterministic interpretation which associates a linear reservoir to each state is easier to understand. Thus, each path may be considered as a cascade of m unequal linear reservoirs and the watershed can be represented by a parallel arrangement of n cascades. The linear GIUH may be expressed as a sum of weighted responses of each cascade j, with the weighting factor p_j, representing the basin area fraction draining rainwater in each specific path. The GIUH is expressed in the form

$$h(t) = \sum_{1}^{n} {}_j \, p_j \sum_{1}^{m(j)} {}_i \, C_{ij} \exp(-K_{x_i} t) \tag{4}$$

where p_j is computed from geomorphologic data as the probability that the cascade j will be followed; $1/K_{x_i}$ is the storage coefficient of the state x_i, depending on the basin lag, and C_{i_j} are coefficients expressed by

$$C_{ij} \equiv \frac{K_{x_1} K_{x_2} \ldots K_{x_{m(j)}}}{(K_{x_1} - K_{x_i}) \ldots (K_{x_{i-1}} - K_{x_i})(K_{x_{i+1}} - K_{x_i}) \ldots (K_{x_{m(j)}} - K_{x_i})} \tag{5}$$

The storage coefficients for channels, $x \equiv c$, and overland regions, $x \equiv r$, of order i may be expressed, respectively, as

$$\frac{1}{K_{c_i}} = \gamma(L)\, \overline{l_i}^{\,1/3} \qquad 1 \leq i \leq W \tag{6}$$

$$\frac{1}{K_{r_i}} = \gamma(L) \left(\frac{a_{r_i}}{2N_i \overline{l_i}}\right)^{1/3} \qquad 1 \leq i \leq W \tag{7}$$

where a_{r_i} is the total area of the i^{th} order overland regions; and γ (L), for a given basin, is an empirical constant explicitly computed by

$$\gamma(L) \equiv \frac{L}{\sum_{1}^{n} {}_j \left(\left(\frac{a_{r_i}}{2N_i \overline{l_i}}\right)^{1/3} + \overline{l_i}^{\,1/3} + \ldots + \overline{l_{m(j)}}^{\,1/3} \right) p_j} \tag{8}$$

where l_i,.........., $l_{m(j)}$ refer to the states x_2,........., $x_{m(j)}$ of the cascade j, respectively.

Given L, the estimate of the GIUH by Eq. (4), in principle, will depend on the precision of the geomorphologic representation used for extracting the relevant information. In particular, the number of cascades and the maximum number of states in each cascade will decrease with the resolution of the map. In order to investigate this problem we started examining the geomorphologic features by the scale map 1:100,000, giving the basin order W. Then the GIUH, denoted here by h, was compared with that obtained by reductions in basin order, that is

$$W \rightarrow h \; ; \; W-1 \rightarrow h_{W=1} \; ; \quad W-2 \rightarrow h_{W=2} \; ; \; \ldots \tag{9}$$

where L was kept constant for successive representations in which the lowest order channels were eliminated and the remainder became of order reduced by a unit. The procedure is equivalent to using successive maps with lower resolution.

The change of the IUH from one basin to another may be mainly ascribed to the variation of L. According to this observation, the dimensionless IUH obtained by scaling the IUH by L for the time basis and by the peak flow for its ordinate (Singh *et al.* 1985) is commonly considered to have a very reduced variability. Here we also investigate the reliability of the technique of determining the GIUH of a given basin by L and a prescribed dimensionless GIUH, without using detailed information on its geomorphologic features. A representative dimensionless GIUH, $h^*(t^*)$, was selected from those derived for each study basin.

Given $h^*(t^*)$ and L, the GIUH can be computed as

$$h(t) = h_p \, h^*\left(\frac{t}{L}\right) \tag{10}$$

where, for h in 1/s, h_p is given through the normalizing condition by

$$h_p = \frac{1}{L \int_0^{\infty} h^*(t^*)\,dt^*} \tag{11}$$

The validity of this technique would imply that h_pL is a constant. Therefore, an error in the basin lag estimate would produce a GIUH peak, $h_p(L^*)$, such that

$$h_p L = h_p(L^*) L^* \tag{12}$$

from which we have

$$\frac{h_p(L) - h_p(L^*)}{h_p(L)} = \frac{L^* - L}{L^*} \tag{13}$$

Design Hydrographs

Design hydrographs were computed as

$$Q(t) = A \int_0^t \frac{dE(\tau)}{d\tau} \, h(t-\tau)\,d\tau \tag{14}$$

where E is the effective rainfall depth estimated by the Soil Conservation Service method from a design hyetograph with the same duration of the GIUH (considered as that when h has values greater than 0.05 h_p). The hyetograph was derived by the alternating block method (Chow *et al.* 1988) using a real rainfall depth-duration curve relative to a 25-year return period.

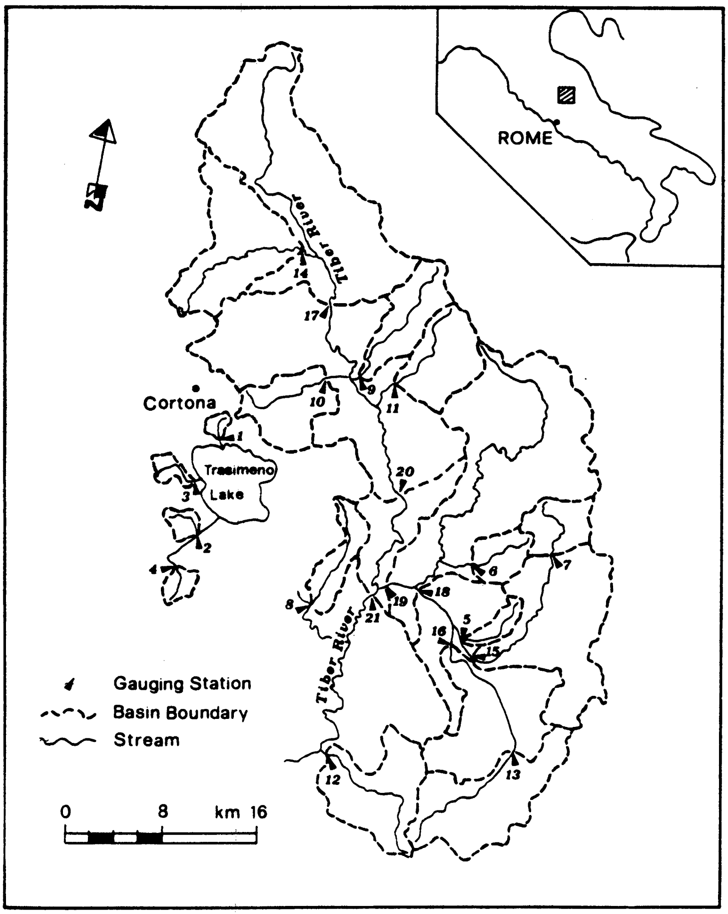

Fig. 1. Map of the study basins.

Experimental Data

Twenty-one basins located in Central Italy were selected for this study. Their general layout is shown in Fig. 1. The formulation chosen for estimating the GIUH (Eqs. (4)-(8)) explicitly involves detailed geometric and geomorphologic features of the actual drainage channel network which were derived from the scale map 1:100,000. Some characteristics which synthesize the structure of each basin are given in Tables 1 and 2. As can be seen, there is an appropriate variability of the quantities frequently involved in the empirical relationships for the lag estimate. Specifically, the basin dimensions range from 12.4 to 4,147 km^2 and the slope from 0.2% to 3%. There are also appropriate distributions of the drainage density and stream frequency; for example, from Table 2 we note a great variability for small basins of comparable area.

Table 1 – Main geometric features of the study basins

Number	Basin	Drainage Area (km^2)	Main Channel Length (km)	Main Channel Slope (%)
1	Macerone at Tuoro	12.4	4.95	2.85
2	Rio Maggiore at Macchie	21.7	8.90	0.43
3	Paganico at C. del Lago	22.7	9.35	0.27
4	Moiano at Casaltondo	24.1	8.50	1.71
5	Chiona at Budino	32.3	14.90	1.53
6	Tescio at P. S. Vetturino	64.7	16.35	1.98
7	Caldognola at Fornace	88.3	17.60	1.05
8	Genna at Palazzetta	89.5	22.20	0.55
9	Carpina at S. M. Sette	131.0	29.50	0.95
10	Niccone at Migianella	136.7	18.25	0.62
11	Assino at Serrapartucci	168.8	31.00	1.20
12	Naia at P. Martino	223.2	38.55	0.82
13	Marroggia at Azzano	257.5	28.30	0.91
14	Cerfone at Lupo	279.4	30.65	0.54
15	Topino at Bevagna	439.6	46.00	0.72
16	Timia at Cantalupo	541.4	52.30	0.40
17	Tiber at S. Lucia	934.0	63.90	0.52
18	Topino at Bettona	1,220.0	60.90	0.50
19	Chiascio at Rosciano	1,956.0	89.60	0,32
20	Tibet at P. Felcino	2,035.0	109.60	0.27
21	Upper Tiber River	4,147.0	136.20	0,23

Table 2 – Some geomorphologic characteristics of the study basins extracted from the 1:100,000 map

Basin	Basin Order	Stream Frequency (km^{-2})	Drainage Density (km^{-1})	Length of Overland Flow (%)
Macerone at Tuoro	3	1.47	1.56	0.32
Rio Maggiore at Macchie	2	0.41	1.14	0.44
Paganico at C. del Lago	4	0.88	1.24	0.40
Moiano at Casaltondo	4	2.45	2.08	0.24
Chiona at Budino	3	0.50	1.00	0.50
Tescio at P. S. Vetturino	4	1.38	1.53	0.33
Caldognola at Fornace	4	1.50	1.67	0.30
Genna at Palazzetta	4	1.20	1.46	0.34
Carpina at S. M. Sette	5	1.28	1.54	0.32
Niccone at Migianella	5	1.13	1.35	0.37
Assino at Serrapartucci	5	1.16	1.35	0.37
Naia at P. Martino	5	0.94	1.35	0.37
Marroggia at Azzano	6	1.12	1.43	0.35
Cerfone at Lupo	5	1.32	1.58	0.32
Topino at Bevagna	5	1.28	1.51	0.33
Timia at Cantalupo	6	1.03	1.49	0.34
Tiber at S. Lucia	6	1.19	1.53	0.33
Topino at Bettona	6	1.03	1.44	0.35
Chiascio at Rosciano	6	1.08	1.46	0.34
Tibet at P. Felcino	6	1.23	1.53	0.33
Upper Tiber River	7	1.15	1.49	0.34

Table 3 – Basin lag of the study basins

Basin	Number of Events	Peak Flow Range ($m^3 s^{-1}$)	Basin Lag (h)
Macerone at Tuoro	5	0.1 ÷ 0.3	3.1
Rio Maggiore at Macchie	5	0.6 ÷ 1.7	5.1
Paganico at C. del Lago	6	1.4 ÷ 4.8	5.7
Moiano at Casaltondo	7	3.6 ÷ 16.3	3.7
Chiona at Budino	5	1.8 ÷ 6.6	7.1
Tescio at P. S. Vetturino	5	4.3 ÷ 8.8	4.8
Caldognola at Fornace	8	5.1 ÷ 75.0	4.9
Genna at Palazzetta	5	26.6 ÷ 104.0	4.9
Carpina at S. M. Sette	5	11.0 ÷ 111.3	5.4
Niccone at Migianella	8	1.4 ÷ 30.8	7.0
Assino at Serrapartucci	5	8.1 ÷ 35.4	5.7
Naia at P. Martino	8	15.4 ÷ 45.0	7.0
Marroggia at Azzano	6	12.1 ÷ 30.8	6.9
Cerfone at Lupo	7	21.8 ÷ 43.2	8.1
Topino at Bevagna	7	19.2 ÷ 109.0	8.5
Timia at Cantalupo	9	17.2 ÷ 75.1	10.6
Tiber at S. Lucia	10	75.0 ÷ 271.0	11.5
Topino at Bettona	10	46.0 ÷ 205.0	13.3
Chiascio at Rosciano	10	55.0 ÷ 393.0	14.7
Tibet at P. Felcino	10	228.0 ÷ 592.0	14.5
Upper Tiber River	10	226.0 ÷ 843.0	18.0

Computations and Discussion of Results

Isolated rainfall-runoff events unaffected by snow melt were used (see Table 3) for the basin lag estimate. They were mainly obtained from local Hydrological Services; data were recorded with minor timing errors on semiconductor memories. All the hydrographs were single-peaked, and most of the rainfall hyetographs had a regular behaviour with time. The basin lag of each basin is given in Table 3, together with the maximum and minimum values of peak flow observed in the runoff events. These values were representative of the variation in flood magnitudes. The variation in lag was weakly linked with peak flow, therefore in this analysis nonlinear effects had a minor role.

Simulations of each event through the GIUH computed by the »observed« lag showed that the shape of the GIUH was appropriate. On average the errors in direct peak runoff were in magnitude within 15%. A comparison between the GIUH and the SCS triangular unit hydrograph was also performed by using the same information content concerning the basin lag. Specifically, denoting by h_T the ordinate of the triangular IUH and D_h its duration, the time to peak t_p', was computed through the relation

$$\int_0^{D_h(t_p)} t\, h_T(t;t_p)\, dt \equiv L \tag{15}$$

which, writing explicitly h_T and D_h in terms of t_p (Chow *et al.* 1988), leads to $t_p \equiv 0.816\,L$. The values of the IUH peak obtained by the triangular approach for the basins of area less than 100 km^2 typically exceeded the GIUH peak values of 20%. This led to a general increase of the simulated peak flows. In addition, the difficulty of the IUH synthesis by classical methods involving the estimate of two empirical parameters was shown by Singh *et al.* (1985).

Except for three basins, Eq. (1) was sufficiently accurate with both $\alpha \equiv 0.38$ and $\alpha \equiv 0.33$, with the last value found to produce better results. The accuracy of the relationship selected is shown in Fig. 2. The best fit line was determined leaving out the basins numbered by 2 (Rio Maggiore), 3 (Paganico) and 5 (Chiona); the angular coefficient was $\beta \equiv 1.19$. For the basins used in the regression analysis (designated henceforth as RA basins), the magnitude of errors in the basin lag was within 15%. The use of the selected empirical relation for other basins would lead in the average to unacceptable errors in basin lag of about -42%. The main variations in the GIUHs due to the use of L^* for L are synthesized in Table 4. For the RA basins the percentage errors in the GIUH peak flow were comparable in magnitude with those in the basin lag, while for the remainder basins these would be about -70%.

The last basins were characterized by small values of both drainage channel density and channel frequency; henceforth we designate them as *LD* basins. Their drainage channel network is shown in Fig. 3. At the scale 1:100,000 these basins have maximum values of D and F of 1.24 km^{-1} and 0.88 km^{-2}, respectively, (see Table 2).

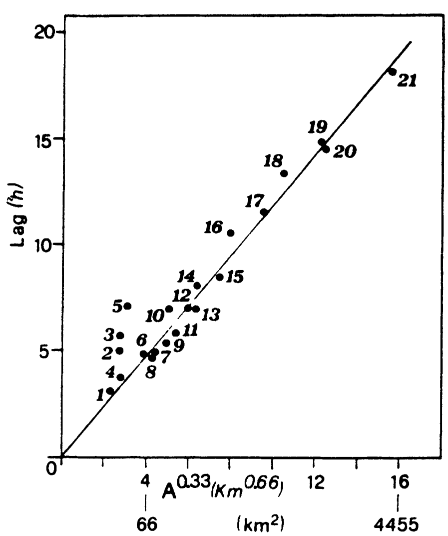

Fig. 2. Lag-area relationship for the study basins.

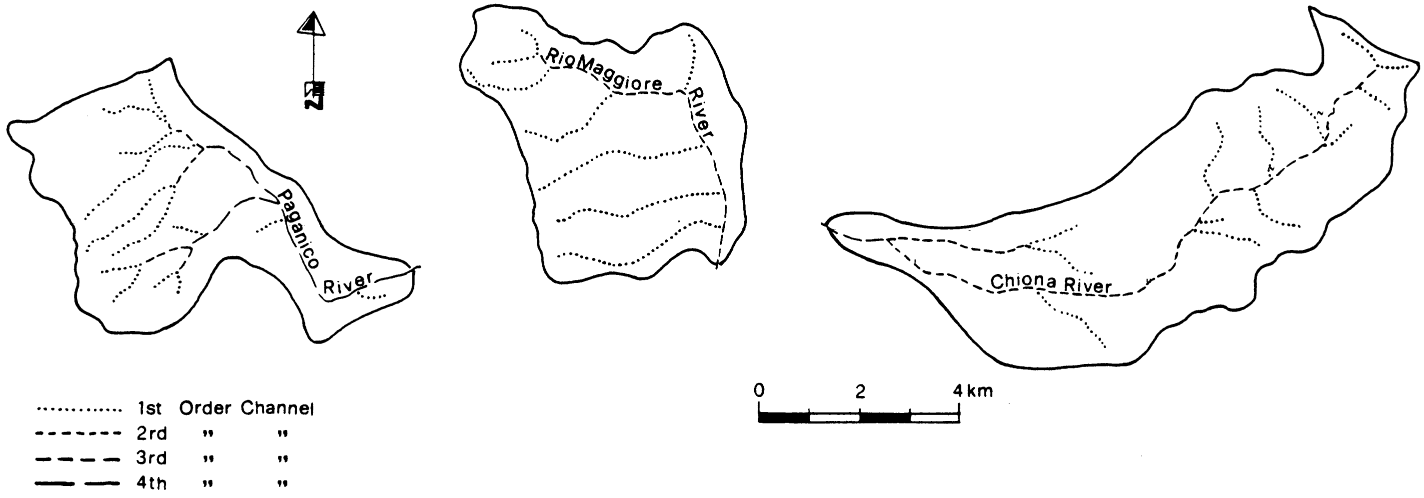

Fig. 3. Drainage channel network of the *LD* basins extracted from the 1:100,000 map.

Table 4 – Variations in the GIUH peak characteristics due to erros in basin lag estimate

Basin	Lag Time L* (h)	Lag Time L (h)	Lag Time Per cent Error	Peak Flow $h_p(L^*)$ (h^{-1})	Peak Flow $h_p(L)$ (h^{-1})	Peak Flow Per cent Error	Time to Peak $t_{h_p}(L^*)$ (h)	Time to Peak $t_{h_p}(L)$ (h)	Time to Peak Per cent Error
Macerone at Tuoro	2.7	3.1	-12.9	0.280	0.236	18.6	1.7	2.0	-15.0
Rio Maggiore at Macchie	3.3	5.1	-35.3	0.228	0.147	54.5	1.8	2.9	-37.9
Paganico at C. del Lago	3.3	5.7	-42.1	0.221	0.128	72.7	2.2	3.8	-42.1
Moiano at Casaltondo	3.4	3.7	-8.1	0.235	0.216	8.8	2.5	2.7	-7.4
Chiona at Budino	3.7	7.1	-47.9	0.206	0.113	81.9	2.6	4.6	-44.6

The values of D and F for the *RA* basins are not less than 1.35 km^{-1} and 0.94 km^{-2}, respectively. Even if well separated, the lower and upper extremes for the two basin groups are not considerably different. However, these differences get much more significant when examined together with basin areas. From Table 2 it can be seen that the *LD* basins have areas less than 33 km^2 and that within this range the variations of D and F from one basin group to the other are very large. Furthermore, the average length of the slopes contributing to direct runoff, $L_0 = 1/(2D)$, is considerably larger for the *LD* basins (see Table 2).

From an overall analysis of results, it seems appropriate to deduce that for the larger basins ($A > 64$ km^2) the values of L were substantially produced by the routing process through the channel network, while for some smaller basins they were produced by the same mechanism and for others by a significant additional contribution linked with the transfer of rainwater through the overland regions. The role of the last process accounts for the anomalous behaviour of the basins with higher values of L_0. This interpretation suggests that a general empirical relation for basin lag should consider the sum of two terms linked with water routing through the drainage channel network and through the overland regions, respectively. The first term should be similar to that of Eq. (1) and predominate from large down to small basins characterized by high values of D. The second, similar to that proposed by Hickok *et al.* (1959), should be important for small basins with low values of D. The basins used in this analysis are substantially characterized by fine-textured soils, for which we ignored the contribution of subsurface flow to direct runoff. However, this assumption may be considered reasonable on the basis of the short basin lags summarized in Table 3. For basins with important contributions from sub-surface flow a similar structure of the lag-area relationship should be expected, but with a more extended range of basin area where the travel time in the regions has a considerable role. Furthermore, in any case, also the representation of the hillslope travel time (Eq. (7)) in the GIUH should be improved.

Table 5 – Sensitivity of the GIUH peak characteristics to basin order reductions (see text for symbols)

	$W^*=W-1$		$W^*=1$	
Basin	$\frac{h_{w-1,p}}{h_p}$	$\frac{t_{w-1,p}}{t_p}$	$\frac{h_{l,p}}{h_p}$	$\frac{t_{l,p}}{t_p}$
Macerone at Tuoro	1.00	0.95	1.00	0.75
Paganico at C. del Lago	0.99	0.97	1.00	0.71
Moiano at Casaltondo	0.98	0.96	0.92	0.69
Chiona at Budino	0.99	0.97	0.93	0.69
Carpina at S. Maria di Sette	0.98	0.97	0.95	0.71
Niccone at Migianella	0.98	0.96	0.92	0.65
Marroggia at Azzano	0.99	0.98	0.87	0.49

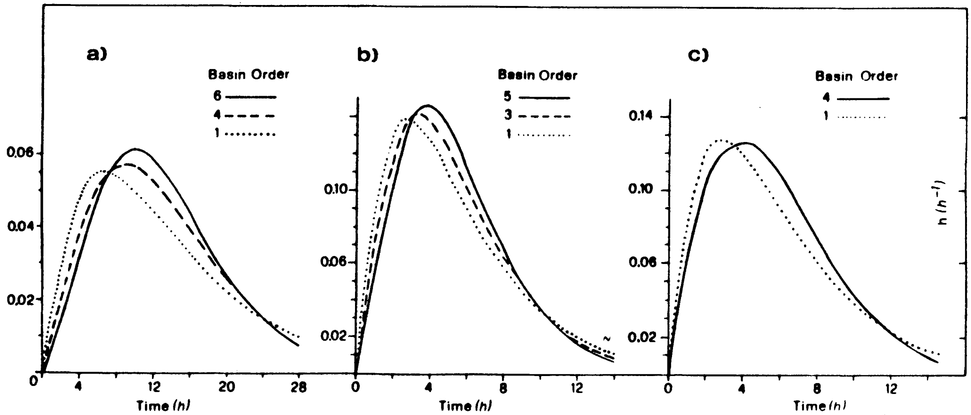

Fig. 4. Variation of the GIUH with basin order reduction. Sample basins of: a) Topino River, b) Carpina River and c) Paganico River.

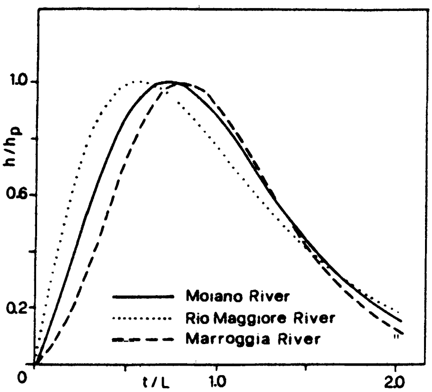

Fig. 5.
Extreme and »Average« dimensionless GIUHs for the study basins. L is the basin lag and h_p is the GIUH peak.

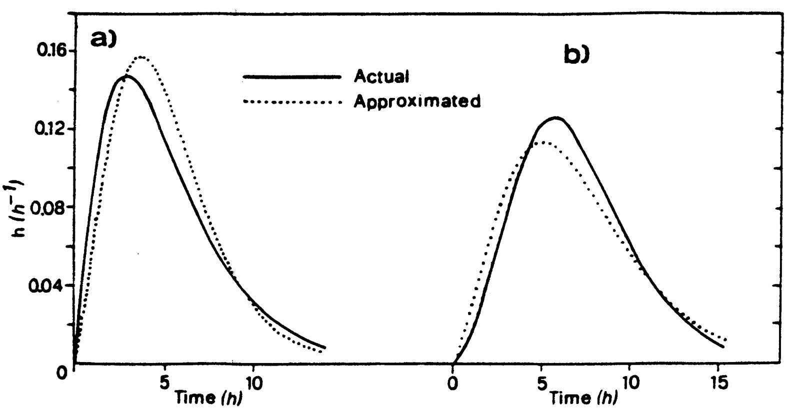

Fig. 6. Comparison of the actual GIUH with that approximated through the »Average« dimensionless GIUH. Sample basins of: a) Rio Maggiore River and b) Marroggia River.

Some results obtained for the analysis of the GIUH sensitivity to reductions in basin order are summarized in Table 5. They are added to those given earlier by Corradini *et al.* (1986) for the four larger basins of Table 1. We denote by W^* the basin order after reductions. The GIUH peak flow was found to have a small decrease with decrease in basin order for reductions down to $W^* = 1$. The errors were limited to -12%. Further, the shape of the hydrograph experienced a slight change linked with time to peak which was usually anticipated of a quantity which increased with lowering of the basin order. Figs. 4a-4c show these results for three sample basins with different areas. The errors in time to peak for $W^* = 1$ were typically rather large, however, they did not appear to be important in computing design hydrographs.

A dimensionless GIUH can be derived for the ensemble of basins considered here. Fig. 5 illustrates the extreme curves obtained for the Rio Maggiore and Marroggia River basins, respectively, together with the curve for the Moiano River basin which may be considered approximately as an average among the 21 dimensionless GIUHs computed here. By adopting the last curve as $h^*(t^*)$ and using the basin lag, for each study basin an approximate GIUH was computed. The maximum changes between actual and approximated GIUH were obviously obtained for the Rio Maggiore and Marroggia River basins (see Figs. 6a and 6b) with errors in peak flow of 6.5% and -10.1%, respectively. Similar errors may be reasonably expected in the same region for basins not used in the determination of $h^*(t^*)$.

The role of possible errors arising from the use of the lag-area relationship over the design hydrograph accuracy was examined. The alternating block hyetograph computed from the rainfall depth-duration curve given in Fig. 7 was used. For a given basin, the Curve Number determined for average soil moisture conditions was adopted. The error in peak flow obtained for the Moiano River basin was 4.5% which was considerably less than that in the GIUH peak (8.8%). A similar behaviour of this error was obtained for the other basins of Table 1. As a further example, we examined the changes in the design hydrograph for the Mucchia River basin at Ritorto, which is characterized by values of A (24.6 km^2), D (0.85 km^{-1}) and F (0.49 km^{-2}) comparable with those of the *LD* basins of Fig. 2 and is located in the same region. The value of L^*, if inappropriately estimated from Eq. (1) with the optimal values of α and β, was 3.4 h. The corresponding design hydrograph was compared with

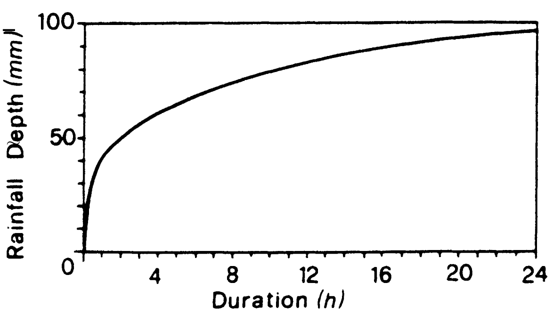

Fig. 7.
Rainfall depth-duration curve for a 25-year return period.
Raingauge of Cortona (see Fig. 1).

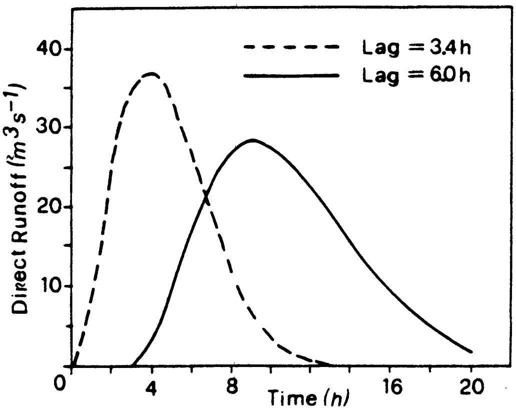

Fig. 8.
Design hydrograph of the Mucchia River basin for a 25-year return period and for different lag times.

that obtained by the basin lag (L=5.9h) expected on the basis of the results for the *LD* basins. From the comparison shown in Fig. 8, it can be seen that the error in basin lag led to overestimate the peak flow by 28%. For extreme initial soil moisture conditions the design hydrographs changed considerably but the effects produced by errors in lag estimate were similar.

Lastly, the errors in the design hydrograph peak for use of a maximum reduction of order, $W^*=1$, or of a prescribed dimensionless GIUH were found to be lower than 10%.

Conclusions

The Gupta *et al.* (1980) formulation of the GIUH requires the estimate of the geometric features of channels and overland regions which are then incorporated in an averaged form. Really, these features could be used to derive, under the same assumption of a spatially constant wave velocity, an IUH based directly on the actual network geometry (Beven 1979; Beven 1991). However, the last procedure becomes more complex with the increase of basin area and therefore an approach which involves an adequate schematization of the actual network appears to be reasonable for practical hydrology. In this context the GIUH, as an element for the estimate of design hydrographs in ungaged basins, is a reliable approach whose application is very simple considering that

1) With the basin lag correctly assessed, a minimum detail is required in representing the geomorphologic features because the basin order may be reduced without considerable errors down to $W^* = 1$. This means that L and the form of the analytical relation for $h(t)$ are sufficient to constrain the main GIUH properties.

2) As an acceptable approximation, a dimensionless form of the GIUH, to be used together with L, may be derived for a given region.

A correct determination of the basin lag is crucial for the reliability of both GIUH and design hydrograph. However, for some small basins with dimensions up to some tens of square kilometres it was found that a simple estimate of L by basin area led to large errors in the design hydrographs. An explicit consideration of the role of drainage channel density appeared to be sufficient to reduce this shortcoming. Lastly, the GIUH computational simplicity together with its link with the main features of channel network indicates that the use of other less accurate approximations is not warranted.

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Address:
Corrado Corradini,
Facoltá di Ingegneria, Istituto di Idraulica,
Universitá di Perugia,
S. Lucia,
I-06100 Perugia,
Italy,

F. Melone,
National Research Council – IRPI,
Perugia,
Italy.

V. P. Singh,
Dept. of Civil and Environmental Engrg.,
Louisiana State University,
Baton Rouge, LA-70803-6405,
U.S.A.