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A Deterministic Gamma-Type Geomorphologic Instantaneous Unit Hydrograph Based on Path Types

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A geomorphological instantaneous unit hydrograph is obtained by dividing the whole catchment into subcatchments, according to the different "path types" which water follows to the outlet of catchment. Each subcatchment produces, at its own outlet, an impulse response which is described by a two-parameter (n, K) gamma function. In traveling to the outlet of whole catchment, each impulse response undergoes a further pure translation with delay time τ, thus producing at the outlet of the catchment a partial impulse response described by three parameters (n, K, and τ). Summation of these partial impulse responses with area weights W forms the impulse response of whole catchment. The parameters K and τ are estimated from catchment characteristics and the flow velocity of each flood event. Area weights W can be calculated from maps after defining the subcatchments. The parameter n is estimated by optimization. The proposed model is tested in two catchments in China and shows encouraging results.

INTRODUCTION

In the past 10 years, several attempts have been made to relate the response of a catchment to its morphologic or topographic features using different hypotheses to model the damping effect of the drainage network [*Rodriguez-Iturbe and Valdes*, 1979; *Gupta et al.*, 1980; *Karlingar and Troutman*, 1985; *Mesa and Mifflin*, 1986; *Chutha and Dooge*, 1990]. Most of these are based on classifying the channel network of the catchment according to Strahler's ordering scheme (for its simplicity and freedom from subjectivity) and assuming that the impulse response of each stream area is an exponential distribution function. This assumption is convenient for finding the catchment response analytically. The resulting impulse response is mathematically equivalent to the response of a conceptual model consisting of linear storage elements in parallel and in series [*Chutha*, 1987; *Bras*, 1989].

Experience has shown that the catchment impulse response can be described more adequately by a gamma-type function than by the simple exponential function [*Nash*, 1957; *Dooge*, 1973; *Rodriguez-Iturbe and Valdes*, 1979; *Bras*, 1989]. In this work the catchment is divided into several subcatchments according to the different "path types" followed by the water, and the impulse response of each such subcatchment is described by a three-parameter gamma distribution function. The whole catchment impulse response is then formed by summation of the impulse responses of all its subcatchments weighted according to their respective areas.

THE IDEA OF A GAMMA-TYPE GEOMORPHOLOGIC UNIT HYDROGRAPH BASED ON SUBCATCHMENTS

The drainage channels of a catchment can be classified according to Strahler's ordering scheme (see Figure 1*a*) as follows: (1) Streams which originate at a source are defined to be of first order. (2) Those formed by the junction of two streams of the order of ω are defined as being of the order of $\omega + 1$. (3) Those formed by the junction of two streams of different order are considered to have the same order as the higher of the joining streams.

For each stream there is a "stream area" which contributes water directly to it. This stream area is assigned an order equal to that of its stream. The order of the catchment Ω is that of the highest stream order occurring.

From precipitation to outflow, water falling on different parts of the catchment may follow different "path types," consisting of one stream area and a series of streams of different orders. Let $C_i (i = 1, 2, \cdots,)$ represent streams of the order of i, then for a third-order catchment, four such path types can be identified as follows:

path type I	$C_1 \rightarrow C_2 \rightarrow C_3$
path type II	$C_1 \rightarrow C_3$
path type III	$C_2 \rightarrow C_3$
path type IV	C_3

With each different "path type" is associated a subcatchment area, a path length, $L_0(L_{01}, L_{02}, L_{03}, L_{04})$, and a delay time, $\tau(\tau_1, \tau_2, \tau_3, \tau_4)$.

For a catchment of the order of Ω the number of possible "path types" is $2^{\Omega-1}$. Thus a catchment of the order of Ω can be divided into $2^{\Omega-1}$ subcatchments according to "path type" as shown in the above example.

Figure 1 schematically depicts a third-order catchment and its four subcatchments according to the four "path types" defined above. From Figure 1 we can see that some subcatchments may have more than one outlet. The proper outlet of a subcatchment is defined as that outlet which has the shortest distance along successive channel segments to the outlet of the total catchment. The length of this shortest distance is designated the path length L_0. In Figure 1*b* the outlet of the subcatchment is at C and the path length L_{01} is the length of the segment CH. In Figure 1*c* the outlet of the subcatchment is at E and the path length L_{02} is the length of the segment EH, etc.

When a unit of effective rainfall, distributed uniformly

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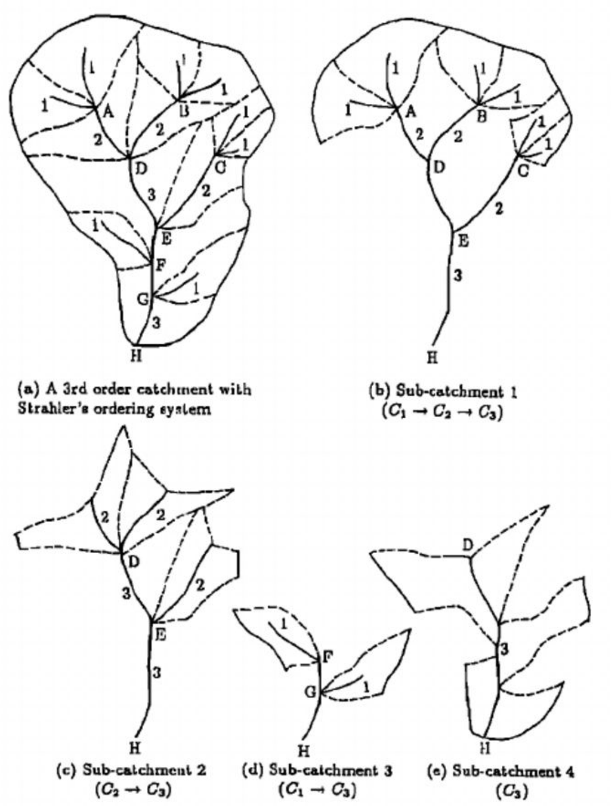

(a) A 3rd order catchment with Strahler's ordering system

(b) Sub-catchment 1 $(C_1 \rightarrow C_2 \rightarrow C_3)$

(c) Sub-catchment 2 $(C_2 \rightarrow C_3)$

(d) Sub-catchment 3 $(C_1 \rightarrow C_3)$

(e) Sub-catchment 4 (C_3)

Fig. 1. A third-order catchment with Strahler's ordering system and its four subcatchments.

over the whole catchment, occurs at time $t = 0$, each subcatchment is assumed to respond, at its own proper outlet, as a two-parameter gamma impulse response function.

$$u(t) = \frac{1}{K\Gamma(n)} \left(\frac{t}{K}\right)^{n-1} e^{-(t/K)} \tag{1}$$

whose parameters depend only on the subcatchment. This impulse response travels along the river channels and eventually arrives at the outlet of the whole catchment, undergoing, in the process, a time delay τ, which depends on the length of the path L_0 and the stream flow velocity V. Thus each subcatchment produces, at the catchment outlet, a partial impulse response in the form of a three-parameter gamma distribution,

$$u(t) = \frac{1}{K\Gamma(n)} \left(\frac{t-\tau}{K}\right)^{n-1} e^{-(t-\tau)/K} \tag{2}$$

The values of the three parameters are unique to each path type within a particular catchment and constitute the parameters of the proposed model in its most general form. Thus for a third-order catchment there would be 12 (four by three) parameters: $n_1, n_2, n_3, n_4, K_1, K_2, K_3, K_4$, and $\tau_1, \tau_2, \tau_3, \tau_4$.

Summation of these partial impulse responses, weighted by the subcatchment area $W_i (i = 1, \cdots, 4)$, gives the impulse response of the whole catchment,

$$U(t) = \sum_{i=1}^{4} W_i u_i(t) \tag{3}$$

where

$$\sum_{i=1}^{4} W_i = 1 \tag{4}$$

IMPLEMENTATION OF THE MODEL

To reduce the number of parameters the following assumptions are made:

1. For a given rainfall-runoff event the shape parameter n is the same for all subcatchments within a single catchment.
2. For a given rainfall-runoff event the streamflow velocity is approximately the same at any moment throughout the whole catchment [*Leopold and Maddock*, 1953; *Pilgram*, 1977; *Rodriguez-Iturbe and Valdes*, 1979]. This velocity can be taken as the velocity at the peak discharge time for a given rainfall-runoff event [*Rodriguez-Iturbe et al.*, 1979].
3. If the length of a path is L_0, then the delay time τ along the path, i.e., the time of transit of the impulse response from the outlet of the subcatchment to the outlet of whole catchment is

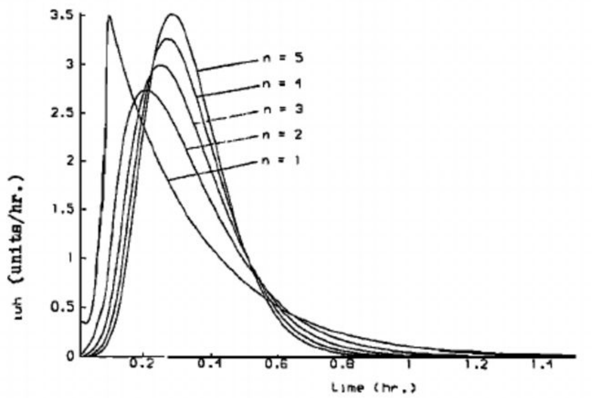

Fig. 2. Effect of parameter n on geomorphologic unit hydrograph with $V = 3.0$ (catchment characteristics are listed in Table 2).

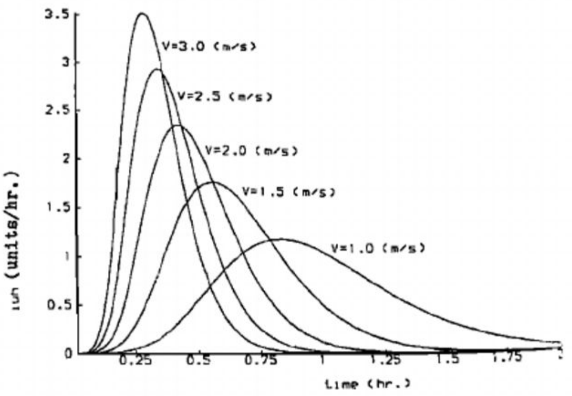

Fig. 3. Effect of velocity on geomorphologic unit hydrograph with $n = 5$ (catchment characteristics are listed in Table 2).

TABLE 1. Parameters of Geomorphologic Unit Hydrograph for the Third-Order Example Catchment

	Path Type			
	I	II	III	IV
W	$\frac{6\bar{A}_1}{A_3}$	$\frac{3(\bar{A}_2 - 2\bar{A}_1)}{\bar{A}_3}$	$\frac{2\bar{A}_1}{\bar{A}_3}$	$\frac{\bar{A}_3 - 3\bar{A}_2 - 2\bar{A}_1}{\bar{A}_3}$
L_0	$\bar{L}_2 + \frac{3\bar{L}_3}{4}$	$\frac{3\bar{L}_3}{4}$	$\frac{\bar{L}_3}{4}$	0
L_{ca}	$\frac{\bar{L}_1}{2} + \bar{L}_2 + \frac{11\bar{L}_3}{12}$	$\frac{\bar{L}_2}{2} + \frac{11\bar{L}_3}{12}$	$\frac{3\bar{L}_3}{8} + \frac{\bar{L}_1}{2}$	$\frac{\bar{L}_3}{2}$
$\tau = \frac{L_0}{V}$	$\frac{\bar{L}_2 + \frac{3\bar{L}_3}{4}}{V}$	$\frac{3\bar{L}_3}{4V}$	$\frac{\bar{L}_3}{4V}$	0
$K = \frac{L_{ca} - L_0}{nV}$	$\frac{\frac{\bar{L}_1}{2} + \frac{\bar{L}_3}{6}}{nV}$	$\frac{\frac{\bar{L}_2}{2} + \frac{\bar{L}_3}{6}}{nV}$	$\frac{\frac{\bar{L}_1}{2} + \frac{\bar{L}_3}{8}}{nV}$	$\frac{\bar{L}_3}{2nV}$

Where V will be obtained by observation, n by optimization, and $\bar{A}_i$, $\bar{L}_i (i = 1, 2, 3)$ from a map of the catchment.

$$\tau = L_0/V \tag{5}$$

4. Mean lag time $nK + \tau$ of each subcatchment is taken as the length (L_{ca}) from the centroid of the subcatchment to the outlet of whole catchment divided by streamflow velocity V, i.e.,

$$nK + \tau = L_{ca}/V \tag{6}$$

Parameter n is a factor which reflects the shape of the geomorphologic instantaneous unit hydrograph (GIUH). Figure 2 depicts the effect of n on GIUH. From Figure 2 we can see that the value of n changes the shape of GIUH changes slightly. In application, n will be decided by optimization.

Velocity V is a parameter which reflects the effect of the catchment's dynamic characteristics on the GIUH. From Figure 3 we can see that even very small changes in V cause relatively large changes in the shape of GIUH. Thus V is a most sensitive factor in the GIUH. In each flood event the value of V depends on the rainfall intensity and duration [*Rodriguez-Iturbe et al.*, 1979] and the catchment hydraulic characteristics. There may exist some relationships between them, but, before these relationships are established, V is

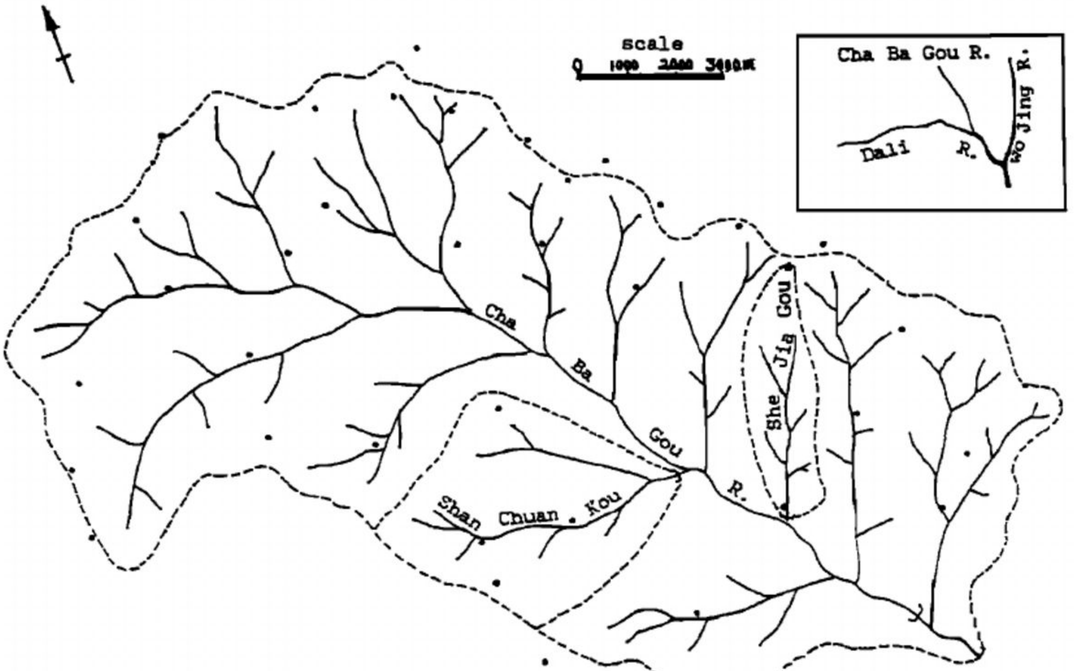

Fig. 4. Sketch of the Cha Ba Gou catchment with the Shan Chuan Kou and She Jia Gou subcatchments (solid dots represents rainfall gauge).

TABLE 2. Characteristics of Catchment Shan Chuan Kou

	Order i			
	1	2	3	4
Number of stream, N_i	237	45	6	1
Average stream length $\bar{L}_i$, km	0.21	0.59	1.69	5.26
Average stream area $\bar{A}_i$, km^2	0.05	0.32	2.46	21.17
Total area drains directly by overland flow to ith order stream $\bar{A}_i$, km^2	12.8	4.67	1.87	1.83
Average stream slope, $\bar{S}_i$, %	19.2	7.6	3.9	1.7

TABLE 3. Characteristics of Catchment She Jia Gou

	Order i			
	1	2	3	4
Number of stream, N_i	76	19	3	1
Average stream length $\bar{L}_i$, km	0.18	0.41	0.71	2.55
Average stream area $\bar{A}_i$, km^2	0.03	0.16	0.66	4.24
Total area drains directly by overland flow to ith order stream, $\bar{A}_i$, km^2	2.43	1.05	0.88	0.22
Average stream slope $\bar{S}_i$, %	10.1	5.5	2.5	22.9

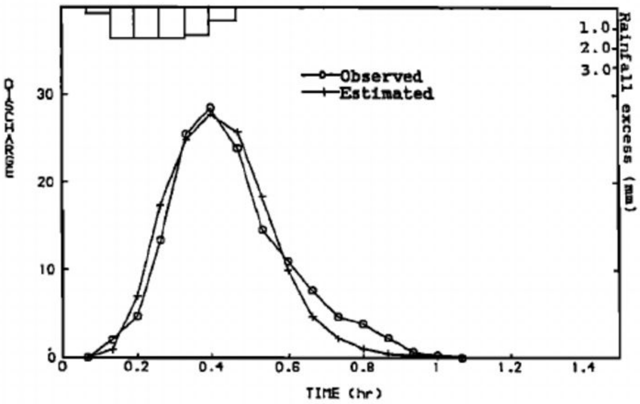

Fig. 5. The estimated and observed discharges for flood July 5, 1964, with $n = 1.25$ (catchment She Jia Gou).

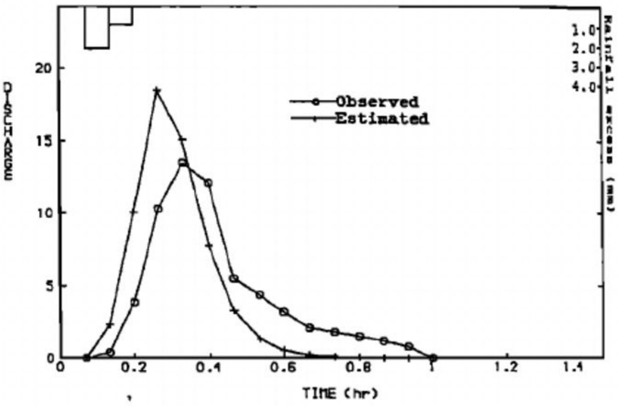

Fig. 7. The estimated and observed discharges for flood August 8, 1966, with $n = 2.25$ (catchment She Jia Gou).

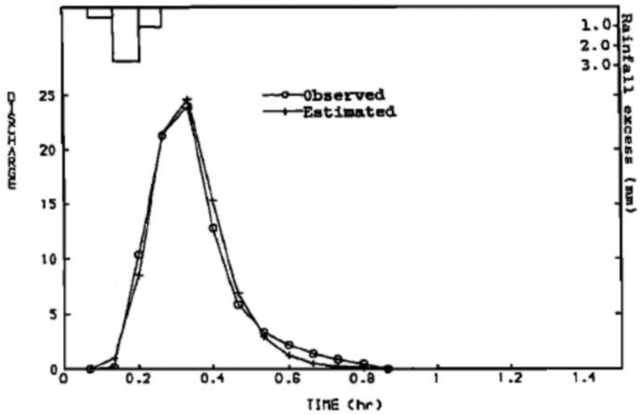

Fig. 6. The estimated and observed discharges for flood July 14, 1964, with $n = 1.75$ (catchment She Jia Gou).

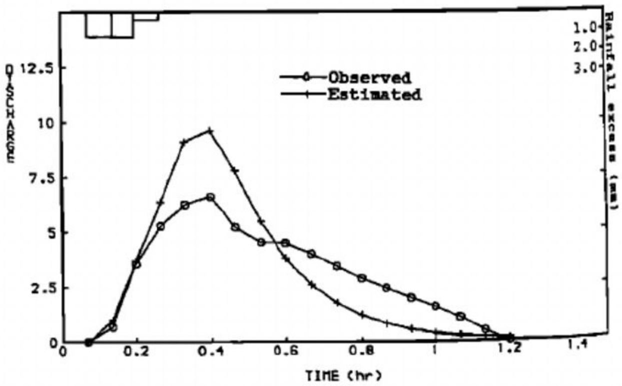

Fig. 8. The estimated and observed discharges for flood August 22, 1967, with $n = 1.25$ (catchment She Jia Gou).

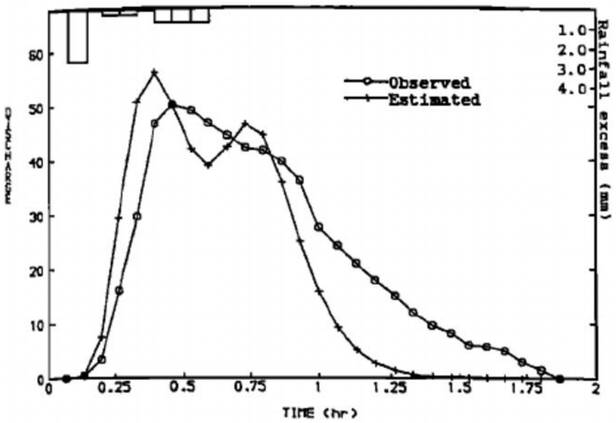

Fig. 9*a*. The estimated and observed discharges for flood August 28, 1963, with $n = 4$ (catchment Shan Chuan Kou).

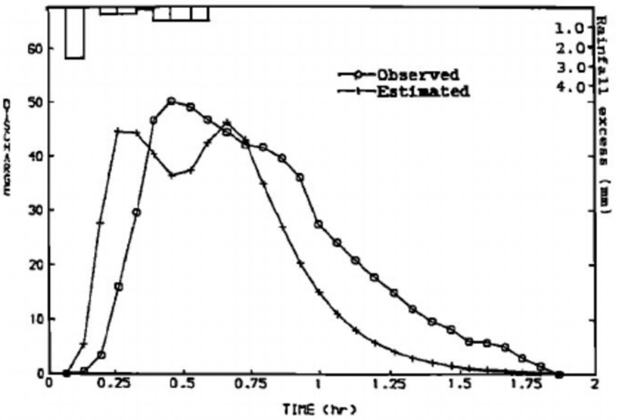

Fig. 9*b*. The estimated and observed discharges for flood August 28, 1963, with $n = 1.5$ (catchment Shan Chuan Kou).

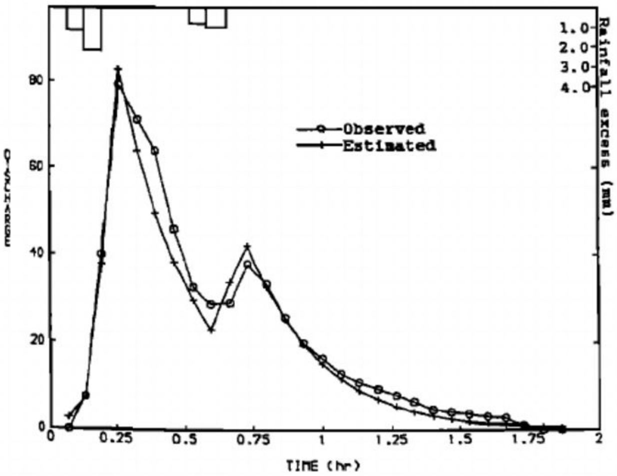

Fig. 10. The estimated and observed discharges for flood July 17, 1966, with $n = 1$ (catchment Shan Chuan Kou).

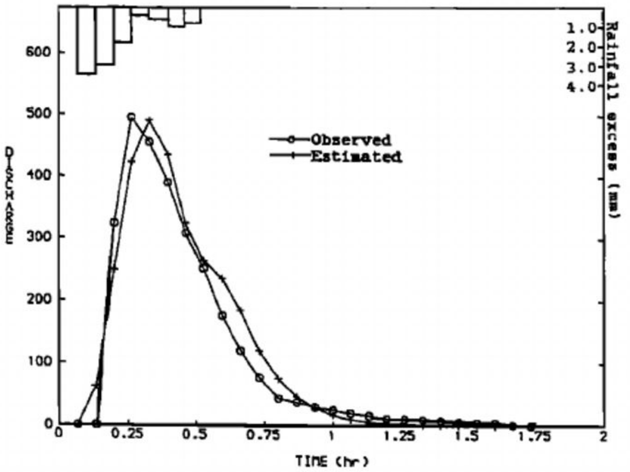

Fig. 11. The estimated and observed discharges for flood August 15, 1966, with $n = 1.25$ (catchment Shan Chuan Kou).

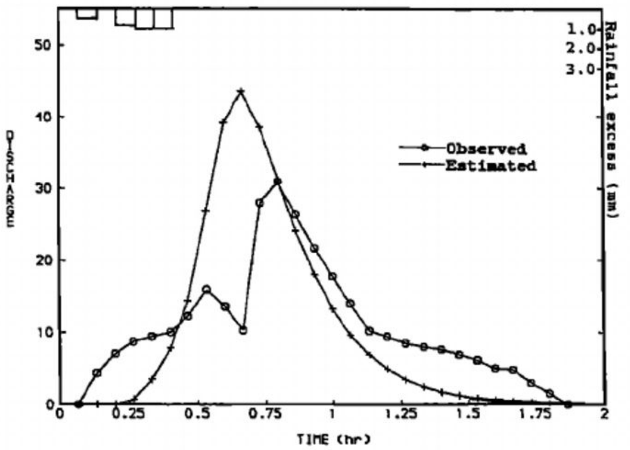

Fig. 12. The estimated and observed discharges for flood August 26, 1967, with $n = 1.25$ (catchment Shan Chuan Kou).

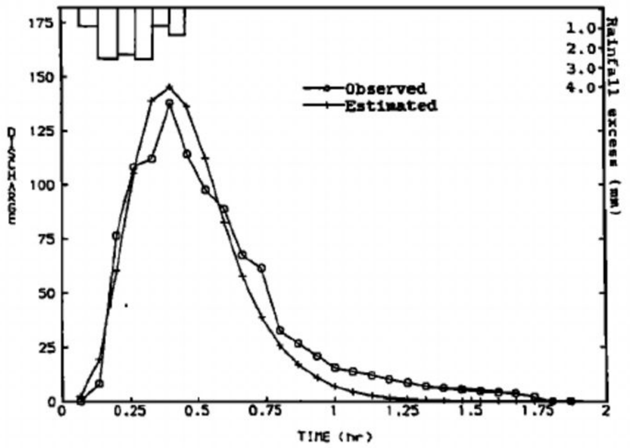

Fig. 13. The estimated and observed discharges for flood May 11, 1969, with $n = 1.75$ (catchment Shan Chuan Kou).

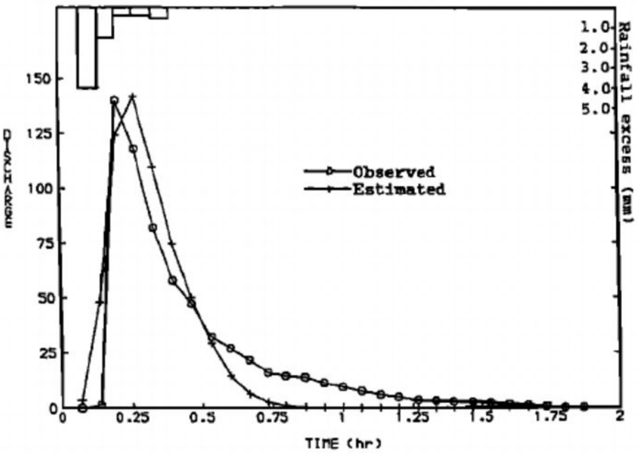

Fig. 14*a*. The estimated and observed discharges for flood August 22, 1968, with $n = 4$ (catchment Shan Chuan Kou).

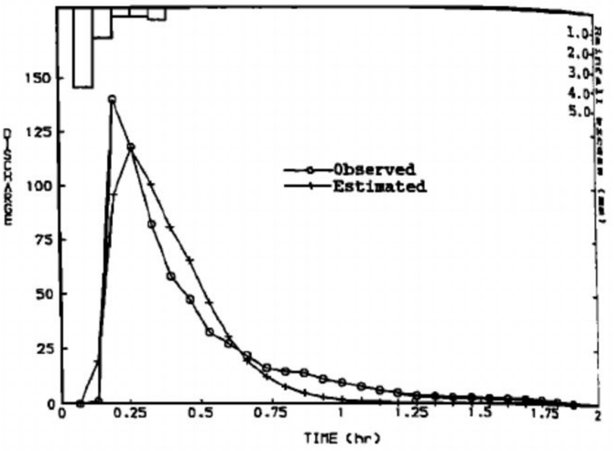

Fig. 14*b*. The estimated and observed discharges for flood August 22, 1968, with $n = 1.5$ (catchment Shan Chuan Kou).

taken as that of the peak observed discharge at the outlet of the catchment.

Area weights W, path lengths L_0, and lengths L_{ca}, can be derived from maps. Taking Figure 1 as an example, $\bar{L}_i$, $\bar{A}_i (i = 1, 2, 3)$ represent the mean length and mean subcatchment area of a stream of the order i. Subcatchment 1 consists of six first-order streams with mean area $\bar{A}_1$. Thus the area of the subcatchment is $6\bar{A}_1$ and the area weight is $W_1 = 6\bar{A}_1/\bar{A}_3$. Subcatchment 2 consists of three second-order streams. The area which drains directly to each second-order stream is equal to the area of the second-order stream minus the area draining directly to first-order streams contained within the second-order catchment. The area of subcatchment 2 is therefore $3(\bar{A}_2 - 2\bar{A}_1)$ and the area weight is $W_2 = 3(\bar{A}_2 - 2\bar{A}_1)/\bar{A}_3$. Similarly, the area weights for subcatchments 3 and 4 are $W_3 = 2\bar{A}_1/\bar{A}_3$ and $W_4 = (\bar{A}_3 - 3\bar{A}_2 - 2\bar{A}_1)/\bar{A}_3$.

The path lengths are given as follows. Two first-order streams and one second-order stream divide the third-order stream into four segments with mean length $\bar{L}_3/4$. Thus the length of path 1 from C to H is equal to the length of segments CE plus EH, i.e., $L_{01} = \bar{L}_2 + 3\bar{L}_3/4$. The length of path 2 is equal to the length of segment EH, i.e., $L_{02} = 3\bar{L}_3/4$. Similarly, $L_{03} = \bar{L}_3/4$ and $L_{04} = 0$.

The length to the catchment centroid is approximated by the appropriate stream midpoint. For example, subcatchment 4 consists of only one third-order stream and the centroid of the subcatchment can be taken as $L_{ca4} = \bar{L}_3/2$. Subcatchment 3 consists of two first-order streams which are not connected. The distance from the subcatchment centroid must therefore be made up of the first-order stream midpoint, $\bar{L}_1/2$, half the distance FG and the distance GH. Thus $L_{ca3} = 3\bar{L}_3/8 + \bar{L}_1/2$. Using a similar procedure, L_{ca1} and L_{ca2} can be calculated (see Table 1).

APPLICATIONS

Description of the Catchments

Two catchments, She Jia Gou (4.24 km^2) and Shan Chuan Kou (21.17 km^2), in North Shaanxi province of China have been selected to test the proposed GIUH model. Both catchments are subcatchments of Cha Ba Gou which is a tributary of the Dali river (Figure 4).

Cha Ba Gou catchment is located in 37°31′N and 109°47′E.

TABLE 4. The Main Characteristics of Rainfall and Runoff for the Selected Flood Events

Events	R, mm	r, mm	Φ	i, mm/min	Q_P, m^3/s	V, m/s	P_a, mm
			Catchment Shan Chuan Kou				
Aug. 28, 1963	31.8	5.56	0.18	0.17	50.0	2.91	31.0
July 17, 1966	38.1	6.21	0.16	0.14	80.0	2.93	19.7
Aug. 15, 1966	47.0	27.0	0.58	0.96	496.0	4.94	41.4
Aug. 26, 1967	15.6	3.25	0.21	0.16	31.0	2.79	38.6
Aug. 22, 1968	21.8	6.75	0.31	0.40	140.0	4.22	27.9
May 11, 1969	40.3	10.8	0.27	0.45	138.0	3.50	16.4
			Catchment She Jia Gou				
July 5, 1964	89.2	7.15	0.08	0.30	28.5	2.90	17.8
July 14, 1964	14.0	4.2	0.30	0.35	24.0	2.71	27.3
Aug. 8, 1966	15.3	3.0	0.20	0.38	13.5	2.38	23.1
Aug. 22, 1967	15.9	3.2	0.20	0.27	6.6	1.45	44.0

R is the total rainfall depth; r is effective rainfall depth; Φ is runoff coefficient equal to r/R; i is average effective rainfall intensity; Q_p is the observed peak discharge at the catchment outlet; V is velocity corresponding to the peak discharge; P_a is the initial soil moisture.

TABLE 5. Parameters W, L_0, and L_{ca} for Catchment Shan Chuan Kou

Path Type	W	L_0, km	L_{ca}, km
I $C_1 \rightarrow C_2 \rightarrow C_3 \rightarrow C_4$	0.35	1.03	3.88
II $C_1 \rightarrow C_2 \rightarrow C_4$	0.11	0.48	3.03
III $C_1 \rightarrow C_3 \rightarrow C_4$	0.09	0.92	3.58
IV $C_1 \rightarrow C_4$	0.05	0.26	2.74
V $C_2 \rightarrow C_3 \rightarrow C_4$	0.17	0.93	3.78
VI $C_2 \rightarrow C_4$	0.05	0.48	2.93
VII $C_3 \rightarrow C_4$	0.09	0.88	3.48
VIII C_4	0.09	0	2.63

Mean annual precipitation is 500 mm and falls mainly between July and September. The precipitation is usually of high intensity, short duration, and large spatial variability. Uniform loess (10 to 60 m in depth) forms the top soil of the catchment which has poor vegetation and is extensively gullied. In each storm event, soil can barely become saturated, and runoff generation is predominantly Horton overland flow. Rainfall intensity and the initial soil moisture state are the main factors affecting runoff production. The proportion of base flow is relatively small in each flood event.

From 1959 to 1969 the Yellow Valley Commission of China set up a number of stations in the catchment to measure precipitation, discharge, soil moisture, etc. Thus resulted 11 years of observed data.

Analysis of Catchment Geomorphology

The drainage network analysis of the two catchments has been performed using a 1/10,000 scale map. Both catchments are fourth order. The main characteristics of the two catchments are listed in Tables 2 and 3.

Calculating Effective Rainfall

To make the problem simple, rainfall-runoff events in which the rainfall is nearly uniformly distributed over the catchment were chosen. The areal rainfall is estimated by the method of arithmetic mean (i.e., to average arithmetically the gauged amounts in the area) and distributed through time according to the automatic gauge inside or near the boundary of the catchment. Six areally uniformly distributed rainfall events were selected for the Shan Chuan Kou catchment and four for the She Jia Gou catchment.

Since the proportion of base flow is relatively small in each flood event, the straight-line method has been used for simplicity to separate the base flow. Once the base flow has been separated, the surface runoff and therefore effective rainfall was obtained by measuring the area above the base flow and below the flood hydrograph. The distribution of rainfall losses during a storm was made using an empirical infiltration equation of the Yellow Valley Commission of China

$$f = \frac{\beta}{2} t^{-1/2} \tag{7}$$

where f is the infiltration rate at time t and β is a parameter reflecting the properties of soil. Equation (7) is a Philip-type infiltration equation without the constant term. Parameter β was determined by trial and error such that the calculated effective rainfall was equal to the surface runoff. For the selected flood events the estimated effective rainfalls and the observed discharges are shown in Figures 5 through 14. The main characteristics of the rainfall and runoff are summarized in Table 4.

TABLE 6. Parameters W, L_0, and L_{ca} for Catchment She Jia Gou

Path Type	W	L_0, km	L_{ca}, km
I $C_1 \rightarrow C_2 \rightarrow C_3 \rightarrow C_4$	0.13	0.98	1.92
II $C_1 \rightarrow C_2 \rightarrow C_4$	0.29	0.20	1.57
III $C_1 \rightarrow C_3 \rightarrow C_4$	0.04	0.99	1.72
IV $C_1 \rightarrow C_4$	0.07	0.26	1.36
V $C_2 \rightarrow C_3 \rightarrow C_4$	0.07	0.97	1.83
VI $C_2 \rightarrow C_4$	0.16	0.20	1.48
VII $C_3 \rightarrow C_4$	0.19	0.85	1.63
VIII C_4	0.05	0	1.28

TABLE 7. The Optimized n for the Test Flood Events

Events	n
Catchment Shan Chuan Kou	
Aug. 28, 1963	4.0
July 17, 1966	1.0
Aug. 15, 1966	1.25
Aug. 26, 1967	1.25
Aug. 22, 1968	4.0
May 11, 1969	1.75
Catchment She Jia Gou	
July 5, 1964	1.25
July 14, 1964	1.75
Aug. 8, 1966	2.25
Aug. 22, 1967	1.25

Calculating Outflow Discharge by GIUH

The area weight W, path length L_0, and length from the centroid of each subcatchment to the outlet of the whole catchment L_{ca} for each of the two catchments were calculated as previously described and the results are given in Tables 5 and 6. For each flood event, V is taken as the velocity corresponding to the peak discharge at the outlet of the catchment (see Table 4). Parameter n is found by successive trial to obtain the best agreement between the estimated and observed discharges. The optimized n for the floods analyzed are listed in Table 7. The calculated and observed discharges are shown in Figures 5 to 14.

The best value of n for the 10 flood events is between 1 and 2.25 except for floods on August 28, 1963, and on August 22, 1968, in which the best value of n is 4. However, even in these two cases, if n is taken to be 1.5, the estimated discharges do not change significantly (see Figures 9*b* and 14*b*).

CONCLUSIONS

1. A relationship between catchment hydrologic response and catchment geomorphologic characteristics has been established. The catchment is divided into several subcatchments according to the different "path types" followed by the water, and the impulse response of each such subcatchment is described by a three-parameter gamma distribution function. The whole catchment impulse re-

sponse is then formed by summation of the impulse responses of all its subcatchments weighted according to their respective areas. The derived GIUH of the catchment varies from storm to storm as a function of flow velocity which reflects the effect of catchment dynamic characteristics on the catchment response.

2. The results of the application show that the value of parameter n varies only slightly for different storms. This is a useful finding for synthesizing a unit hydrograph for an ungauged catchment.

3. By comparing the calculated and observed outflows it seems that the proposed GIUH model is a reasonable approach for obtaining the response function of a catchment.

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