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Development of geomorphologic instantaneous unit hydrograph for a large watershed

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Abstract Hill torrents cause a lot of environmental and property damage in Pakistan every year. Proper assessment of direct runoff in the form of hill torrents is essential for protection of environment, property, and human life. In this paper, direct surface runoff hydrograph (DSRH) was derived for a large catchment using the geomorphologic instantaneous unit hydrograph concept. The catchment with hill torrent flows in semi-arid region of Pakistan was selected for this study. It was divided into series of linear cascades and hydrologic parameters required for Nash's conceptual model, and were estimated using geomorphology of the basin. Geomorphologic parameters were derived from satellite images of the basin and ERDAS and ArcGIS were used for data processing. Computer program was developed to systematically estimate the dynamic velocity, its related parameters by optimization and thereby to simulate the DSRH. The data regarding rainfall–runoff and satellite images were collected from Punjab Irrigation and Power Department, Pakistan. Model calibration and validation was made for 15 rainfall–runoff events. Ten events were used for calibration and five for validation. Model efficiency was found to be more than 90% and root mean square error to be about 5%. Impact of variation in model parameters (shape parameter and storage coefficient) on DSRH was investigated. For shape parameter, the number of linear cascades varied from 1 to 3 and it was found that the shaper parameter value of 3 produced the best DSRH. Various values of storage coefficient were used and it was observed that the value determined from geomorphology and the dynamic velocity produced the best results.

Keywords GIUH · Nash model · Storage coefficient · Peak discharge · The dynamic velocity

Introduction

Sustainable water resources planning and development is the need of the day. On the one hand there is

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acute shortage of water and on the other hand floods cause a lot of environmental damage every year. Solution to such a problem requires evaluation of the intensity of floods for various rainfall events. The rainfall–runoff process is very complicated and the problem of finding the flood magnitudes becomes more challenging when the data is limited or scantily available (Ahmad et al. 2010; Bekele and Knapp 2010; Bahremand and De Smedt 2010; Ahmad 2009; Bahremand and De Smedt 2008). It requires a hydrologic model which may provide the flood magnitudes using limited parameters and data. For such situations, geomorphologic instantaneous unit hydrograph (GIUH) is a very useful tool to predict hydrographs at the basin outlet especially due to recent developments of satellite images and data processing tools. The conceptual models like the linear cascade model (Nash Model) and Clark Model are the most commonly used in this family of models. These models are very effective for operational forecasting (Ahmad 2009; Ahmad et al. 2009; Zelazinski 1986).

Due to the above-mentioned facts, the use of geomorphology GIS, remote sensing GIUH for rainfall–runoff models for poorly gauged basins has attracted the attention of many researchers and presently a lot of work is being published in this regard (Ahmad et al. 2010; Dave et al. 2010; Coskun et al. 2010; Cao et al. 2010; Ahmad 2009; Rai et al. 2009; Nguyen 2008; Sarangi et al. 2007). Bhaskar et al. (1997) showed that temporal distribution of rainfall excess has no marked effect on GIUH simulation. Ramirez (2000) has done extensive research and has elaborated various areas of GIUH. Singh (2004) proposed a simplified method for developing GIUH. Jain et al. (2006) introduced a third hydrologic parameter in IUH to get smooth recession limb of the simulated hydrograph. Jena and Tiwari (2006) correlated unit hydrograph parameters with geomorphologic parameters through regression analysis. Such approach is applicable to a particular region. Singh et al. (2007) developed synthetic unit hydrograph by concept of a number of linear cascades with different storage coefficient "*k*" values. Ahmad et al. (2010) have done extensive work on GIUH; however, the dynamic velocity parameter was not addressed. In GIUH, the dynamic velocity is one of the very important parameters.

Rodriguez-Iturbe et al. (1979) expressed the dynamic velocity as a function of excess rainfall intensity. Kumar et al. (2004) used an arbitrary value of the dynamic velocity due to absence of gauge data for GIUH analysis. Sahoo et al. (2006) showed that if the rainfall excess is assumed to be distributed uniformly over the entire watershed both with respect to space and time, average excess rainfall intensity corresponding to the event peak discharge ($Q_{\max}$) can be calculated from the ratio of peak discharge $Q_{\max}$ and basin area $A_c(Q_{\max}/A_c)$, and can be related to the dynamic velocity. Elaborative work was done to correlate the dynamic velocity with maximum discharge in the present study. Rodriguez-Iturbe et al. (1979) and Zelazinski (1986) proposed this technique for estimation of maximum velocity. A watershed can be categorized as small, medium, and large watershed. A small watershed has area less than 2.5 km^2 and the time of concentration less than 2 h. A medium watershed has area in the range of 2.5 to 25 km^2 and the time of concentration less than 10 h. A large watershed has area greater than 25 km^2 and the time of concentration greater than 10 h. In this way, the data processing in case of large watersheds is highly challenging. The dimensionless parameters, Horton's Ratios, explained in the coming sections, describe the geomorphology of the catchment. These parameters play an important role for rainfall–runoff process. The other parameters which distinguish between large, medium, and small catchments are the number of streams, average length of streams, average area of streams, and the order of streams (see Rai et al. 2009, for definition of these parameters). All these factors have comparatively higher values in case of large catchments.

Geomorphology of watershed

Horton (1945) derived relationships in the form of geometric progressions between number of streams, stream lengths, and corresponding drainage areas. These relationships are known as Horton's laws. The expressions for peak discharge parameter q_p and time to peak t_p were derived by Rodriguez-Iturbe et al. (1979) as:

$$q_p = 1.31 R_L{}^{0.43} \left[\frac{V}{L_\Omega} \right] \tag{1}$$

$$t_{\mathrm{p}} = 0.44\left(\frac{L_{\Omega}}{V}\right)\left(\frac{R_{\mathrm{B}}}{R_{\mathrm{A}}}\right)^{0.55} R_{\mathrm{L}}{}^{-0.38} \qquad (2)$$

Where L_{Ω} is length of the highest order stream in kilometers; V is velocity in meters per second, R_{A}, R_{B}, and R_{L} are Horton's Ratios representing the area ratio, bifurcation ratio, and length ratio, respectively. These are given as:

$$R_{\mathrm{A}} = \left(\frac{\overline{A_{\omega}}}{\overline{A_1}}\right)^{\frac{1}{\omega-1}}, \quad R_{\mathrm{B}} = [N_{\omega}]^{\frac{1}{\Omega-\omega}}, \text{ and } \quad R_{\mathrm{L}} = \left(\frac{\overline{L_{\omega}}}{\overline{L_1}}\right)^{\frac{1}{\omega-1}}$$

Here $\omega$is order of the stream, Ω is order of the basin determined from systematic ordering of streams, $\overline{A_{\omega}}$ is the average area drained by the streams of order ω, N_{ω} is number of streams of order ω, $\overline{L_{\omega}}$ is average length of streams of order ω, and $\overline{L_1}$ is average length of streams of first order.

The units of q_{p} and t_{p} are in per hour and in hours, respectively. The product of the q_{p} and t_{p} is therefore a dimensionless impulse response (IR), the hydrologic similarity coefficient. This IR value calculated from geomorphologic parameters of the watershed is used for determination of hydrologic parameters (n, k) of the linear cascade model (Nash Model).

The original Nash's model (Nash 1957, 1960) is based on linear reservoir theory for input and output in a watershed. The ordinates of Nash's instantaneous unit hydrograph are given as:

$$U_n(t) = \left[\frac{1}{k\Gamma(n)}\right]\left[\frac{t}{k}\right]^{n-1} \exp.^{\left(-\frac{t}{k}\right)} \qquad (3)$$

Where n and k are hydrologic parameters of Nash Model, t is time and $\Gamma(n)=(n-1)!=[(n-1)$ factorial] for integer n. Equation 3 is a two-parameter gamma function. The first parameter "n" is the shape factor or degrees of freedom (number of linear cascades attenuating the IUH peak) and second parameter "k" is the scale factor (storage coefficient, equal for all linear cascades). The parameters n and k are related with one another as$[t/k] = n - 1$. The right hand side (RHS) of Eq. 3 is actually the product of q_{p} and t_{p}. Hence, Eq. 3 can be rewritten as follows:

$$\left[\frac{(n-1)^n}{\Gamma(n)}\right]e^{1-n} = 0.58\left(\frac{R_B}{R_A}\right)^{0.55} R_L{}^{0.05} \qquad (4)$$

The RHS of Eq. 4 is IR, the product of peak flow and time to peak. It is to be determined from geomorphologic study of the watershed. This does not give direct value of n, rather numerical simulation are required for this. Rosso (1984) derived the following expressions for estimation of Nash's model parameter "n" and "k":

$$n = 3.29\left(\frac{R_{\mathrm{B}}}{R_{\mathrm{A}}}\right)^{0.78} R_{\mathrm{L}}{}^{0.07} \qquad (5)$$

$$k = 0.7\left(\frac{R_{\mathrm{A}}}{R_{\mathrm{B}}\,R_{\mathrm{L}}}\right)^{0.48}\left[\frac{L_{\Omega}}{V}\right] \qquad (6)$$

Where R_{A}, R_{B}, R_{L} are the Horton's ratios; L_{Ω} is length of highest order stream in kilometers; V is expected peak velocity in meters per second and k is in hours. The term $[L_{\Omega}/V]$ is travel time in the highest order stream, which shows that k is effective when surface runoff enters the highest order stream. Kumar et al. (2004) showed that shape of GIUH is very sensitive to L_{Ω} and V, the dynamic velocity. Zelazinski (1986) reported a similar equation for estimation of "k" in slightly different form as:

$$k = 1.58\left(\frac{R_B}{R_A}\right)^{0.55}\frac{R_L{}^{-0.36}}{(n-1)}\left[\frac{L_{\Omega}}{V}\right] \qquad (7)$$

where L_{Ω} is the length of main stream in meters. All the terms in Eq. 7 are derived from geomorphology of the watershed except velocity. Thus, an important aspect associated with Nash's Model based on GIUH is determination of maximum velocity corresponding to certain hydrologic rainfall–runoff event.

Rodriguez-Iturbe et al. (1979) related the dynamic velocity parameter of GIUH to the peak velocity corresponding to the peak discharge for a particular rainfall–runoff event. Zelazinski (1986) proposed this technique of velocity determination and showed that the representative stream velocity associated with the maximum discharge at a section where main stream leaves the boundary of watershed can be represented as follows:

$$V_{\max} = \alpha(Q_{\max})^{\beta} \qquad (8)$$

Where α and β are constants determined from the set of values of measured discharge. The discharge was measured at a section where the main stream leaves the watershed boundary. A higher value of β means rapid increase in velocity corresponding to discharge. The Eq. 8 is essentially an equation of hydraulic geometry with exponent beta being less than unity. Velocity can be determined if the parameters α and β are identified by optimization, using a set of flood events data. This concept is elaborated in this paper. A subroutine for optimization of parameters α and β was developed on the basis of Downhill Simplex method (Gill et al. 1981; William et al. 1986).

Study area

Pakistan is a developing country and depends heavily on its water resources. Arid/semi-arid regions in the country receive storms for very short duration. So it was felt necessary to apply the concept of GIUH in Pakistan, as direct surface runoff hydrograph based on GIUH has not been developed for any catchment of Pakistan. The study area is located in arid/semi-arid region of Pakistan (Fig. 1a) and is called “Kaha Watershed”. There are a few perennial irrigation schemes called karezes originating from aquifers having negligible flows like 0.02 m^3/s and are charged by hill torrent flows. Local farmers harness moisture from flood flows for cultivation by building various temporary diversions. The geomorphology of the area is very complex due to rugged terrain and sharp bends in natural streams. No detailed maps are available as the area is scarcely populated and is inaccessible due to non-availability of proper road infrastructure. However, presence of satellite images of the area and GIS environment processing (ERDAS) has made possible to know the geomorphologic details of this area. The 60–65% of catchment area consists of barren mountains without or with minor vegetation. Almost all the streams are ephemeral in nature, flowing during monsoon or winter rains only. The catchment is poorly drained with floods carrying heavy sediment load to the River Indus. The land-use map of the area is shown in Fig. 1b. It is a space image taken by NASA World Wind (Oosterbaan (2010)). The Indus River is clearly visible in it. On the right-hand side of Indus, some alluvial fans and spate irrigation (Rod-Kohi) practices can be visualized but the left-hand side related to the study area is mainly barren.

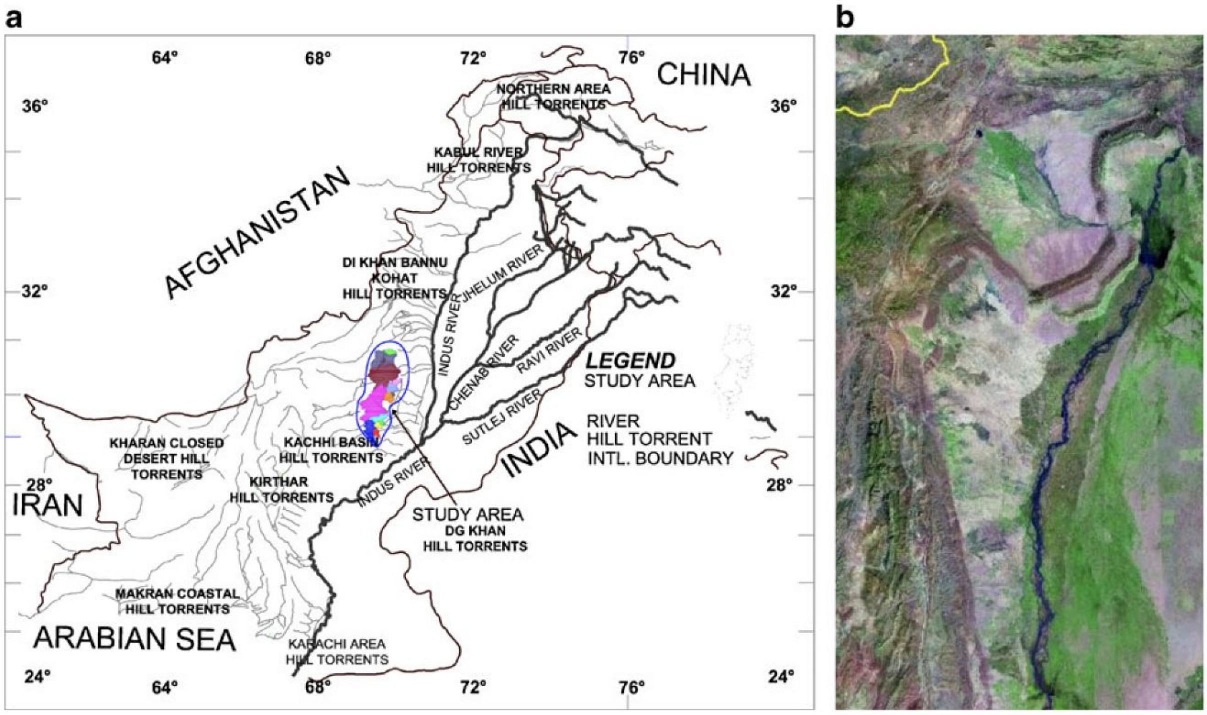


Fig. 1 **a** Map of Pakistan showing geographical location of the study area. **b** Land-use map of the area (Image from space obtained from NASA World Wind; after Oosterbaan (2010))

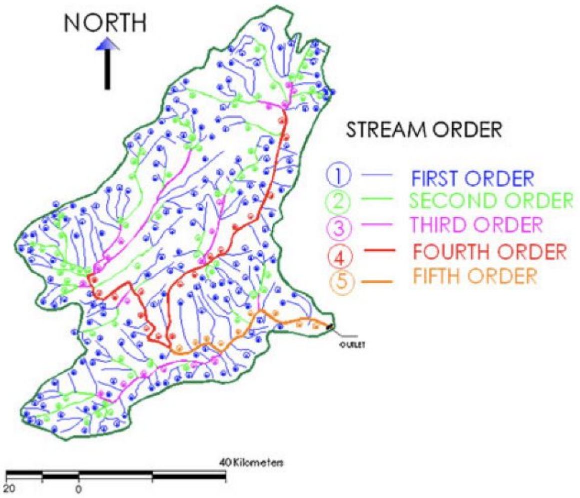


Fig. 2 Drainage pattern and stream order in Kaha Watershed

Digitization of catchment map and data processing

Data processing of the watershed in this study was done using ArcGIS to obtain the required geomorphologic information. The watershed hydrologic area was determined as 5,597.80 km^2. The total length of streams was calculated as 1,711.19 km. Strahler's Method was applied to determine the scheme for stream ordering (Linsley et al. 1982). The drainage density which is the stream's length per unit area of watershed was found to be 0.3 km/km^2. The length of longest stream was estimated to be as 171.06 km and the length of highest order stream was found to be 53.72 km.

The watershed's stream order was determined to be 5 as highlighted in Fig. 2. The data of rainfall–runoff for last 15 years was obtained from Irrigation and Power Department, Pakistan. Although the number of rain gauges needed to fully define rainfall distribution over the drainage area is not limited, a minimum number is normally required to arrive at a realistic conclusion. In this study, data from 13 non-recording type rain gauges was used out of which three stations were installed in Kaha Watershed. The geographic location of rain gauges is shown in Fig. 1a. Various colors in it represent locations of various catchments (Ahmad 2009). Kaha is the largest among these catchments. Each catchment has a gauging station located approximately at the center of the catchment. The Kaha catcment has more than one gauging stations evenly distributed over the area. The total rainfall depth was converted to excess rainfall by subtracting the losses using the percentage runoff technique (Linsley et al. 1982). The rainfall values corresponding to runoff events are given in Table 1. The hill torrent flows are highly dangerous and it is not advisable to measure velocity of flow for determination of observed flows. So the observed discharge hydrographs were obtained by the use of rating curve. The cross-section of the main stream and its bed slope was obtained with the help of survey data and the stage values were recorded by a non-recording gauge with respect to time for the demarcations at various levels of the main stream for different flood events. All this data was taken from Irrigation and Power Department,

Table 1 Rainfall data of Kaha Watershed

Event number	Year	Total rainfall (mm)	Total rainfall excess (mm)	Duration (h)
01	1977	009	03.83	06.0
02	1978	110	32.24	13.0
03	1980	050	15.54	08.0
04	1981	013	04.04	06.0
05	1982	077	23.09	10.0
06	1983	110	32.99	10.0
07	1984	082	23.29	10.0
08	1985	046	14.30	08.0
09	1988	050	15.54	08.0
10	1989	055	16.49	10.0
11	1990	058	17.20	08.0
12	2003	062	17.30	08.0
13	2004	057	17.10	08.0
14	2005	055	17.00	08.0
15	2006	037	11.58	06.0

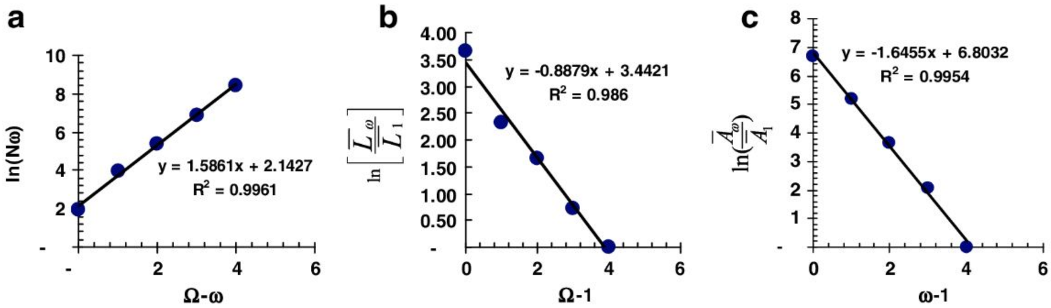


Fig. 3 **a** Plot for Horton's ratio R_B; **b**. Plot for Horton's ratio R_L; **c** Plot for Horton's ratio R_A

Pakistan. It is worth mentioning here that there is some noise in the data regarding observed flow for low stage values due to which all storms have nearly the same base length of 30 h. However, the maximum discharge for various events was estimated by also the authors from the highest flood marks to validate the peak flows in current data.

Horton's geomorphologic descriptors

The Horton's Ratios are dimensionless parameters describing geomorphology of the catchment. These are obtained from the best-fit lines of graphs of number of streams, average length of streams, and average area of streams vs their respective order. The values of bifurcation ratio R_B, length ratio R_L, and area ratio R_A for Kaha watershed were found to be 4.8847, 2.43, and 5.18, respectively, from the plot of Horton's Ratios as shown in Fig. 3a to c.

Model performance test

The following parameters were selected to check the performance of the model (Nash and Sutcliffe 1970 and Ahmad 2009).

$$\eta = \left[1 - \frac{\sum_{i=1}^{i=\mathrm{NQ}} (Q_{\mathrm{oi}} - Q_{\mathrm{ci}})^2}{\sum_{i=1}^{i=\mathrm{NQ}} (Q_{\mathrm{oi}} - \overline{Q}_{\mathrm{o}})^2}\right] \times 100 \tag{9}$$

$$\mathrm{Z} = \left\{\frac{1}{\mathrm{NQ}}\left[\sum_{1}^{\mathrm{NQ}} (Q_{\mathrm{oi}} - Q_{\mathrm{ci}})^2 \left(\frac{Q_{\mathrm{oi}} + \overline{Q}_{\mathrm{o}}}{2\overline{Q}_{\mathrm{o}}}\right)\right]\right\}^{\frac{1}{2}} \tag{10}$$

Where "η" is model efficiency and "Z" is peak weighted root mean square error. NQ is number of ordinates of the hydrograph, i is index varying from 1 to NQ, Q_{oi} is ith ordinate of the observed hydrograph, Q_{ci} is ith ordinate of the computed/simulated hydrograph, and $\overline{Q}_{\mathrm{o}}$ is mean of the ordinates of the observed hydrograph.

Parameters estimation for Nash's conceptual model

Shape parameter "*n*" (number of linear cascades/reservoirs)

The parameter *"n"* is related to Horton's geomorphologic descriptors by Eq. 4. Equation 4 does not give a direct value of *"n"*. The right-hand side of Eq. 4 was estimated from the geomorphologic descriptors of Kaha catchment. A small computer program was developed to solve Eq. 4 by hit and trial method. The value of *"n"* was varied each time by 0.01 and the absolute error (the difference between right-hand side and left-hand side of Eq. 4) was checked. Zero error was obtained for $n = 3.3$. A few values of n and corresponding error in the solution of Eq. 4 are given in Table 2. However, to facilitate the research in future the left-hand side of Eq. 4 for various values of n has been plotted against *"n"* and given in Fig. 4. The value of *"n"* can be obtained directly from this figure against the right-hand side of Eq. 4 estimated from the geomorphologic descriptors of any catchment. The value of *"n"*

Table 2 Error in solution of Eq. 4 for various *n* values

n	1	1.5	2	2.5	3	3.3	3.5	4	4.5	5
ABS (error)	0.58	0.34	0.34	0.12	0.04	0.0	0.03	0.09	0.15	0.2

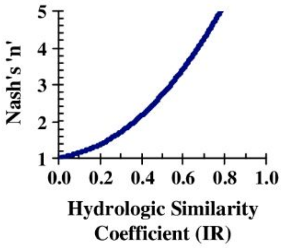


Fig. 4 Parameter *n* and hydrologic similarity coefficient IR

determined as 3.3 using geomorphologic descriptors of Kaha watershed was rounded to the nearest integer as 3 in this paper for further use. The value of *n= 3* have significant meanings. It is highly important parameter in the rainfall–runoff processing. As it is related to the shape of the watershed so it reflects the impact of size of the watershed as well. It is a catch-all-type parameter with respect to the shape of the watershed and its value increases by the increase of size of the watershed. The parameter *"n"* represents the number of linear cascades attenuating the IUH peak; hence, large catchments will have higher values of *n* as compared to the small catchments. As the simulated results are sensitive to the values of *n* parameter so rounding off for this parameter introduces error in the simulated runoff. Figure 4 shows the impact of changing the values of *"n"*. The *n* value equal to 1 does not incorporate all the features of a large watershed and gives high error between simulated and observed runoff. The large watersheds should be modeled by taking *n= 3*.

Scale parameter "*k*"—storage coefficient

As explained earlier, the parameter "*k*" is related to velocity which is a dynamic characteristic of the watershed. It is a catch-all parameter and accounts for variations in hydrologic inputs and outputs. The *k* parameter is inversely related to velocity by Rosso (1984) as given by Eq. 6. The determination of velocity for single rainfall–runoff event requires its relationship to peak discharge. The velocity derived from observed rainfall–runoff event is used to determine "*k*" in this study.

Results and discussion

Sensitivity analysis

In order to study the effect of Nash "*n*" and "*k*" on the degree of error in simulated peak discharge, model was run for all the 15 observed rainfall–runoff events for the values of *n* and *k* in the range their values obtained from the geomorphologic descriptors. The results are shown in Figs. 5 and 6. For a given value of *k*, the value of *n* was varied from 1 to 3 which is an upper limit obtained from geomorphologic descriptors. It was observed that the value of *n* equal to 3 produced the best results as the catchment area was large. This value produced 1:1 slope of best-fit line between observed and simulated maximum discharge. This is in line with the Ponce results who describes that the value of "*n*" is normally 3 for surface runoff simulation in large catchments (Ponce 1989). The value of "*k*" was varied as 3, 3.5, 4, and 4.5 h for a given value of *n*. The 4-h value of "*k*" produced minimum error between observed and computed maximum discharge. This value of *k* corresponds to velocity of 3.7 m/s in the highest order stream. The velocity in this range is normally observed during flood events. The runoff diffusion phenomenon is dominant as compared to translation flow effects when evaluating hydrologic

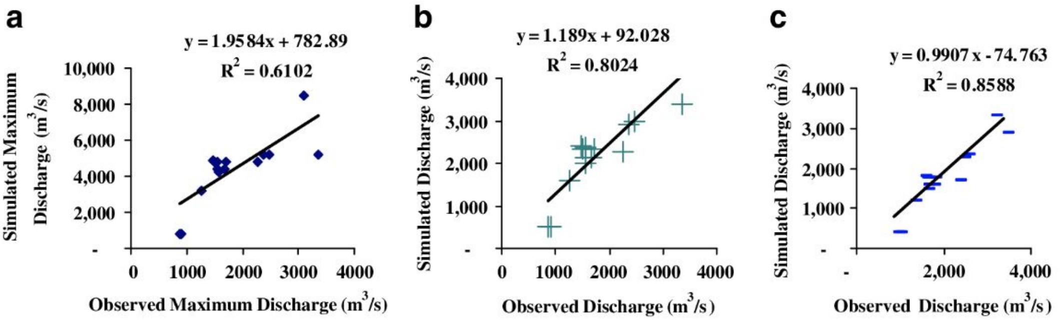
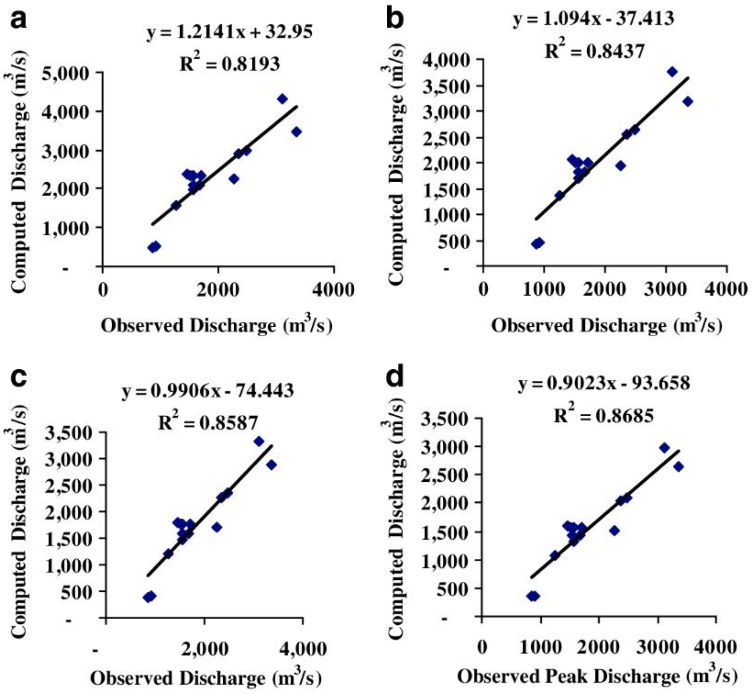


Fig. 5 **a** Observed vs simulated discharge for *n*=1. **b** Observed vs simulated discharge for *n*=2. **c** Observed vs simulated discharge for *n*=3

Fig. 6 **a** Simulated and observed peak discharges for k=3. **b** Simulated and observed peak discharges for k=3.5. **c** Simulated and observed peak discharges for k=4. **d** Simulated and observed peak discharges for k=4.5



response of catchments of large size. Hence, the direct runoff hydrograph shape is more sensitive to n value than that of k in large catchments.

Calibration of the model

After having an idea about the sensitivity of parameters, the optimization process was made to have global parameters of the catchment. Table 3 shows the optimized values of α, β, V, and k. The velocity V in this table is simulated velocity and represents the optimized value of velocity. It is observed that the events 1 and 4 show comparatively larger values of velocity. It is due to the fact that small discharge values are result of pocket flash floods in the vicinity of outlet and the velocity under discussion represents the peak flows in the highest order stream. Hence, it should not be intermixed with the normal stream velocity applicable to the entire watershed.

Table 3 Parameters of Nash-GIUH obtained by the calibration of the model

Event no.	Q_o (observed) (m³/s)	α	β	V (m/s)	k (h)
1	866	0.5820	0.4750	5.55	1.5
2	3,356	0.1734	0.3021	2.60	3.2
3	1,671	0.1828	0.2875	2.17	3.9
4	913	0.6600	0.4924	6.40	1.3
5	2,364	0.1625	0.2924	2.16	3.9
6	3,109	0.1321	0.2680	1.93	4.3
7	2,478	0.1689	0.2976	2.29	3.7
8	1,570	0.1897	0.3112	2.20	3.8
9	1,557	0.1742	0.2995	2.02	4.2
10	2,265	0.2115	0.3263	2.78	3.0
Optimized		0.2233	0.3280		4.0

Validation of the model

Using the values of “n” and “k” identified by optimization of the velocity parameters, five rainfall events were simulated to confirm the applicability of the derived parameters of the Nash Model. The observed and simulated hydrographs of direct surface runoff for five events 11 to 15 are shown in Fig. 7. Table 4 shows the results obtained for the validation events 11 to 15 in terms of error estimators.

It is observed from Table 4 that Nash's model based on geomorphologic details of watershed gives fairly accurate results. The model efficiency varies from 87% to 95%, which is acceptable as unit hydrograph technique itself have some inherent approximations (Linsley et al. 1982). Hydrologists, while reporting

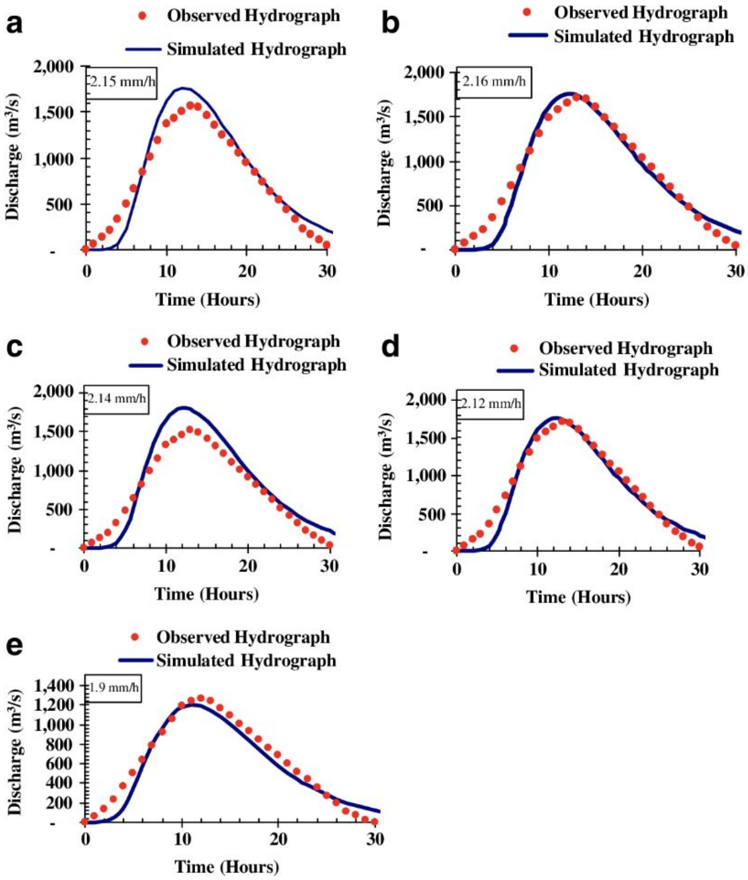


Fig. 7 **a** Hydrographs for event no. 11. **b** Hydrographs for event no. 12. **c** Hydrographs for event no. 13. **d** Hydrographs for event no. 14. **e** Hydrographs for event no. 15

flood hydrograph peak, increase it by 5–20% before using unit hydrograph for the estimation of extreme floods (Linsley et al. 1982). The objective function *Z* has values less than 5%. The percent error in runoff volume is around 10% except for the last event (number 15) which itself is of low potential. This error may be due to bias in data. The hydrograph peak was observed to be slightly over estimated which is expected to be due to rounding off the parameter "*n*" on lower side. It was rounded-off from 3.3 to 3. Zelazinski (1986) reports that this deviation is generated by the rainfall excess estimation or by missing input data.

As shown in Fig. 7, the peak discharge, time to peak, and time base of the observed and computed hydrographs match well. However, the rising limb of hydrograph is under estimated. This error is thought to be due to estimation of parameter "*n*". If *n* is decreased, the time to peak will decrease with associated increase in peak discharge due to quick response from the watershed. It was estimated with the help of Fig. 3 that the length of maximum order

Table 4 Statistical parameters obtained from validation test of Nash's Model

Event no.	η (percent; %)	Percent error in runoff volume	Percent error in peak discharge	Percent error in time to peak	*Z*
11	92	12	13	0	138
12	95	1	2	8	93
13	88	9	17	14	175
14	87	18	19	7	182
15	95	5	5	8	76

stream is about 30% of the maximum hydraulic path. Therefore, runoff will be accumulated abruptly when entering the stream of highest order, but before this time, the response of the watershed will start slowing down.

Conclusion

Nash's model of linear cascades based on Horton's geomorphologic descriptors has been developed for a large watershed of area 5,598 km^2 in a semi-arid region with complex geomorphology and hill torrent flows in Pakistan. The dimensionless parameters (Horton's Ratios) describing geomorphology of the watershed play an important role for rainfall–runoff process in large watersheds These are dependent upon number of streams, average length of streams, average area of streams, and their respective order. All these parameters have comparatively higher values in case of large catchments. The total length of streams was calculated as 1,711.19 km. The drainage density which is the stream's length per unit area of watershed was found to be 0.3 km/km^2. The length of longest stream was estimated to be as 171.06 km and the length of highest order stream was found to be 53.72 km. The watershed's stream order was determined to be 5. The values of bifurcation ratio R_{B}, length ratio R_{L}, and area ratio R_{A} for Kaha watershed were found to be 4.8847, 2.43, and 5.18, respectively. A computer program has been developed for Nash Model and for estimation of expected peak flow velocity. A subroutine based on Downhill Simplex method for optimization of parameters of velocity has been developed. Sparse watershed hydrologic data has been used to develop Nash's-GIUH model which is easy to use and requires minimum updating of the hydrologic parameters. The conceptual model gives results of acceptable accuracy. It is established that hydrologic response of the watershed is closely related to geomorphology. The GIUH theory can be applied to large watersheds in arid to semi-arid regions. The dynamic velocity parameter can be related to peak flow of rainfall event. Two parameters need to be optimized for this purpose. The parameter n is an important parameter. It is related to the shape and size of the watershed. It is a catch-all-type parameter with respect to the shape of the watershed and its importance increases by the increase of size of the watershed. It represents the number of linear cascades attenuating the IUH peak. Rounding off for the parameter n introduces error in the simulated runoff. The n value equal to 1 does not incorporate all the features of a large watershed. The best value of Nash parameter n obtained from geomorphologic descriptors may vary from catchment to catchment and is equal to 3 for a large catchment like Kaha. The parameter k should be determined from velocity–discharge relationship that produces best results for the observed peak discharge events. It is concluded that the value of k equal to four produces the best results. The runoff diffusion phenomenon is dominant as compared to translation flow effects when evaluating hydrologic response of catchments of large size. Hence, the direct runoff hydrograph shape is more sensitive to n value than that of k in large catchments.

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