WATER RESOURCES
AND THE REGIME OF WATER BODIES

Investigating Parameters of Geomorphic Direct Runoff Hydrograph Models[1]

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Abstract—Formulation of rainfall runoff models and identification of their parameters is difficult step especially for catchments having scanty or no data. Parameters of geomorphic instantaneous unit hydrograph (GIUH) models have been investigated in this research. Recorded data of Shahpur Dam Catchment, Pakistan was used for developing direct runoff hydrograph model. Satellite imageries of the catchment were processed using ArcGIS 10.1 to estimate geomorphologic parameters. The rainfall and runoff data for 10 events was collected from Meteorological Department Lahore and from Small Dam Organization, Rawalpindi, Pakistan. Rainfall data was analyzed and excess rainfall was estimated using Percent Runoff Method. Using estimated geomorphologic parameters the ordinates of GIUH- Nash Model were obtained by standard equations of Nash instantaneous unit hydrograph (IUH). These ordinates of Nash-IUH, were converted into the ordinates of direct runoff hydrographs through their convolution with the excess rainfall. The results of model were evaluated on the basis of their deviation from the observed runoff data. Statistical parameter Nash-Sutcliffe Coefficient and percent error between observed and simulated direct runoff were used for this purpose. The impact of using digital elevation models (DEM) of two different resolutions; 30 and 90 m, was then investigated. It is observed that the geomorphic parameters are affected due to DEM's resolution. Hence the resolution of DEM impacts the direct runoff as well.

INTRODUCTION

Research in the field of water resources engineering and management has always remained hot issue world-wide. A lot of work in this field has been done in the near past [1, 13, 16, 18, 20, 24]. Chowdhury and Al-Zahrani [8] have investigated trends of water resources consumption. Chowdhury [9] explored the adverse effects of climate changes on crop-water-requirements. Matishov [28], Sharif [37] and Corduneanu [6] have highlighted the hazards of extreme hydrologic events. Kim [23] have studied characteristics of water-infrastructure of a catchment.

The rainfall runoff process is highly complex hydrologic phenomenon. It is non-linear and dynamic process. The parameters involved in rainfall runoff modeling have both spatial and temporal variability. These parameters are interrelated but the relations are not well defined. Accordingly, a large number of physically based and conceptual rainfall runoff models are in use [14, 15, 17, 21]. The physically based models need extensive data regarding the catchment parameters related to climate, topography, soil and land-use etc. Moreover these parameters are subject to change in their values due to the time to time changes in climate and land-use. A lot of funds are required to acquire detailed and long term data for physically based models, because installation of a thick network of measurement stations for long durations is needed at several locations in the catchment.

The conceptual rainfall runoff models based on geomorphic instantaneous unit hydrograph (**GIUH**) approach are being the most commonly used due to advancements in remote sensing and geographical information system (**GIS**) tools [14, 25, 29, 38, 39].

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This family of rainfall runoff models uses geomorphologic parameters like area, shape, topography, stream density and slope of the catchment. The channel network, slope of channels, and channel storage are also important for these models. As the runoff travels to the catchment outlet through channels of various orders and different paths in the catchment so it can be related to the geomorphologic parameters. Various researchers have explored this aspect rigorously. The work done by Horton [19], Rodriguez-Iturbe and Valdes and their colleagues [34, 35], Zelazinski [40] and Rosso [36] can be considered as pioneer in this field. Some of the authors have compared performance of various GIUH models and investigated possible improvements in modeling for catchments having scanty data [2, 10, 26]. The analysis of above mentioned researchers shows that any error in estimation of catchment parameters results into an error in the GIUH. The main parameters determined by GIS tools are stream-area and length ratios, maximum and minimum elevations of catchment and bifurcation ratio. Jaiswal [21], Bhimjiani [5], Choi [7], Almeida [4] and Emmerik [12] also studied the difficulties in parameter estimation and uncertainty in stream flows of ungauged catchments due to data errors, change in catchment characteristics and model structure errors. Results of these researchers showed that no standard model can be designed for modeling ungauged basins, because there is always uncertainty in predicting the parameters of a model especially for ungauged catchment.

The above discussion shows that it is very important to understand the importance of parameters used in GIUH models. There are several factors affecting the values of geomorphic parameters. One of these might be the resolution of digital elevation model used for evaluation of the parameters. Some of the above mentioned papers have used 30 m DEM, a few have used 90 m and others have used even more rough resolutions. This paper has investigated the impact of using 30 and 90 m DEM on runoff estimated by GIUH. Some researchers have executed work in this regards and shown better results from DEM of good resolution. For example the elevation of Makkah was found to be closer to real heights when calculated through a DEM of comparatively better resolution [29]. Similarly the Soil and Water Assessment Tool (**SWAT**) was shown too sensitive to the resolution of the DEM because the DEM of resampled resolution were not showing the same trend as the DEM of original resolution [11]. River networking was done on 10 and 30 m DEM taken from United States Geological Survey and the results showed that 10 m DEM is the closest to real data [22]. Most of the work done in this regards is related to the estimation of parameters using DEM of different resolutions. Very little work however has been done to estimate the impact of resolution of DEM on the runoff from a catchment.

STUDY AREA

Shahpur Dam located on Nandna River in Punjab, Pakistan (Fig. 1) is a concrete gravity type dam. The dam height is 26 m and it has storage of $17\,620\,000$ m^3. It was constructed by Government of Punjab in 1986. It is a component of small dam series in Punjab arid areas. The dam is in semi-arid district of Attock. The coordinates of the site are 72°41′51″ E and 33°37′30″ N. The dam is situated in Kala Chitta Range in Attock District, at about 50 km away from Islamabad. The topography of the area including the watershed ranges from level 424 to 540 m. It covers a catchment area of about 202 km^2. The soil is sandy-silty-clay.

MATERIALS AND METHODS

The methodology is described with the help of schematic flow chart given in Fig. 2. There mainly four steps for the work done in this research. The first one is data collection, second is data processing and analyzing, third is estimation of direct runoff and finally the fourth one is evaluation of the models. These are further discussed in detail in the following paragraphs.

Data Collection and Analysis

Small Dams Organization, Rawalpindi, Pakistan is responsible for reservoir operation and other and aspects of Shahpur Dam. They have recorded rainfall data from Meteorological Station Fatehjan and Attock, close to the Shahpur Dam. Rainfall data for 10 events was taken from this organization. The observed direct runoff for these rainfall events was also collected them. Isohyetal method was used to determine average rain over the catchment. Three techniques mainly are used to find the excess rainfall. These are Percentage Runoff Method Curve Number Technique, and Constant Loss Approach [27]. The Constant-loss Method is comparative lesser realistic as the losses do not remain constant over the entire rainfall duration. The Percentage Runoff Technique is considered better than the other two techniques [3]. This method uses a constant ratio of the excess rainfall to the total rainfall. In this paper the excess rainfall was estimated by the Percentage Runoff Method. Estimated excess rainfall in this way is given in Table 1. The 30 and 90 m DEMs were processed to find the geomorphological parameters of catchment using Arc-GIS-10.1.

Geomorphologic Characteristics of Watershed

Geomorphologic characteristics of the Shahpur Dam watershed shown in Table 2 were estimated from DEM processed by using Arc GIS 10.1 software. The satellite imagery of the catchment was processed to determine catchment area, stream order, stream areas and lengths. The corresponding length and area of the surface runoff of each channel order was measured.
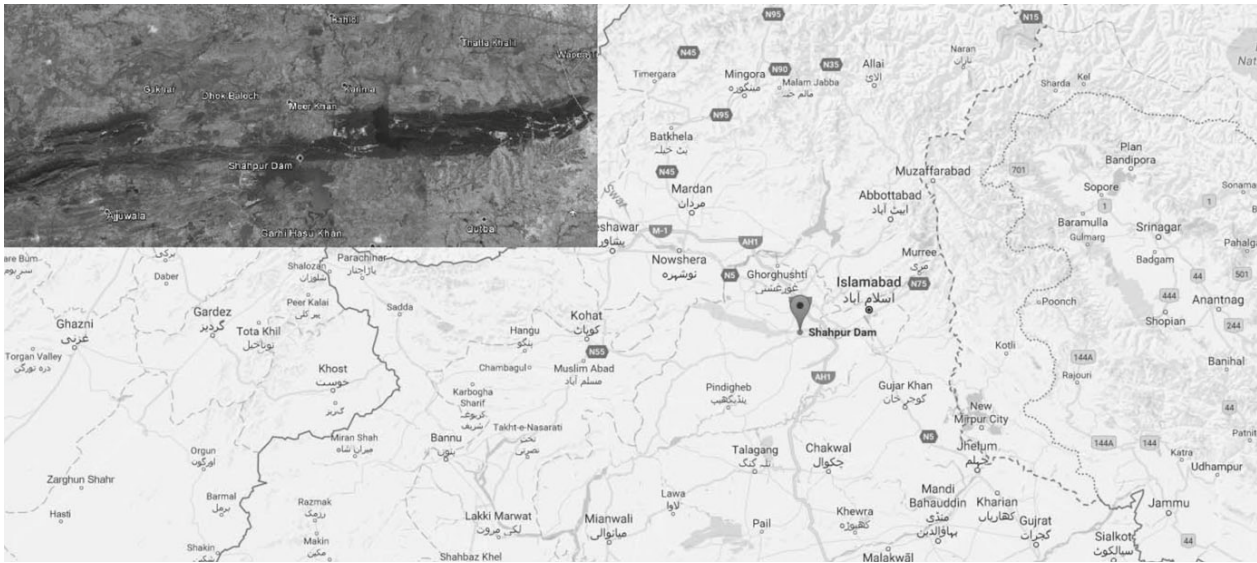
Fig. 1. Map showing location of Shahpur Dam with respect to Islamabad the capital of Pakistan.

Using Horton's Law, the geomorphologic parameters, such as bifurcation ratio (R_b), stream length ratio (R_l) and stream area ratio (R_a) were calculated for each order channel. To check how these parameters affect the model efficiency two DEMs of different resolution of Shahpur Dam catchment were used and different parameters were calculated for each of the DEM. Parameters affecting the Nash GIUH models are shown in Table 2.

Stream order shown in Figs. 3 and 4 and given in Table 2 is a simple characteristic of catchment used for classifying stream segments based on the number of tributaries upstream of a particular stream. Stream order has two ways of classification; Strahler order and Shreve. Strahler order is considered here according to which 1st order stream does not have any tributary on its upstream. A segment downstream of the confluence of two first order streams is a second order stream. Thus, an nth order stream is always located downstream of the confluence of two ($n - 1$)th order streams. Stream order is dependent upon the geography and topography of the watershed. Table 3 is showing total number of streams, stream lengths and drainage areas for respective stream order of 30 and 90 m DEM.

Table 4 shows calculated Horton ratios (bifurcation ratio, stream length ratio and stream area ratio) for 30 and 90 m DEMs. Average values of R_b 3.59 and 3.0, R_l 1.95 and 1.58, R_a 3.94 and 3.25 were found respectively for 30 and 90 m DEMs.

Nash Conceptual Model

Nash [30, 31] proposed that the instantaneous unit hydrograph (**IUH**) can be derived by routing the instantaneous inflow through a cascade of linear res-

ervoirs (n numbers) having same storage coefficient k. The out flow from the first reservoir is considered as inflow into the second reservoir, and so on. The outflow from the nth reservoir yields the IUH given by

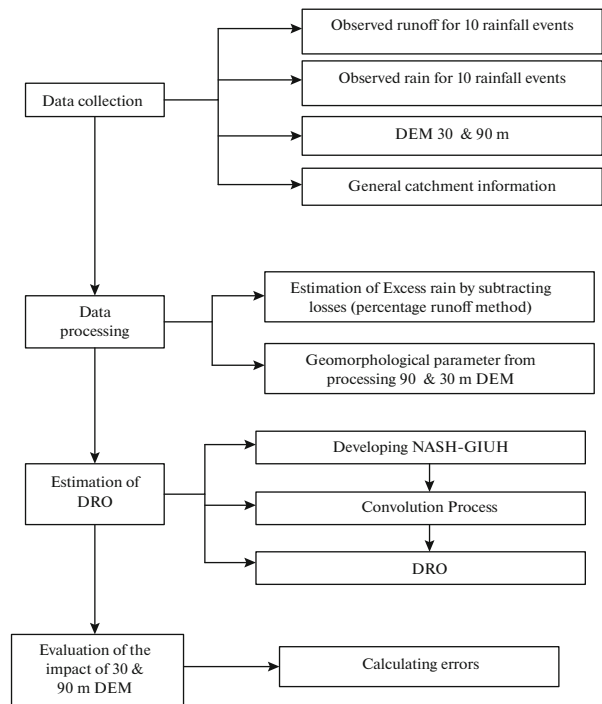$$Q_{\text{IUH}}(t) = \frac{0.2778At^{n-1}e^{-t/k}}{(n-1)!k^n}, \qquad (1)$$

Fig. 2. Flowchart of research methodology.

Table 1. Estimated excess rainfall, mm, for 10 rainfall events

Time, h	Even1 30-7-09	Even2 9-9-13	Even3 14-7-11	Even4 2-3-10	Even5 2-4-09	Even6 14-8-10	Even7 7-6-12	Even8 11-12-12	Even9 14-7-11	Even10 10-6-13
0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	1.7	0	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00
1	1.8	0	0.00	0.00	0.00	0.00	0.00	0.60	0.00	0.00
1.5	1.9	0	0.30	0.00	0.00	0.00	0.00	1.20	0.00	0.00
2	1.9	1	0.50	0.00	0.00	0.00	0.00	0.30	0.00	0.00
2.5	2	1	0.10	0.00	0.00	0.00	0.00	0.20	0.00	0.00
3	2	1.6	0.05	0.00	0.00	0.00	0.00	0.20	0.00	0.00
3.5	2.1	1.3	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00
4	2.2	0.7	0.00	0.00	0.40	0.10	0.00	0.00	0.00	0.00
4.5	2.3	0.4	0.00	0.00	0.70	0.70	0.00	0.00	0.00	0.00
5	2.4	0.1	0.50	0.00	1.20	1.20	0.00		0.00	0.00
5.5	2.5	0	0.60	0.00	1.80	1.80	0.00		0.00	0.00
6	2.6	0	0.60	0.00	2.50	3.50	0.50		0.50	0.00
6.5	2.8	0	1.00	0.00	4.70	5.50	0.90		0.90	0.00
7	3		0.40	0.00	7.10	7.10	1.10		1.10	0.00
7.5	3.2		0.30	0.00	12.30	12.30	1.70		1.70	0.00
8	3.4		0.20	0.00	8.90	8.90	2.50		2.50	0.00
8.5	3.7		0.10	0.00	5.00	5.00	5.20		5.20	0.00
9	4		0.10	0.00	3.10	3.10	9.30		9.30	0.00
9.5	4.5		0.10	0.00	0.10	0.60	15.60		15.60	0.00
10	5.1		0.05	0.00	0.00	0.20	17.40		17.40	0.00
10.5	6		2.00	0.00	0.00	0.00	14.60		14.60	0.00
1111.5	7.4		4.10	0.00	0.00	0.00	7.10		7.10	0.00
12	10		6.00	0.00	0.00	0.00	5.30		5.30	0.00
12.5	17.9		9.10	0.03	0.00	0.00	2.10		2.10	0.00
13	68.8		5.50	0.04		0.00	0.70		0.70	0.00
13.5	12.5		3.30	0.07		0.00	0.70		0.70	0.00
14	8.4		0.90	0.12		0.00	0.50		0.50	0.00
14.5	6.6		0.50	0.09		0.00	0.20		0.20	0.30
15	5.5		0.00	0.11		0.00				0.90
15.5	4.3		0.00	0.01		0.00				1.20
16	4.4		0.00	0.01		0.00				0.20
16.5	3.9		0.00	0.05						0.20
17	3.5		0.00							0.10
										0.10
25	1.8									
25.5	1.8									

where n is a parameter which is called shape parameter, which defines the shape of the IUH. A lower value of n produces a higher peak of IUH because of less storage flow attenuating the peak flow; a higher value of n leads to a lower peak of IUH signifying higher storage for attenuating peak flow. The parameter k is delay time parameter expressed in units of hours. A smaller value of k means lower time to peak of the direct surface runoff hydrograph and vice versa. These two parameters can be determined by calibration and

Table 2. Geomorphic parameters used in Nash GIUH

Sr. no.	Parameter	Symbol	30 m DEM	90 m DEM
1	Maximum stream order	X	5	3
2	Number of streams	$N = x_1 + x_2 + x_3 + x_4 + x_5$ (30 m DEM) $N = x_1 + x_2 + x_3$ (90 m DEM)	172	11
3	Bifurcation ratio	$(R_b = N_x/N_{x+1})$	3.589	3.00
4	Stream area ratio	R_a = ratio of the areas contributed by particular stream order to the whole watershed area	3.943	3.245
5	Stream length ratio	R_l = ratio of the lengths of a particular order to the length of the highest order stream	1.948	1.576
6	Shape parameter	N	3.203	3.194
7	Scalar parameter	K	1.16−6.45	0.73−4.04
8	Watershed area	A, km^2	204.898	206.359
9	Basin length	L_B, km	17.335	17.144
10	Stream length	L_x, km	8.883	7.585
11	Main channel length	L (It is maximum length of the watercourse from outflow point of watershed to the upper boundary limit of catchment area), km	22.854	18.002
12	Mean basin slope	(Sm) (by GIS software)	3.6	3.7

optimization of the model. In this process n and k are adjusted such that the simulated hydrograph matches the observed hydrograph. For this purpose n and k are optimized and best values of the parameters are estimated.

Nash-GIUH

The values of n and k parameters are obtained from geomorphic characteristics of the catchment in case of Nash GIUH. There is a lot of research on determining the geomorphic parameters of Nash GIUH. Rosso [36] through regression analysis obtained the expressions for estimation of the model parameter n and k as:
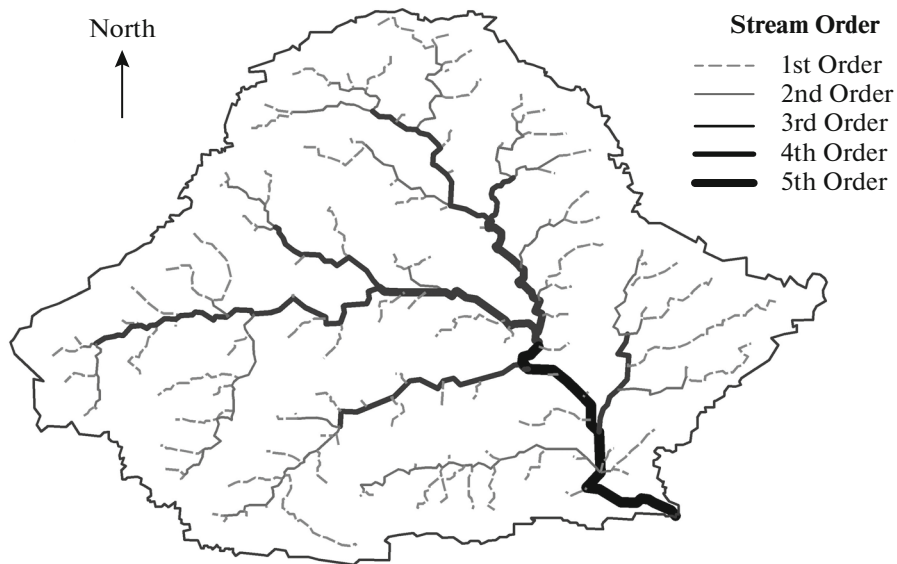

Fig. 3. Horton's Stream ordering for Shahpur Dam Catchment (30 m DEM).

Fig. 4. Horton's Stream ordering for Shahpur Dam Catchment (90 m DEM).

$$n = 3.29 \left(\frac{R_b}{R_a} \right)^{0.78} R_l^{0.07}, \qquad (2)$$

$$k = 0.7 \left(\frac{R_a}{R_b R_l} \right)^{0.48} \frac{L_x}{V_{\max}}, \qquad (3)$$

where R_a is average value of stream area ratio, R_b is average value of bifurcation ratio, R_l is average value of stream length ratio, L_x is stream length and $V_{\max}$ is maximum velocity. Definitions of R_a, R_b, R_l and L_x are given in Table 2. Determination of velocity parameter has been investigated by various researchers.

Expected Maximum Velocity (V_{max})

$V_{\max}$ is expected maximum (peak) velocity and is calculated at the outlet of watershed using equation given below.

$$V_{\max} = 0.665 \left(a_\Omega \right)^{0.6} \left(i_r A \right)^{0.4}, \qquad (4)$$

where i_r is intensity of excess rainfall, a_Ω is the kinematic wave parameter for highest-order streams, A is watershed area in km^2. Rodriguez-Iturbe [34] investigated characteristic velocity by applying the kinematics wave assumptions. Kinematic wave perimeter was calculated by equations given by Rodriguez-Iturbe [34] and Ponce [33]. Velocity calculated through 90 m DEM is in the range of 1.095 to 6.05 m/s for different storm events. When it is calculated through 30 m DEM it comes out to be 1.06 to 5.87 m/s for different storm events.

Direct Runoff Calculations

After having calculated the values of n and k the ordinates of GIUH-Nash Model were calculated using Eq. 1. The Nash-IUH ordinates, thus obtained, were used to get the ordinates of direct runoff hydrographs by the process of their convolution with the excess rainfall given in Table 1. The ordinates of simulated direct runoff hydrographs shown in Figs. 5 and 6 were used to find various errors using observed runoff

Table 3. Geographical characteristics of Shahpur catchment: streams and drainage areas details

Order of stream		Total number of streams		Total Lengths of stream, km		Drainage area, km^2	
30 m DEM	90 m DEM	30 m DEM	90 m DEM	30 m DEM	90 m DEM	30 m DEM	90 m DEM
1	1	135	8	132.22	24.83	134.21	156.87
2	2	27	2	49.29	11.03	111.69	123.6
3	3	7	1	41.62	7.59	163.71	206.36
4		2		9.35		123.34	
5		1		8.88		204.9	
Sum		172	11	241.36	43.45	204.9	206.36

Table 4. Horton ratio comparison of 30 and 90 m DEMs

Stream order	1		2		3		4		5	
DEM	30 m	90 m	30 m	90 m	30 m	90 m	30 m	90 m	30 m	90 m
Number of streams	135	8	27	2	7	1	2	−	1	−
Average length, km	0.987	3.103	1.825	5.513	5.94	7.585	4.676	−	8.88	−
Average area, km^2	0.994	19.61	4.137	61.799	23.387	206.358	61.671	−	204.89	−
R_b	5	4	3.857	2	3.5	−	2	−	−	−
R_l	−	−	1.849	1.777	3.257	1.376	0.786	−	1.899	−
R_a	−	−	4.161	3.152	5.653	3.339	2.636	−	3.322	−

data taken from Small Dams Organization Islamabad as given in Table 5. MS EXEL Spread sheets were used for model and other calculations.

Model Accuracy Checking Parameters

The following statistical parameters were used to check accuracy of model [32].

$$\text{EFF} = \left(1 - \frac{\sum_{i=1}^{j}(Q_{oi} - Q_{si})^2}{\sum_{i=1}^{j}(Q_{oi} - \bar{Q}_{oi})^2} \right) \times 100, \qquad (5)$$

here EFF shows percentage efficiency of the model, a well-known statistical parameter Nash and Sutcliffe coefficient, observed discharge of ith ordinate is Q_{oi}, simulated discharge of ith ordinate is Q_{si} and j is the total no of ordinates of hydrograph.

$$Q_{pep} = \left(1 - \frac{Q_{ps}}{Q_{po}} \right) \times 100, \qquad (6)$$

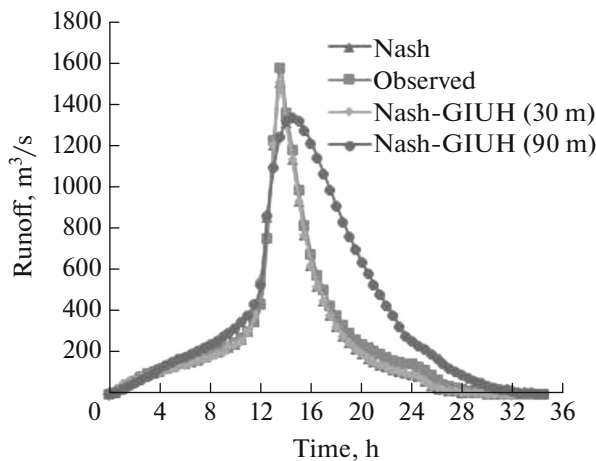where Q_{pep} is percentage error in peak of discharge, Q_{ps} is the calculated peak discharge and Q_{po} is the observed peak discharge. The error in time to peak was also calculated in similar way replacing Q by T in Eq. 6.

RESULTS AND DISCUSSIONS

Geomorphologic Parameter

Stream order depends upon the resolution of the DEM. It is observed that maximum stream order comes out to be 5 for the catchment in case of using 30 m DEM. However when a DEM of 90 m is used the highest stream order comes out to be 3. The sum of streams of all orders was estimated to be 172 by 30 m DEM and 11 by 90 m DEM. Number of Streams affects the value of bifurcation ratio (R_b). It is an important geomorphic parameter that affects the efficiency of the GIUH model. R_b is used to calculate parameters n and k by Eqs. 1 and 2. It plays important role for calculating Nash GIUH. Using 30 m DEM bifurcation ratio was calculated and it resulted to be 3.59 whereas in case of 90 m DEM it was 3. There is a change of 16.42% in R_b value for the two DEMs.
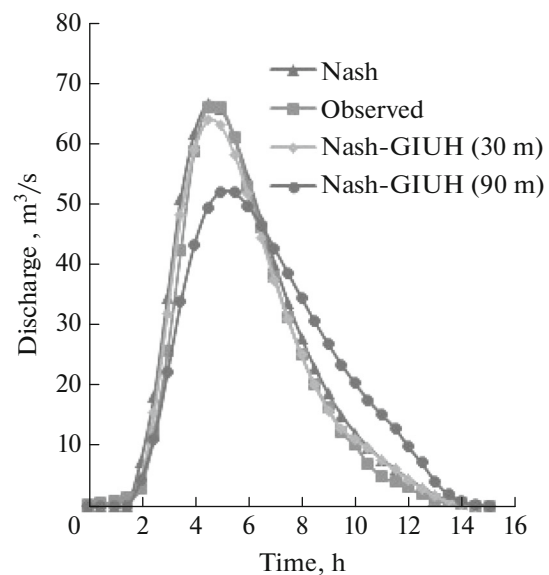

Fig. 5. Direct runoff hydrograph (Event 1).

Fig. 6. Direct runoff hydrograph (Event 2).

Table 5. Model efficiency, percent error in peak (PEP), time to peak (PET$_p$) and volume (PEV)

Event	Nash GIUH								Nash			
	EFF 30	EFF 90	PEP 30	PEP 90	PET$_p$ 30	PET$_p$ 90	PEV 30	PEV 90	EFF	PEP	PETp	PEV
1	98.75	89.96	4.76	12.12	0	−7.41	7.68	−12.5	98.74	4.762	0	7.41
2	99.1	88.67	3.41	16.67	0	−11.1	−2.24	−7.36	98.17	−0.68	0	−9.31
3	98.92	90.92	8.24	19.11	0	3.57	−0.5	−5.46	99.98	−0.43	0	1.65
4	99.25	90.30	3.75	16.99	−3.33	−6.67	−4	−8.76	99.67	−4.89	0	−0.51
5	39.48	31.55	2.13	7.206	−9.09	−14.3	−55.5	−61.3	88.29	1.49	4.54	15.2
6	54.93	42.44	1.00	8.87	−20	−40	−17.3	−22.7	57.17	−14.9	−20	−11.7
7	88.13	73.10	4.88	10.59	0	−9.09	27.84	−35.5	84.24	1.49	−4.55	15.2
8	73.19	61.16	−10	14.88	0	−3.7	−24.3	−33.8	69.74	5.048	0	−34.8
9	70.68	53.51	−6.9	−14.1	0	−6.25	−51.8	−56.5	63.44	−13.8	0	−57
10	77.72	68.89	−1.7	−5.87	−4	−8	−48.5	−55.4	74.05	−6.71	−4	−54.6

Stream Area Ratio (R_a) is also an important geomorphic parameter which is dependent on the topography of the area. R_a was calculated using a 30 and 90 m DEM which comes to be 3.94 and 3.25 respectively. There is a difference of 17.7% in R_a values for two DEMs. Stream Length Ratio R_l comes to be 1.943 for a DEM of 30 m and 1.58 for 90 m DEM. There is a difference of about 18.9%. The Shape Parameter (n) is highly important parameter. In Nash GIUH the shape parameter is calculated using Eq. 1. If 30 m DEM is used, the value of n comes to be 3.20 and in case of 90 m DEM it comes to be 3.195. The difference is only of 0.28% which is not so important. Hence it can be said that this parameter is not significantly dependent upon the resolution of the DEM. The Scalar Parameter (k) is related to time to peak of runoff and is expressed in units of hours. In case of simple Nash model the most efficient value of k is estimated using optimization. The best pair of n and k is obtained by optimization. For $k = 1.7$ h the model efficiency was 98%. If k is changed away from 1.7, the model efficiency was noted to be decreased. A 6% change in value of k resulted in 1% decrease in the model efficiency. In case of Nash GIUH the values of k were determined using 90 m and 30 m DEMs. The value of k comes to be in range of 0.73−4.04 in case of 90 m and for 30 m DEM its value ranged from 1.16−6.45. Increase in k value means increase in time to reach to the peak of flood hydrograph.

DEMs of 30 and 90 m resolution were used to delineate the boundary of the catchment. Watershed area comes to be 204.88 km^2 for 30 m and 206.36 km^2 for 90 m DEM. If there is an error in delineating the watershed boundary the RMSE and Nash-Sutcliffe coefficient may change. The Basin Length for the DEM of 30 m comes to be 17.34 km. When a DEM of 90 m was used it came to be 17.14 km with an error of 1.10% with change of DEM resolution from 30 m to 90 m. Stream Length (L_x) is the length of the stream of

highest order. It comes to be 8.88 km when a DEM of 30 m was used and 7.36 km for a DEM of 90 m. The stream of highest order is connected to a number of tributaries further. Main channel length values were found to be 22.85 and 18.0 km respectively for 30 and 90 m DEMs. It varies due to topographical characteristics of the basins.

Direct Runoff Hydrograph and Model Performance

Results from Nash and Nash GIUH based on 30 m DEM and Nash GIUH based on 90 m DEM are shown in Table 5. It shows model efficiency and values of various types of errors between the observed and simulated hydrographs.

It is observed that the efficiencies have been improved when a DEM of comparatively higher resolution has been used. Efficiency ranges from 99.25 to 39.48% in case of 30 m DEM whereas in case of 90 m DEM its values vary from 90.92 to 31.55% for simulation of various events. It is observed that the percentage error in peak discharge (**PEP**) reduces even up to 1.0% by use of 30 m DEM. The maximum error in peak discharge does not exceed 10% for simulation of various events. Whereas in case of 90 m DEM the error in peak discharge reaches up to 19.1. In case of 30 m DEM the percentage error in time to peak (**PET$_p$**) is reduced even to a very small percentage and the error in volume (**PEV**) is reduced to 0.5% when DEM of 30 m resolution is used instead of 90 m resolution where the error in these two parameters remains up to 3 and 5%, respectively.

Hydrographs from model results of events 1 to 10 were observed carefully. Figures 5 and 6 show hydrograph samples for event 1 and 2. Graphs for other events can be obtained from authors if needed. It is noticed that the hydrographs obtained from 30 m DEM is comparatively closer to the observed hydrograph as compared to that from 90 m DEM (Figs. 5

and 6). For event 1 (Fig. 4), the efficiency in case of 30 m DEM is 98.75% whereas in case of 90 m DEM it is 89.96%. When 30m DEM is used the percent errors are reduced up to 4.76, 0.0 and 7.68% in peak, time to peak and volume respectively. In event 2 (Fig. 6) the model efficiency is higher by about 10.4% for DEM of 30 m as compared to that of 90 m DEM. Percentage error in peak, time to peak and volume are also reduced by 13.26, 11.11 and 5.12% respectively. Similar trend can be seen in Table 5 for all the other events.

CONCLUSIONS

DEM resolution has significant impact on DEMs derived geomorphological parameters; specially stream order, stream number, lengths, catchment area. When DEM of higher resolution are used these parameters become comparatively more accurate. Higher resolution DEM produces a more detailed delineation of watershed. Higher resolution offers the capability of improving the quality of hydrological features extracted from DEM.

The developed hydrographs by Nash GIUH with 30 m DEM for different storm events are closer to observed hydrographs. When hydrographs are simulated through DEM of comparatively higher resolution (i.e. 30 m DEM) the efficiency of the model increased as compared to those developed through DEM of 90 m. Efficiency of GIUH model can be achieved up to ranges 99.25% by use of 30 m DEM whereas in case of 90 m DEM its value is up to 90.92% only. The errors in various simulated results can be reduced by use of a high resolution DEM. There is significant decrease in errors especially in case of simulated peak discharge and error in time to peak of hydrograph. The error in simulated volume of runoff is also reduced up to some extent. The percentage error in time to peak can be reduced even close to very small percentage (zero in some cases) and percentage error in volume may be reduced to 0.5% when DEM of higher resolution is used.

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