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Watershed Modelling with GIS Based Distributed Unit Hydrograph Approach

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ABSTRACT

This report is aimed at derivation of a spatially distributed unit hydrograph for Temur watershed at railway bridge no. 293. The method for distributed unit hydrograph computation allows for spatial non-uniformity of excess rainfall. Consequently, it is based on the time-area method (Clark, 1945) derived using GIS. The GIS allows development of a watershed's channel network for calculation of realistic travel times, it handles the distributed excess rainfall in calculating local surface runoff rates as inputs for channel flow and it compiles the time-area diagram from which distributed unit hydrograph is derived.

Simulation results shows that the errors between observed and simulated peak discharge are from -5.8% to 22.1% which is well within acceptable limits for designing small structures on this stream. However, the errors between observed and simulated time to peak is large compared to errors in peak discharge simulation. Graphical comparison of observed and simulated discharge shows that the rising limb of computed hydrograph match well with rising limb of observed hydrograph in all cases, however, the recession shape of observed and simulated hydrograph do not match very well. This could be attributed to the fact that a very simple method for velocity simulation was used and no calibration of parameters has been performed. Also a pure translation model is used in this study which could be responsible for lack of agreement in the shape of hydrograph. As can be seen from topographic map of the catchment, the catchment is having mild slopes in majority of area and there is very likelihood of storage effects due to this mild slope. From this study it can be concluded that the method work well for simulation of peak discharge. However, for overall shape and time to peak discharge simulation, further refinements in the method are required. It is, therefore, appropriate to simulate this catchment with model, which take both translation and storage effects into consideration for further study.

1.0 INTRODUCTION

Ever since its conception by Sherman (1932), the unit hydrograph (UH) has been widely used in hydrological rainfall-runoff modelling. Unit hydrograph of a watershed is defined as direct runoff hydrograph resulting from a unit depth of excess rainfall generated uniformly over the drainage area at a constant rate for an effective duration (Chow et al. 1988). The unit hydrograph is a lumped linear model of a watershed where it is assumed that a catchment acts on an input of effective precipitation in a linear and time-invariant manner to produce an output of direct storm runoff (Dooge, 1959). Methods for determining a UH from storm events with observed direct runoff hydrograph and effective rainfall hyetograph are umpteen. They have been systematically categorized by Singh (1988).

The unit hydrograph theory suffers from limitation that the response function is lumped over the whole watershed and does not explicitly account for the spatially distributed nature of the watershed properties. Efforts have been made to overcome this limitation of unit hydrograph theory by introduction of geographical information system for spatial descretization of watershed into a interlinked system of grid cells (Maidment et al., 1996; Muzik, 1996). It is now becoming common to represent land surface elevation over the watershed by grid cell digital elevation model (DEM). Standardized algorithms are available in geographic information systems which use the local terrain slope to link each cell with one of its neighbors along the line of steepest descent, thus creating a one dimensional flow network over the entire land surface. It has been shown by Maidment et al. (1996) that this terrain representation can be utilized for runoff computation under spatially varying, but time- and discharge-invariant, velocity field, the linear system response at the watershed outlet can be spatially decomposed into a set of cell based linear systems whose individual response functions sum to give the watershed response function.

This report is aimed at derivation of a spatially distributed unit hydrograph for Temur watershed at railway bridge no. 293. The method for distributed unit hydrograph computation allows for spatial non-uniformity of excess rainfall. Consequently, it is based on the time-area method (Clark, 1945) derived using GIS. The GIS allows development of a watershed's channel network for calculation of realistic travel times, it handles the distributed excess rainfall in calculating local surface runoff rates as inputs for channel flow and it compiles the time-area diagram from which distributed unit hydrograph is derived.

2.0 DISTRIBUTED UNIT HYDROGRAPH

Mathematical representation of the unit hydrograph has a long history in hydrology. Clark (1945) formulated a unit hydrograph model by combining the time-area diagram of the watershed with a linear reservoir at the outlet. Nash (1957) proposed a cascade of linear reservoirs as a unit hydrograph model, and Dooge (1959) presented a unit hydrograph theory combining linear channels and linear reservoirs. Many unit hydrograph models involving combinations of linear elements have been proposed, notably the theory of the geomorphological instantaneous unit hydrograph (Rodriguez-Iturbe & Valdes, 1979) in which Horton's stream laws are used to integrate over the watershed the delay effect of channel links characterized by a mean holding time to produce a unit hydrograph as the probability density function of travel time of water to the outlet. This approach implicitly assumes the runoff is produced by Hortonian overland flow throughout the watershed.

The spatially distributed unit hydrograph described here is similar in concept to the geomorphological instantaneous unit hydrograph except that GIS is used to describe the connectivity of the links in the watershed flow network, which eliminates the need for using probability arguments to combine the movement of water through the links. Moreover, the GIS based approach permits the spatial pattern of excess rainfall to vary by isochrone zones within the watershed, thus relaxing the requirement for uniform excess rainfall over the whole watershed.

2.1 Grid-based Flow Pattern

Most of the raster based GIS systems contain routines which determine the flow direction over land surface terrain using pour point model. Water on grid cell is permitted to flow to one of its eight neighboring cells. By taking a grid of terrain elevations, determine the slope of the line joining each cell with each of its neighboring cells, a grid of flow direction is created with one direction for each cell which represents the direction of steepest descent among the eight permitted choices. The concept of grid based flow pattern is represented in Figs. 1(a), 1(b), 1(c) and 1(d). The grid in fig 1(c) is shown as a set of arrows but infect is stored in GIS as a grid of numbers where each flow direction has a unique identifying number. By assigning water flow to one of its eight neighboring cells, equivalent one dimensional flow network is constructed by connecting the cell centres in the direction of flow as shown in Fig. 1(d). There is thus a duality between the grid and equivalent flow network and one might call the network so created a hybrid grid-network.

2.2 Mathematical Formulation

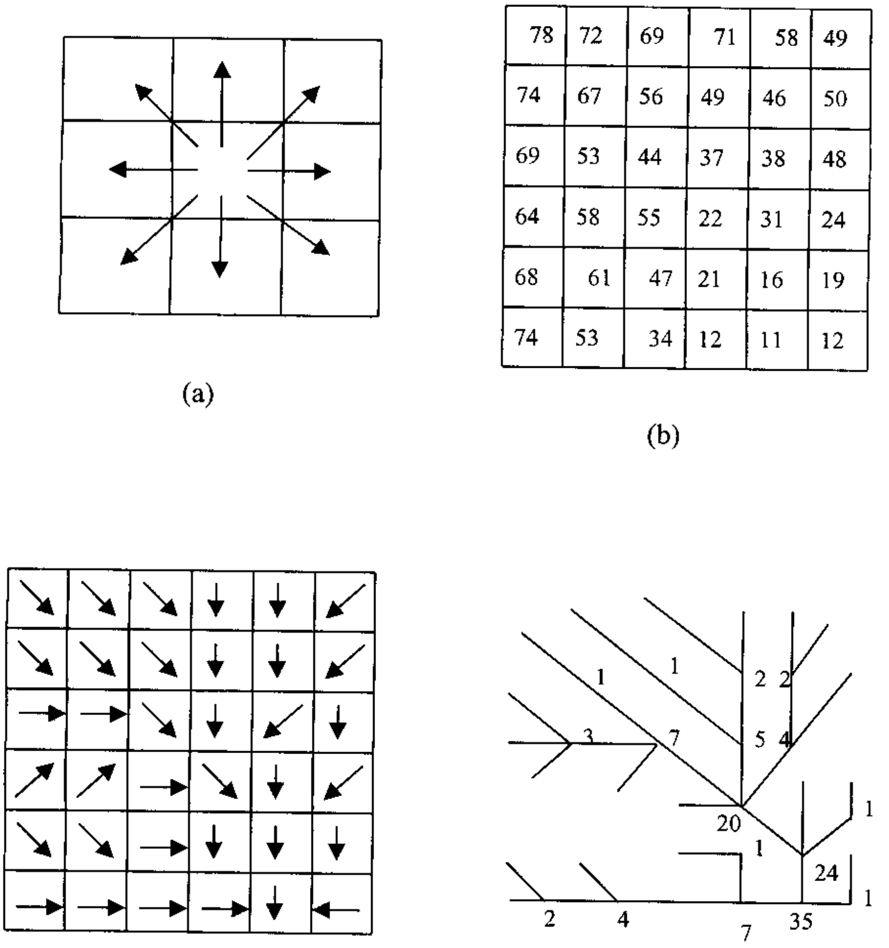
The concept of spatially distributed unit hydrograph, proposed by Maidment (1993), is based on the fact that the unit hydrograph ordinates at time t is given by the slope of the watershed time-area diagram over the interval [t-Δt, t]. The time-area diagram is a graph of cumulative drainage area contributing to discharge at the watershed outlet within a specified time of travel. The validity of the above can be proved by considering the S-hydrograph method. An S-hydrograph, defined as the runoff at the outlet of a watershed resulting from a continuous excess rainfall occurring at rate i_e over the watershed, is given by:

$$Q_s(t) = i_e A(t) \qquad \text{... 1}$$

where A(t) is the watershed area contributing to flow $Q_s(t)$ at the outlet at time t. The direct runoff hydrograph discharge at time t, resulting from a pulse of excess rainfall $P_e = i_e \Delta t$, is equal to the difference between the S-hydrograph value at time t and its value lagged by time Δt, i.e.

$$Q_D(t) = i_e A(t) - i_e A(t - \Delta t) \qquad \text{... 2}$$

The unit hydrograph ordinates are $U(t) = Q_D(t) / P_e$, and thus



(a)

78	72	69	71	58	49
74	67	56	49	46	50
69	53	44	37	38	48
64	58	55	22	31	24
68	61	47	21	16	19
74	53	34	12	11	12

(b)

(c)

(d)

Fig. 1 Watershed terrain analysis using grid GIS method: (a) the eight direction pour point model; (b) a grid of terrain elevations; (c) the corresponding grid of flow directions; (d) the equivalent network showing flow accumulation.

$$U(t) = \frac{A(t) - A(t - \Delta t)}{\Delta t} \qquad \ldots 3$$

Thus the unit hydrograph can be constructed by standard S-hydrograph method (Chow et al., 1988); i.e. the time-area curve is lagged by one hour and subtracted from original curve. Thus, the discharge values obtained, adjusted for unit input, yield the one-hour distributed unit hydrograph.

3.0 THE STUDY AREA

For the present study Temur basin at railway bridge no 249 in Narmada river system is selected. The study area encompass a total drainage area of 532 km^2. The study area lies between 79°39′E longitude, 22°30′N latitude and 80°E longitude, 22°55′N latitude. The area is characterized by flat topography with scattered hillocks in southern and south western part of the basin. The northern and central part of the basin have mild slopes and the area adjoining watershed divide in southern and south-western part have moderate slopes. The elevation of the basin is 420m at the outlet and goes upto 640 m at southern part of the watershed divide. The area is characterized by barren and scanty shrub lands with sandy and sandy loam soils. Fig 2. shows the boundary of the study area along with stream network. Table 1 shows the selected runoff events considered for simulation.

Table 1. Selected runoff events for simulation

Event no.	Peak discharge (cumec)	Time to peak discharge (hr)	DSRO volume (cm)
1	135.92	6	0.672
2	58.16	8	0.258
3	124.59	10	0.810
4	59.50	6	0.311
5	214.93	8	1.325
6	181.23	12	1.081

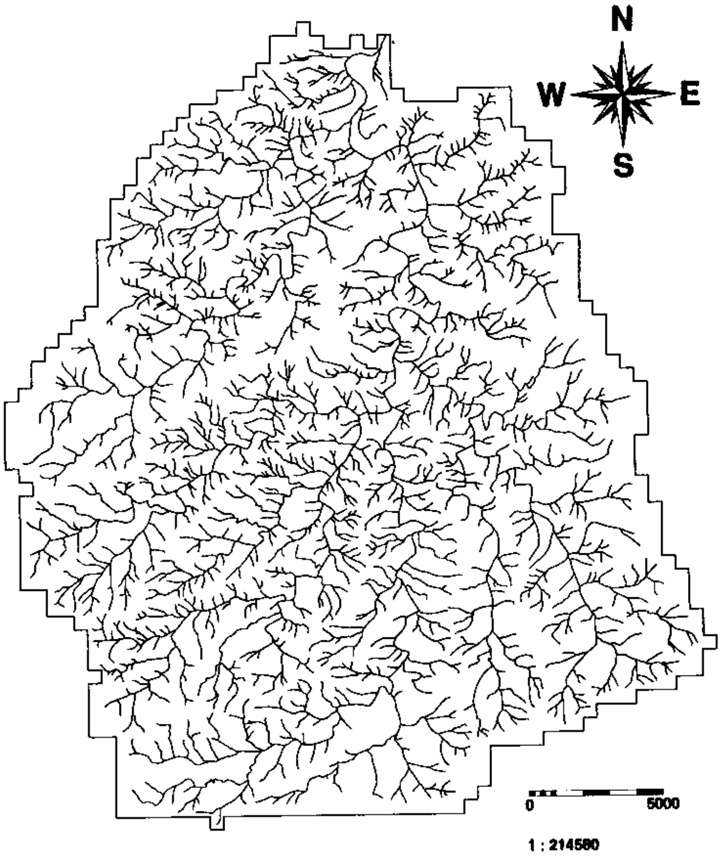


Fig. 2 Temur catchment with stream network

4.0 ANALYSIS

4.1 Generation of Digital Input Maps

The river network and contour map of the study area has been derived from Survey of India toposheets in 1:50,000 scale. Derived contour and drainage maps were then digitized on Integrated Land and Water Information System (ILWIS). Digitized segment contour map, rasterized to 500m pixel size is then interpolated to generate a Digital Elevation Model (DEM) of the area. This DEM was further analysed to remove pits and flat areas in it using neighborhood functions available in ILWIS. Further a slope map and flow direction map is generated from this DEM. Figs. 3, 4, 5, shows respectively the classified DEM of the basin, classified slope map of the basin and flow direction map of the basin.

To derive landuse map of the study area, digital remote sensing data of LISS-II sensor of IRS-1B satellite for path 25/52 A1 for date of pass (DOP) 25.3.91 was analysed. The scene corresponding to the area of interest was first cut from entire path/row scene and further it was geocoded as per standard practice at 36.5 metre pixel resolution. The geocoded scene is then masked by the boundary of the basin to delineate area lying with in the basin. Land use map is then generated from this satellite scene using supervised classification scheme. Based on experience and field data, five training samples were selected and were further analysed for spectral characteristics by plotting them in different colours in feature space. The scene is then classified using maximum likelihood classification algorithm. Fig. 6 shows the classified land use map of the area.

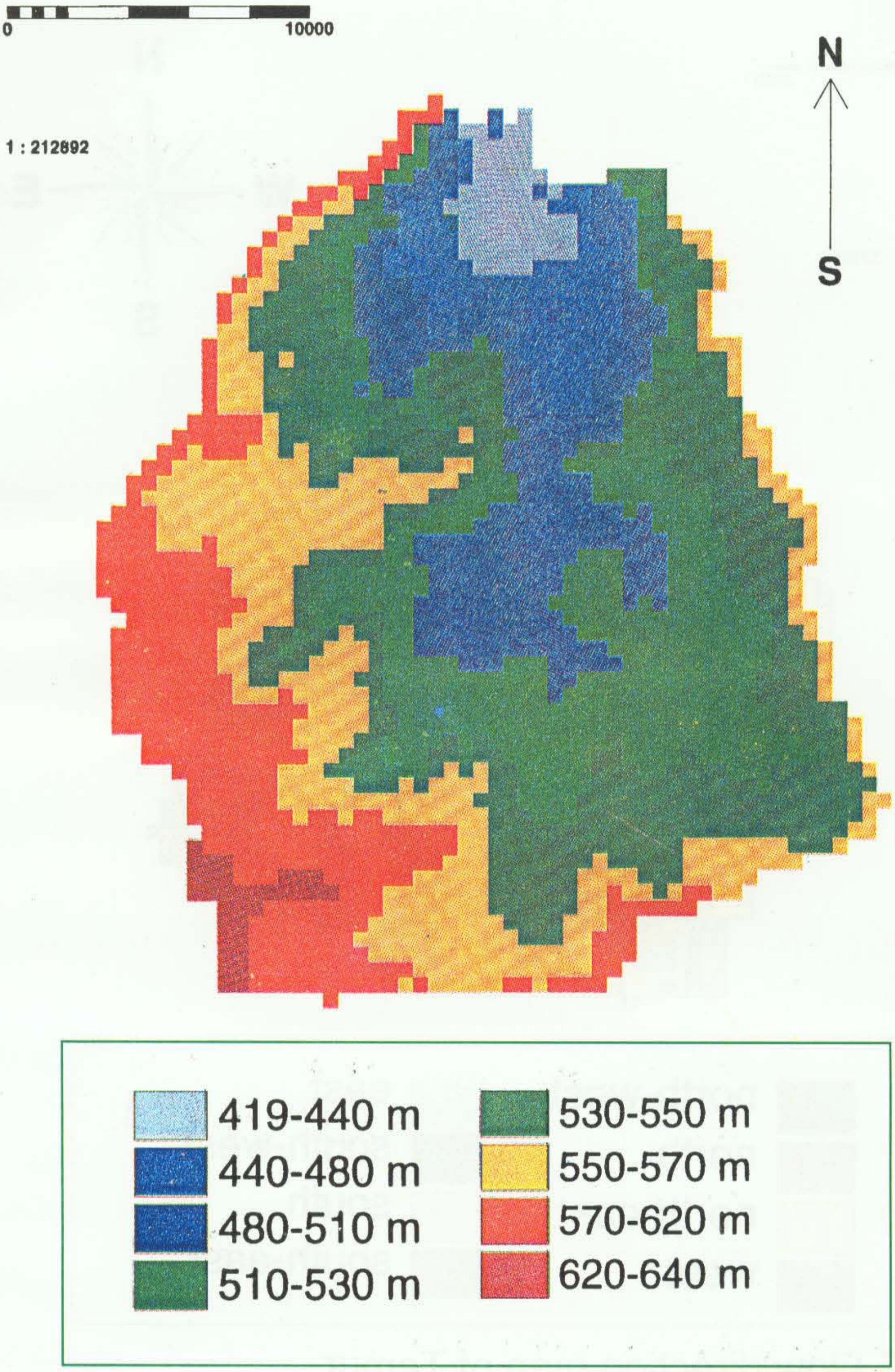


Fig. 3 Classified DEM of Temur

4.2 Time Area Diagram

Velocity is a vector quantity specified my magnitude and direction of flow. In grid based GIS analysis, the direction of flow from one cell to other neighboring cell can be ascertained using pour point algorithm as reported in section 2.1. Once the pour point identified the flow direction in each cell, a cell to cell flow path exists to the watershed outlet. If a flow path from cell j to the outlet traverses m cells, $m = 1,2,.....M_j$, the flow length L_j is defined as the flow distances through each cell along the path

$$L_j = \sum_{m=1}^{M_j} l_m \qquad \ldots 4$$

where cell flow distance l_m is equal to the cell size or 1.41 times the cell size depending on whether the flow direction is along the coordinate axis or along a diagonal, respectively. If the velocity of flow in cell m is V_m, the flow time T_j from cell j to the outlet can similarly be computed by summing the time through each of M_j cells on the path as

$$T_j = \sum_{m=1}^{M_j} \frac{l_m}{V_m} \qquad \ldots 5$$

Determination of flow time by the method described above requires the specification of the velocity for each cell on the watershed. This velocity is a typical or representative value for conditions during the types of events that the unit hydrograph simulates. There are a number of methods by which this can be done. However for the present study, method proposed by U S Soil Conservation Service for overland flow velocity as a function of land surface slope and land cover is chosen for its simplicity and availability of information. In mathematical form

$$V_m = a\, S_m^b$$

where S_m is slope of cell m and a and b are coefficients related to land use taken from McCuen (1982). Equation (6) was used by Sircar *et al.* (1991) for computation of time-area curve. Parameter "a" of the area, was derived based on land use map obtained from satellite data. The parameter b is kept constant and equal to 0.5.

Since for each cell both flow direction and flow velocity area now known, and the paths from each cell to the watershed outlet has been specified, it follows that one can create a grid of flow travel times where the value in each cell is the time taken for water from that cell to flow to the watershed outlet. The cells may then be classified into zones i, i=1,2,...., whose travel time t falls into time interval $0 \leq t < \Delta t$, zone 2 has travel time $\Delta t \leq t < 2\Delta t$, and so on. The line bounding the outer limit of the cells in zone i is the isochrone of travel time $t = i\Delta t$ to the watershed outlet. The total area of the cells in zone i is A_i. In this way, the isochrone map of the watershed is created and is shown in Fig. 8.

The time-area diagram is a graph of cumulative drainage area flowing to the outlet within a specified time of travel. Thus at time points $t = 0, \Delta t, 2\Delta t, \ldots, i\Delta t, \ldots$, the cumulative area draining to the outlet $A(i\Delta t)$ is given by

$$A(i\Delta t) = \sum_{k=1}^{i} A_k \qquad \ldots 7$$

and conversely, the incremental areas are given by

$$A_i = A[i\Delta t] - A[(i-1)\Delta t] \qquad \ldots 8$$

Once we know the time-area of the watershed, the unit hydrograph is derived based on the mathematical formulation presented in section 2.2. The derived unit hydrograph is shown in Fig. 8.

4.3 Determination of effective rainfall

Since for the present study, limited number of SRRG's were available within or near to the basin, therefore, the ORG records for various representative rainfall stations were distributed into hourly records based on available SRRG station for various selected storm events. Thiessen weights for each raingauge station were calculated and weighted average hourly precipitation was calculated for all the basins. Infiltration for each rainfall-runoff event was determined using Philip two term infiltration model (Philip 1957). The Philip two term infiltration model can be written as

$$f = A + \tfrac{1}{2} S t^{-\frac{1}{2}} \qquad \ldots 9$$

where f is infiltration rate (cm h^{-1}), A is a parameter dependent on soil characteristics that, as a first approximation is equivalent to saturated hydraulic conductivity (cm h^{-1}), S is sorptivity (cm $h^{-1/2}$), depending on soil characteristics and initial moisture content, and t is time in hours. Both parameters are estimated from measured direct runoff, apart from surface runoff computation. They are considered constant in space, but sorptivity is computed for each event independently with a view to take into account initial conditions of humidity.

4.4 Direct Runoff Hydrograph

The portion of rainfall which produces direct runoff is called the excess rainfall, and its values are symbolized by P_1, P_2, ..., P_j, ..., where P is the excess rainfall and corresponding direct runoff values are given by Q_1, Q_2, ..., Q_j, ..., where Q is the discharge rate at the watershed outlet. Once we know the excess rainfall hyetograph and unit hydrograph ordinates, the direct runoff hydrograph can be calculated by convoluting excess rainfall hyetograph with unit hydrograph.

5.0 RESULTS AND DISCUSSIONS

As discussed in previous chapters, the distributed unit hydrograph of Temur catchment was constructed using methodology discussed in chapter 2.0. The volume adjusted unit hydrograph derived from time-area diagram of the basin is shown in Fig. 8. This unit hydrograph is then used to convolute the excess rainfall hyetograph for all six observed events available from the basin to calculate direct surface runoff for each of the events. The comparison of errors between observed and simulated peak discharge and time to peak discharge is given in Table. 2.

Table 2. Errors between observed and simulated peak discharge and time to peak discharge

Event no	Peak discharge			Time to peak discharge		
	Observed	Simulated	% Error	Observed	Simulated	% Error
1	135.92	114.73	15.5	6	9	-50
2	58.16	52.23	10.1	8	10	-25
3	124.59	143.32	-15.0	10	11	-10
4	59.5	62.97	-5.8	6	7	-16.6
5	214.93	240.44	-11.8	8	7	12.5
6	181.23	141.14	22.1	12	15	-25

It can be seen from Table 2, that the errors between observed and simulated peak discharge are from -5.8% to 22.1% which is well within acceptable limits for designing small structures on this stream. However, the errors between observed and simulated time to peak is large compared to errors in peak discharge simulation. Graphical comparison of observed and simulated discharge are shown in Figs 9(a), 9(b) and 9(c) for events number

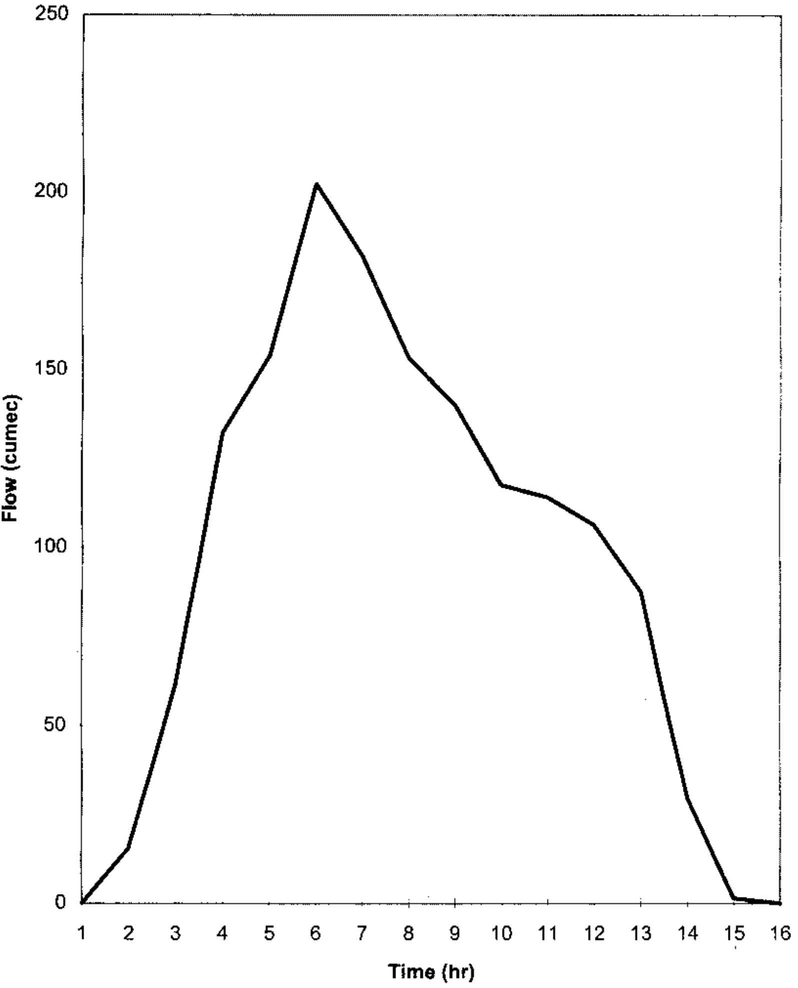


Fig. 8 Derived unit hydrograph of Temur catchment

Fig. 9(a) Observed and simulated discharge for event no. 1

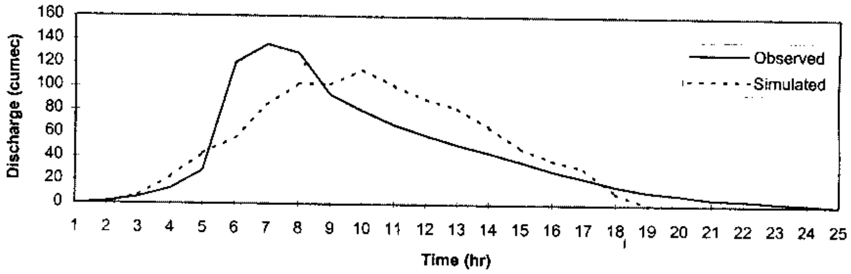


Fig. 9(b) Observed and simulated discharge for event no. 3

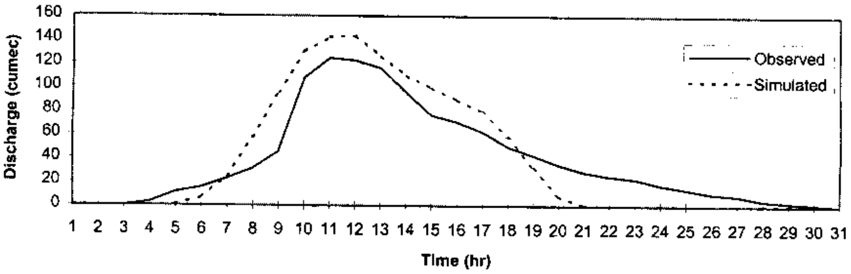
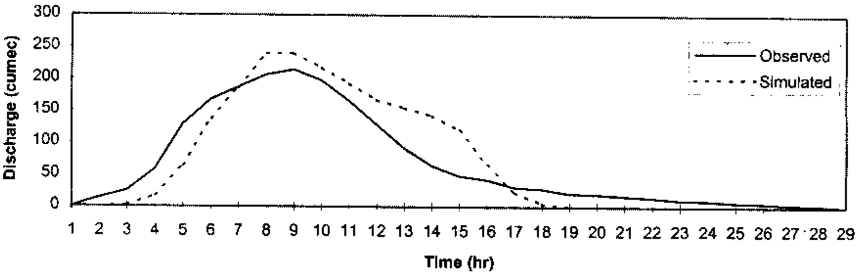


Fig. 9(c) Observed and simulated discharge for event no. 5



1,3 and 5 respectively. As can be seen from these plots, that the rising limb of computed hydrograph match well with rising limb of observed hydrograph in all cases, however, the recession shape of observed and simulated hydrograph do not match very well. This could be attributed to the fact that a very simple method for velocity simulation was used and no calibration of parameters has been performed. Also a pure translation model is used in this study which could be responsible for lack of agreement in the shape of hydrograph. As can be seen from topographic map of the catchment, the catchment is having mild slopes in majority of area and there is very likelihood of storage effects due to this mild slope. From this study it can be concluded that the method work well for simulation of peak discharge. However, for overall shape and time to peak discharge simulation, further refinements in the method are required. It is, therefore, appropriate to simulate this catchment with model which take both translation and storage effects into consideration for further study.

6.0 CONCLUSIONS

A spatially distributed unit hydrograph for Temur watershed at railway bridge no. 293 has been developed. The method for distributed unit hydrograph computation allows for spatial non-uniformity of excess rainfall. Consequently, it is based on the time-area method (Clark, 1945) derived using GIS. The GIS allows development of a watershed's channel network for calculation of realistic travel times, it handles the distributed excess rainfall in calculating local surface runoff rates as inputs for channel flow and it compiles the time-area diagram from which distributed unit hydrograph is derived.

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