GIS Integrated Rainfall Runoff Modelling by Development of Spatially Distributed Unit Hydrograph

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Abstract— **Knowledge of peak and total runoff due to rainfall is important for designing any hydrologic structure. But direct measurement of runoff is not possible at the desired time and location. So a rainfall runoff simulation is necessary for the understanding of the interaction between the topographic, climatic and hydrological elements of a watershed. The model used here is a Spatially Distributed Unit Hydrograph model. It is based on time area method and is developed using GIS for the Manimala river basin. The unit hydrograph ordinates are derived from the time area diagram developed with the help of GIS. The excess rainfall is calculated using SCS curve number method. The Spatially Distributed Unit Hydrograph ordinates are convoluted with the excess rainfall values to obtain direct runoff hydrograph. The direct runoff hydrograph is simulated for the year 2007 and is compared with the observed discharge values. The agreement between simulated and observed discharge values proves the efficiency of the model.**

Keywords—hydrologic modelling; Geographic Information System;Spatially Distributed Unit Hydrograph Model

I. INTRODUCTION

Hydrologic models are mathematical representations of known or assumed functions expressing the various components of a hydrologic cycle. The hydrologic response varies within a watershed as a function of topology, soil and land use. Watershed modeling consists of computing stream flows that result from precipitation runoff. They provide the design hydrographs used to size hydraulic structures and are used to quantify the impacts of land use changes and watershed development activities. The unit hydrograph is a traditional means of representing the watershed response at the outlet but it suffers from the limitation that the response function is lumped over the whole watershed. The unit hydrograph is defined as a direct runoff hydrograph resulting from a unit depth of excess rainfall for an effective duration. A spatially distributed unit hydrograph is a unit hydrograph derived from a spatially distributed excess rainfall. It is based on time area rainfall runoff routing technique. Reference [1] first developed the distributed unit hydrograph method for modelling hydrologic processes in watersheds. The watershed is divided into sub areas by isochrones and the unit hydrograph ordinates are derived from it. Reference [2] derived a unit hydrograph from a spatially distributed velocity field in which the watershed is decomposed into sub areas and the unit hydrograph is found for each sub area. The response at the outlet is summed to produce the watershed runoff hydrograph. The time lag between the sub area input and the response at the outlet is found by integrating the flow time along the path from the sub area to the outlet. Reference [3] derived a distributed unit hydrograph with the help of Geographic Information System (GIS). The direct unit hydrograph is computed from the time area diagram compiled by means of GIS. The excess rainfall is calculated by means of Soil Conservation Service (SCS) curve number method and is spatially distributed by GIS. A flow routing algorithm is used in GIS to compute the travel times through a channel network. Reference [5] integrated remote sensing and GIS to evaluate a distributed unit hydrograph which is linked to an excess rainfall model for calculating the stream flow response. Different ranges over hill slopes and along the stream are considered. SCS curve number model is used for calculating the rainfall excess. The present study aims at the derivation of a distributed Unit hydrograph for Manimala river basin, Kerala by using GIS and remote sensing techniques.

II. DISTRIBUTED UNIT HYDROGRAPH MODEL

Distributed unit hydrograph is a unit hydrograph derived from a spatially distributed excess rainfall. Maidment suggested the name spatially distributed unit hydrograph (SDUH) for his new approach in order to distinguish from the traditional unit hydrograph requiring uniform distribution of excess rainfall. The distributed unit hydrograph approach is GIS based which 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.

Assumptions of the distributed unit hydrograph model

1. Hydrograph is time and discharge invariant
2. Flow process in the cell pertains to a wide rectangular channel.
3. Stream cells are not separately considered

A. Determination of Spatial Velocity Field

The specification of velocity for each cell on the watershed is required in order to determine the distributed unit hydrograph ordinates. Velocity distribution map is determined by using raster calculator in ArcGIS 9.3 from the formula

$$V = 1/n^{3/5}\tan(\beta)^{0.3}R(A_{c}) \qquad (1)$$

where $\tan\beta$ is the local slope of the cell, n is the Manning's coefficient and $R(A_c)$ represents the total contributing area.

B. Time Area Diagram

Time Area (TA) rainfall runoff analysis is widely known as a hydrologic watershed routing technique to derive the discharge hydrograph due to a given excess rainfall hyetograph. Many hydrologists consider TA as a lumped model but TA has the potential to perform as a distributed model by including non uniform excess rainfall and spatially variable watershed characteristics. The concept of a spatially distributed unit hydrograph proposed by Maidment [Reference 1] is based on the fact that the unit hydrograph ordinate at time t is given by the slope of the watershed time area diagram over the interval (t-Δt, t). The basic idea of the time area method is the time area histogram shown in Fig. 1 which indicates the distribution of partial watershed areas contributing to runoff at the watershed outlet as a function of travel time. These areas are bounded by isochrones as shown in Fig. 1. The time area diagram is a graph of cumulative watershed area whose time of travel is less than or equal to a given value t =iΔt where i = 1,2,…n plotted against the value of t .

C. Distributed Unit Hydrograph Ordinates

The unit hydrograph of a watershed can be derived from the time area diagram of the watershed by the method analogous to the S-hydrograph procedure. If an excess rainfall occurs at a rate I over the watershed, the runoff at the outlet is given by Q(t) = IA(t), which is an S- hydrograph of runoff tending to an equilibrium discharge of IA where A is the total area of the watershed and A(t) is the watershed area contributing to flow Q(t) at the outlet at time t. Lagging the S- hydrograph by Δt and subtracting it from the original S hydrograph yields the Δt time unit hydrograph ordinates as shown in (2).

$$U(t)= [IA(t)- IA(t- \Delta t)]/[I\ \Delta t] \qquad (2)$$

(or)

$$U(t)= [A(t)- A(t- \Delta t)]/ \Delta t \qquad (3)$$

Because the time area diagram values are known only at discrete time points, t= i Δt, where i = 0, 1,2,…..n, the unit hydrograph ordinates at the corresponding time points are given by (4).

$$U (i\Delta t) = [A(i\Delta t)- A((i-1)\Delta t)]/ \Delta t \qquad (4)$$

(or)

$$U (i) = U(i\Delta t) = Ai/t \qquad (5)$$

where, Ai is the incremental area given by

$$A(i) = [A(i\Delta t)-A((i-1) \Delta t)] \qquad (6)$$

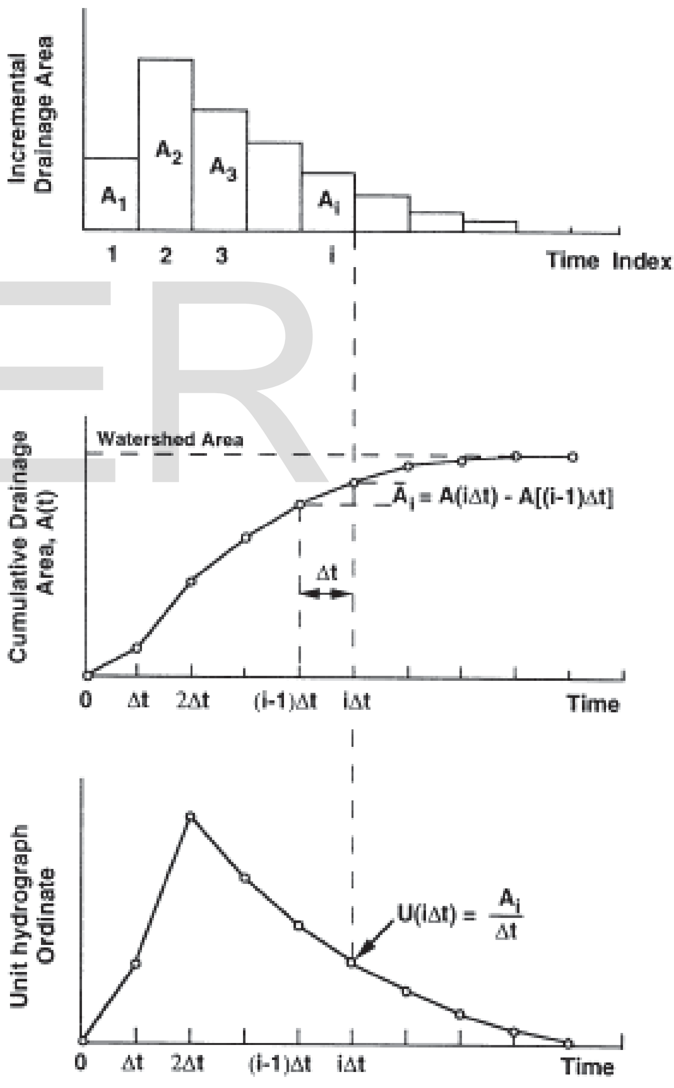

Fig 1 Development of SDUH

III. METHODOLOGY

In order to derive the spatially distributed unit hydrograph (SDUH) ordinates, first of all, watershed delineation is done using ArcGIS 9.3 from Digital Elevation Model (DEM) by fixing Thondra discharge station as the outlet. The flow accumulation and slope maps are derived from the created DEM. The flow length map is then prepared from the flow direction map. The Mannings roughness map is derived from the land use map. The velocity distribution over the watershed is determined using the slope map and the roughness map. Travel time map is then created from the flow length and velocity distribution maps. Time area histogram is derived from the travel time map from which time area diagram is derived. The excess rainfall is calculated using SCS curve number method. The surface runoff is then generated by a discrete convolution between the unit hydrograph ordinates and the excess rainfall values.

The SCS-CN method is the most popular method for computing surface run off for rainfall event. This approach involves the use of simple empirical formula and readily available tables. It was reported that SCS-CN method proves to a viable method for estimating the effects of land treatment and land use changes on volumes of run-off under the wide range of climatic conditions. The SCS-CN method continues to be most satisfactory when used for different types of hydrologic problems that were designed to solve evaluating the effects of land use changes. The advantages of this method are its simplicity, predictability, stability and its reliance on only one parameter namely the Curve Number (CN). The land Use / Land Cover classes can be integrated with the hydrologic soil groups of the sub basin in GIS. The computed daily runoff values can be checked with the observed data. The main inputs required to the SCS-CN method are watershed boundary, soil map, land use/land cover thematic map and antecedent moisture condition to estimate daily runoff.
The general equation of SCS Curve number model is

$$Q = (P - Ia)^2 / (P - Ia + S) \qquad (6)$$

where, Q is Runoff depth in mm, P is Rainfall in mm, S is Maximum recharge capacity of watershed after 5 days rainfall antecedent, Ia(initial abstraction) = 0.2S

Hence, $$Q = (P - 0.2S)^2 / (P + 0.8S) \quad (P>0.2) \qquad (7)$$

The recharge capacity S is calculated by substituting the value of CN in the equation

$$S = 25400/CN - 254 \qquad (8)$$

The parameter CN having the range of values of CN between 0 and 100 is called the curve number. In this method CN is assigned to each watershed or portion of watershed based on land use, soil and Antecedent moisture conditions.

For Indian conditions

$$Q = (P - 0.3S)^2 /(P+0.7S) \quad (P>0.3S) \qquad (9)$$

IV. DERIVATION OF DISTRIBUTED UNIT HYDROGRAPH FOR THE STUDY AREA

A. *Study Area*

Manimala watershed with Thondra as the outlet station is taken as the study area. The area lies between latitudes 9°26'31.2" N and 9°29'24" S and longitudes 76°25'58" E and 76°54'0" W. The watershed lies in the Kottayam and Pathanamthitta districts of Kerala covering an area of 700 km^2. The total length of Manimala river traversing the study area is about 80 km with Elakalthodu and Kokkayar as the major tributaries. The location of study area is shown in the Fig 2.

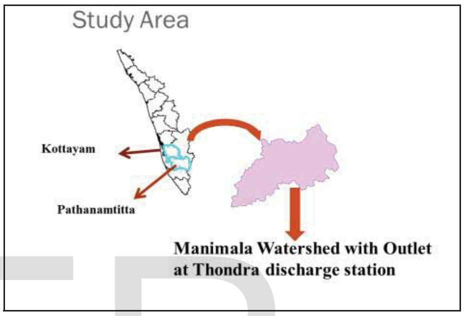

Fig 2 Study area

The base map of study area is shown in Fig 3.

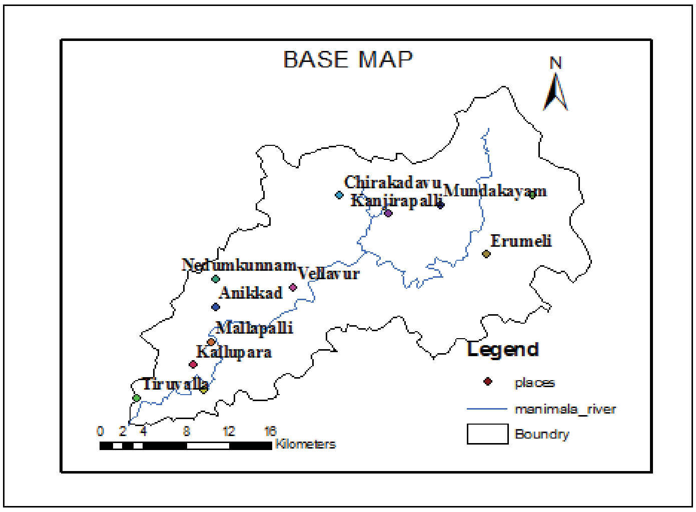

Fig 3 Base map

B. Digital Elevation Model

A DEM is a raster representation of a continuous surface, usually referring to the surface of the earth. It is prepared from the digitized contour map of the region. The errors in DEM are removed to create a depressionless DEM as shown in Fig. 4. The flow direction and slope maps are created from the depressionless DEM. The contributing area to each cell in the basin is prepared from the flow accumulation map which gives the accumulated flow of all cells flowing into each down slope cell.

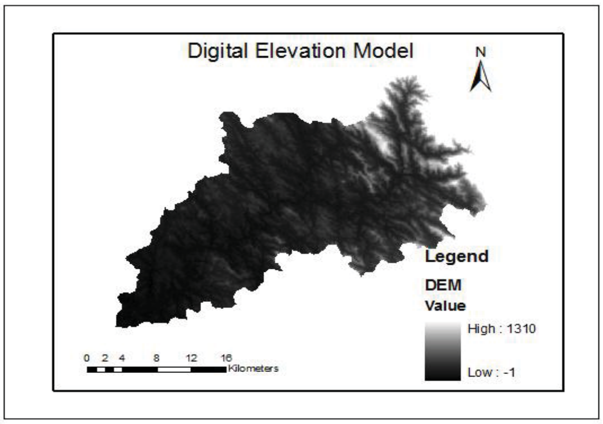

Fig 4 Digital Elevation model

C. Flow Length Map

It is the distance from any point in the watershed to the watershed outlet. It is measured along the direction of flow. The flow direction is given as input to obtain the flow length map. The flow length map is shown in Fig. 5.

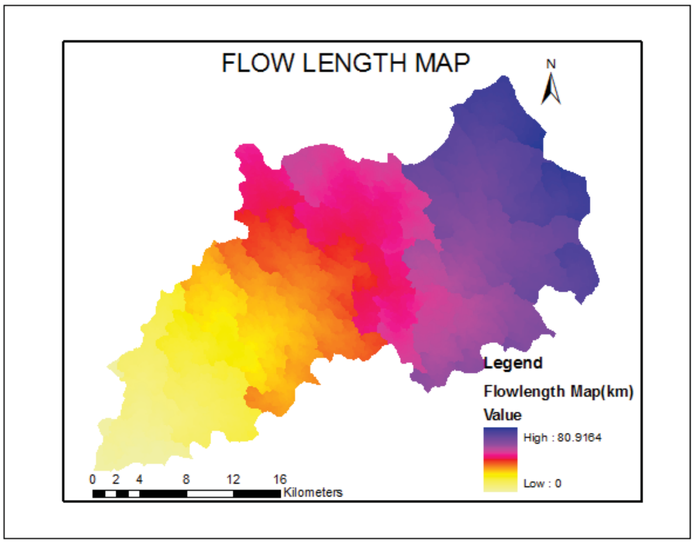

Fig 5 Flow length map

D. Flow accumulation map

It represents the accumulation of flow to a particular point. Flow accumulation map is shown n Fig 6.

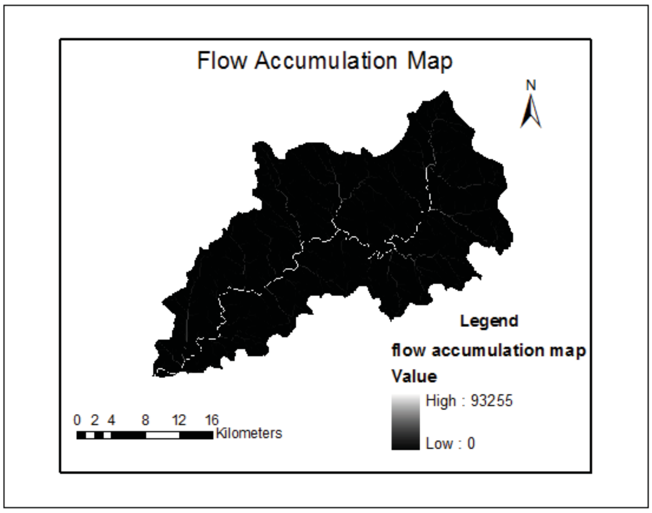

Fig 6 Flow accumulation map

E. Landuse Map

Land use for study area is clipped from the land use map of kerala. Land use map of study area is shown in Fig 7.

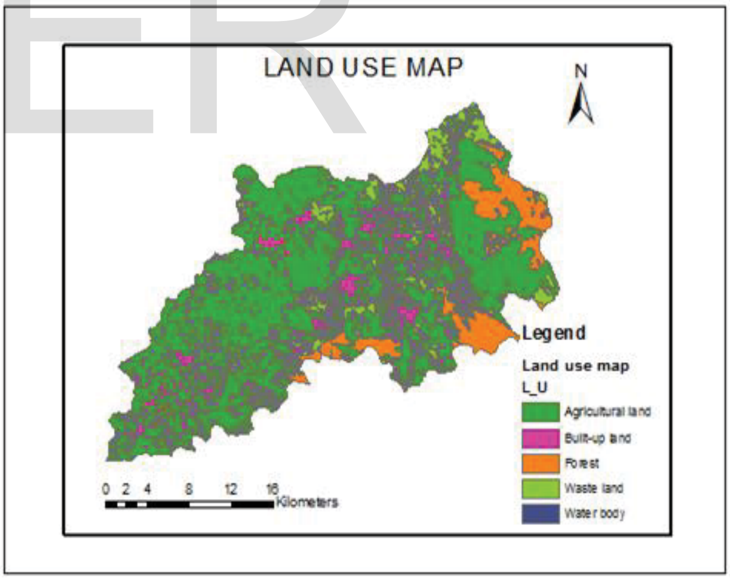

Fig 7 Land use map

F. Mannings 'n' Map

The mannings 'n' values are assigned based on the land use classification as in Table 1.

TABLE 1 Assigned mannings 'n' values

Land use	*Mannings 'n' value*
Agricultural Land	0.2
Water body	0.006
Built up land	0.01
Forest	0.4
Waste land	0.045

The prepared mannings 'n' map is shown in Fig 8.

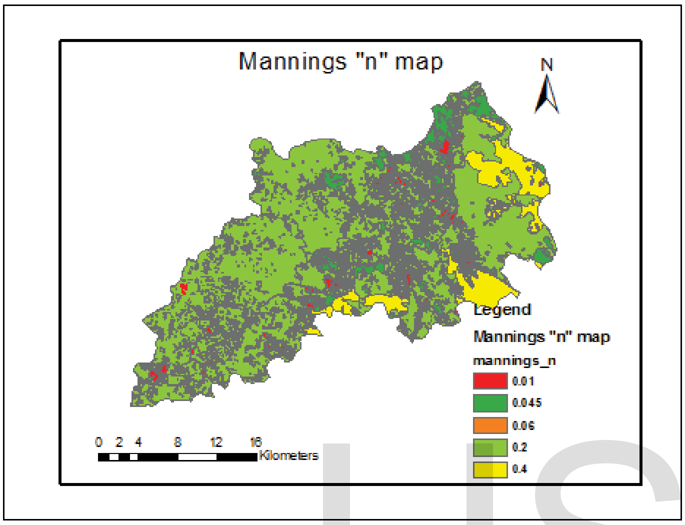

Fig 8 Mannings 'n' map

G. Slope Map

The slope map prepared is shown in Fig 9.

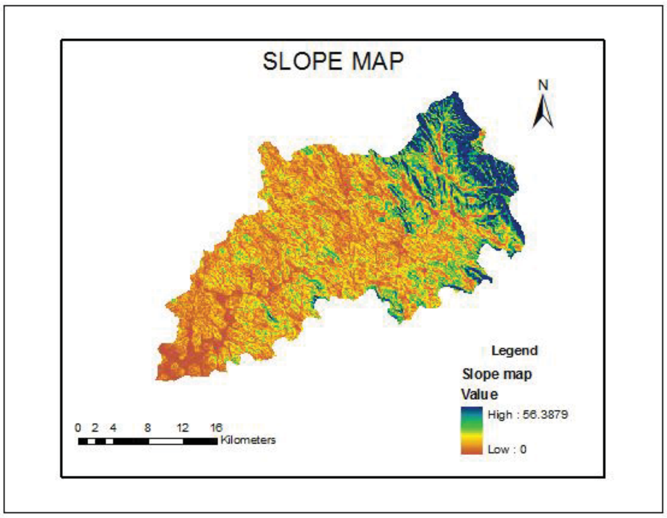

Fig 9 Slope map

H. Soil Map

The prepared soil map is shown in Fig 10.

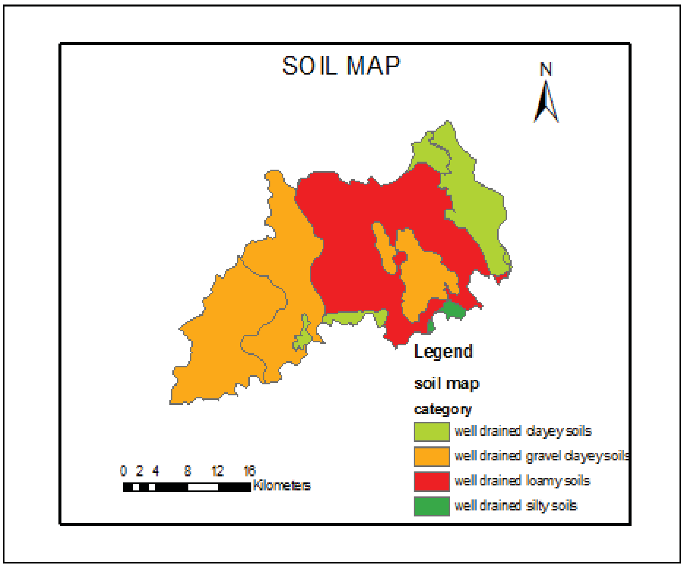

Fig 10 Soil Map

I. Velocity Map

From the algorithm for spatial velocity field derivation, spatial velocity distribution is determined in the form of velocity map as shown in Fig 11.

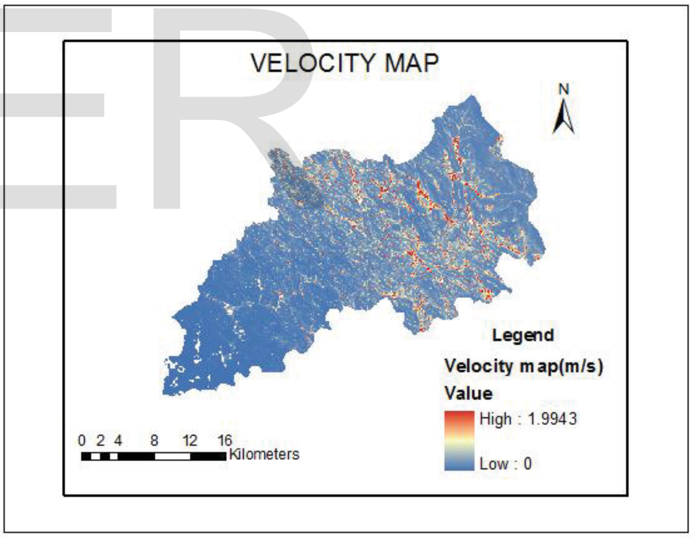

Fig 11 Velocity Map

J. Travel Time Map

The travel time map is obtained by dividing flow length map by flow velocity map shown in Fig 12.

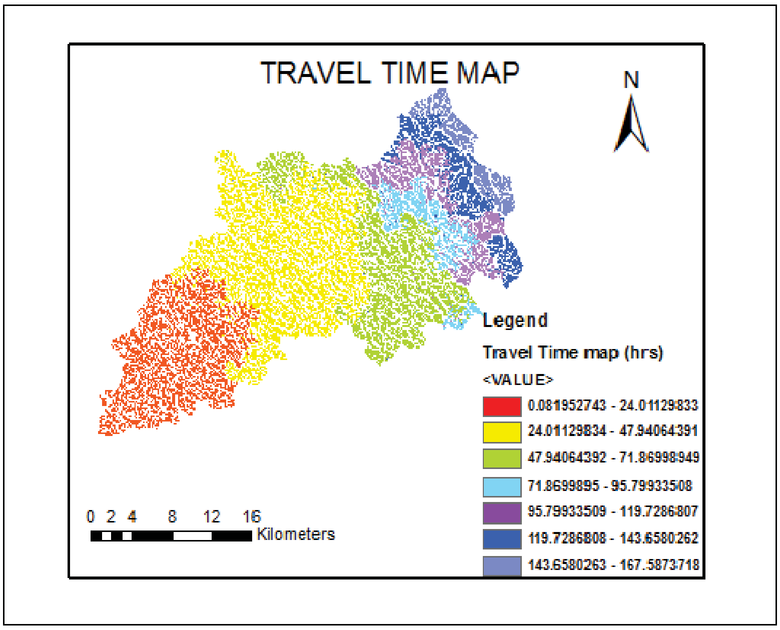

Fig 12 Travel time Map

V. RESULTS AND DISCUSSIONS

From the travel time map with time of concentration of 168 hrs, the drainage area covered in time of concentration of 24 hr incremental interval is determined and time area histogram is plotted. Time area histogram indicates the distribution of partial watershed areas contributing to runoff at the watershed outlet as function of travel time. The time area histogram is prepared such that the time of concentration is fixed as 120 hours. Therefore the minor contributing areas beyond 120 hours is distributed to the previous ordinates of time area histogram. The corrected time area histogram and time area diagram are shown in Fig 13 and 14 respectively. The SDUH ordinates which shows the slope of time area diagram is shown in Fig 15.

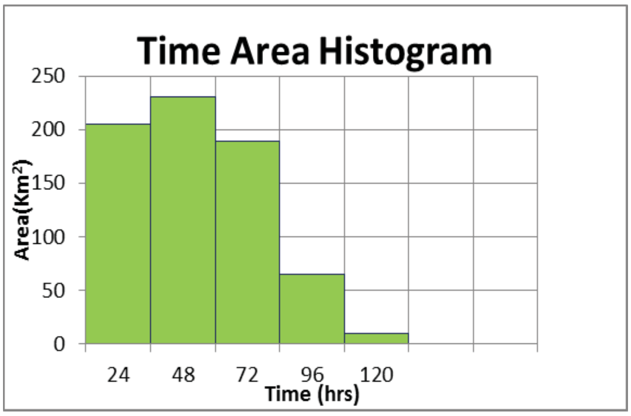

Fig 13 Time area histogram

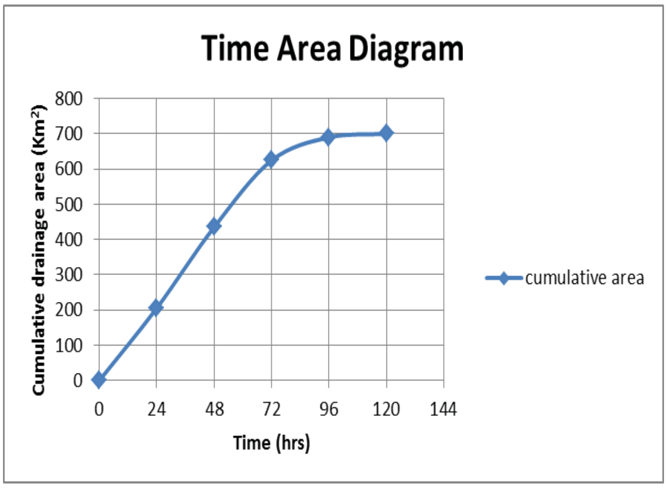

Fig 14 Time area diagram

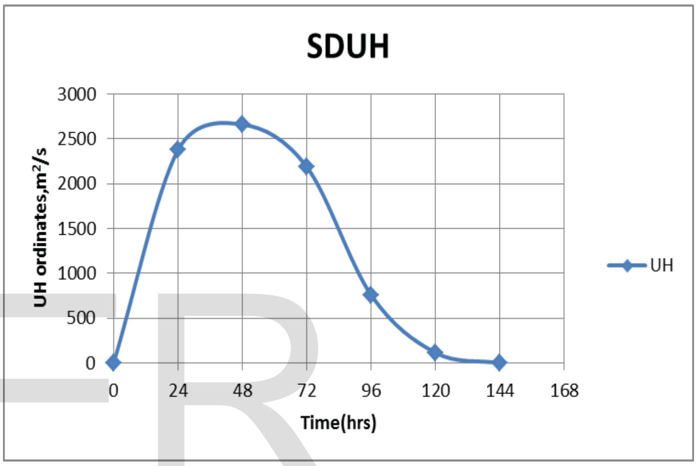

Fig 15 SDUH ordinates

The excess rainfall is determined from SCS curve number method. The vector coverage of soil and land use are overlaid to estimate curve numbers and runoff depths for the entire study area. From the attribute table of the spatially joined land use map and soil map the CN values are assigned by using equation 8 and 9, runoff depth maps are generated for every input of rainfall events.

The excess rainfall values are convoluted with the unit hydrograph ordinates to get the direct runoff values. The hydrograph is simulated for the year 2007 and it is compared with the observed values as shown in Fig 16.

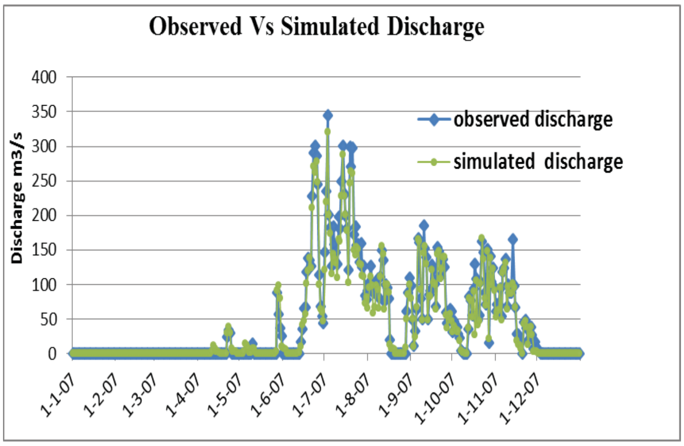

Fig 16 Comparison of observed and simulated discharge

The observed peak discharge is found to be higher than the simulated discharge. The RMSE error calculated is 28 and the correlation coefficient obtained is 0.86. The relative error in peak discharge is about 7.7%. The Nash Sutcliff Coefficient, R^2 is 0.84. Hence it can be concluded that SDUH is a good rainfall runoff model. The agreement between the simulated and the observed flood hydrographs are found good, considering that no parameter optimization is performed.

VI. CONCLUSION

A 24 hour Spatially Distributed Unit Hydrograph is developed for the Manimala watershed. The time area diagram is developed by compiling the time of concentration of 24 hour incremental interval against drainage area. Flow velocity distribution is derived by combining Continuity equation and Mannings equations. The direct runoff hydrograph ordinates are calculated using a discrete convolution between the excess rainfall computed by SCS curve number method and the unit hydrograph ordinates. Direct runoff hydrograph is simulated for the year 2007. The RMSE error calculated is 28 and the correlation coefficient obtained is 0.86. The relative error in peak discharge is about 7.7%. The simulated discharge seems to conform with the observed discharge values. The slight variation may be due to the assumption that unit hydrograph is time and discharge invariant. The unavailability of hourly data also reduces the efficiency of the model.
The distributed unit hydrograph can be actually derived for ungauged watersheds without observed rainfall and runoff data, because the time-area curve is computed on the basis of watershed hydraulics, for which data may be obtained by field survey. SDUH can be used to estimate runoff for large drainage basin with the help of flow routing technique by sub dividing the watershed. The distributed unit hydrograph model of a watershed can be efficiently implemented with the aid of GIS. The GIS enables to capture and to utilize a number of watershed and rainfall distributed parameters in the model, which is not possible when using the classical unit hydrograph approach.

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