GIS BASED RAINFALL RUNOFF MODELLING

Francis Rex V. J.

II year student, M.E.Hydrology & Water Resources Engineering,
Centre for Water Resources, College of Engineering,
Anna University, Chennai-600025, TamilNadu, India.
E-mail: rex_pec@yahoo.com

Abstract

Hydrological modeling is of prime importance for hydrologists in planning, design and operation of water resources related structures. It also acts as an efficient tool to forecast flood disasters. In gauged basins there are observed rainfall-runoff data for the storms, but in the case of un-gauged basins, a rainfall runoff relationship must be established to meet the requirements of design of hydraulic structures. In this study rainfall runoff modelling is carried out in a GIS environment. Digital Elevation Models can be used to derive a wealth of information about the morphology of a land surface using algorithms traditionally used for processing raster data. The key objectives of this study are to create a Digital Elevation Model in GIS, to derive the parameters required for the modeling process from the created Digital Elevation Model. Various topographic attributes such as slope, catchment area and aspect can be derived from DEM. The parameters obtained namely flow length and slope is used to calculate the time of travel for the segmented flow length. From the flow length map and slope map, the isochrone map is prepared. The area between two isochrones is calculated and tabulated. From the tabulation the Time – Area diagram is derived for the study area. Area routing technique is used to derive the ordinates of the Unit Hydrograph. . The soil and land use maps were digitized and the areas under each soil type and land use were derived. Weighted overlay analysis was done for soil type and land use and the cumulative curve number for the watershed was found. Dependability analysis was done for the available rainfall data. 75% dependable rainfall was taken for analysis. A rainfall event was chosen from this year to find the rainfall excess, using SCS method. The rainfall excess was distributed among the Unit Hydrograph ordinates to arrive at the storm hydrograph. This method can be used to obtain Unit hydrograph of any duration and consequently storm hydrograph in this basin for design purposes. From the results derived it is inferred that GIS is a powerful tool for Rainfall Runoff Modelling.

INTRODUCTION

Progress and growth of a nation is linked with the development and management of water resources. The identification of additional sources of water to increase conservation will play a vital role in developing the nation's wealth. Runoff estimation is one of the prerequisite in development and management of water resources. The population growth and intensive agricultural activity in recent years necessitated increased use of water. Further, the existing surface water resources should be utilized optimally to meet various purposes. Therefore, a physical based approach in estimation of runoff from a catchment is needed. The DEM based rainfall runoff modeling is one such kind. In this study, DEM based estimation of runoff from a watershed using GIS is attempted. Hydrology is concerned with study of the motion of the earth's waters through the hydrologic cycle. Rainfall Runoff Modelling is an important study in hydrology. The use of rainfall runoff models arises because of the inadequacy of hydrologic data (Dooge, 1972). The rainfall runoff relationship is a function to the hydrologic and physiographic characteristics of the catchment. Rainfall runoff modeling involves huge quantity of data pertaining to the spatial and temporal features of the

catchment. Geographical Information System (GIS) plays an important role in handling, analyzing, and presenting the data needed for rainfall runoff modeling. In conventional hydrological model, the input parameters have to be measured through ground truth measurement that involves more cost, time and labor. With the increasing advancement of computer technology, GIS has been applied to extract land surface properties, which vary at spatial and temporal scales. GIS is a computer-based system used to capture, store, analyze, update and display data. GIS can handle mainly two classes of data namely spatial data, identifying the location and topography of map and attribute data, identifying the characteristics of these features. Since, the above-mentioned features are directly related in rainfall runoff modeling, GIS is an ideal environment to aid in the process of modelling.Previously attempts were made to create a rainfall runoff model with the aid of GIS. A Digital Elevation Model was created was used for further anlysis by Esmael Nezamipour (1995).in this study a rainfall runoff model is created for deviar watershed of Vaippar basin in Tamil Nadu. It has an area of 15.96 km^2.

Esmael Nezamipour (1995) created a Digital Elevation Model with rectangular grid of size 50*50m. An integration of time area method, Soil Conservation Service Curve Number (SCS) and unit hydrograph concept was done. Mohan Zade et.al (2005) made an attempt to quantify the runoff potential for all basins of India using remote sensing data. Nayak T.R. et.al (2003) used remote sensing data as an input to the SCS model. Remote sensing data provided spatial information on land cover, soil etc. ILWIS2.2GIS package has been used to store manipulate and estimate sub basin wise weighted average runoff curve numbers. John Nikolaus Callow et.al (2006) reconditioned the surface of DEM to improve their representation of true hydrology. This study investigated three methods to modify a DEM to reflect a known Hydrology. Vincent Chaplot et.al (2006) evaluated the accuracy of several interpolation techniques. At strong spatial structure of altitude kriging was found to yield better estimates and when the spatial structure was weak IDW was found to perform better. Turcotte R. et.al (2001) tried to rectify the limitations of the conventional eight flow direction matrix used to determine the flow directions by using a digital river and lake network (DRLN). A detailed definition of watershed internal drainage system was obtained

SPATIAL DATABASE CREATION

A scientific database is needed prior to rainfall runoff modelling. The database comprises of physical, meteorological and hydraulic characteristics of the watershed. A database is created in a GIS environment which involves a lot of manual labour and is time consuming. Various maps were collected from various departments which are the base for database preparation. The map data were converted to digitized format with their respective attributes using ArcGIS 9.0. The various maps digitized are shown.

The boundary of Deviar watershed was delineated from the Vaippar basin map in the form of toposheet from Survey of India, Chennai. The delineated watershed was digitized and the area of the watershed was also derived. Figure 1 shows the natural drainage pattern in the watershed. Streams of different orders are digitized separately. This drainage network is used to compare it with the artificial drainage network generated in ArcGIS 9.0 with the aid of contours. The contours digitized from the toposheet is shown in figure 2. The contours present in the base map were digitized. The contours vary from 180m to 1480m. Most of the North-Western part of Deviar watershed is hilly and south eastern part is almost flat.
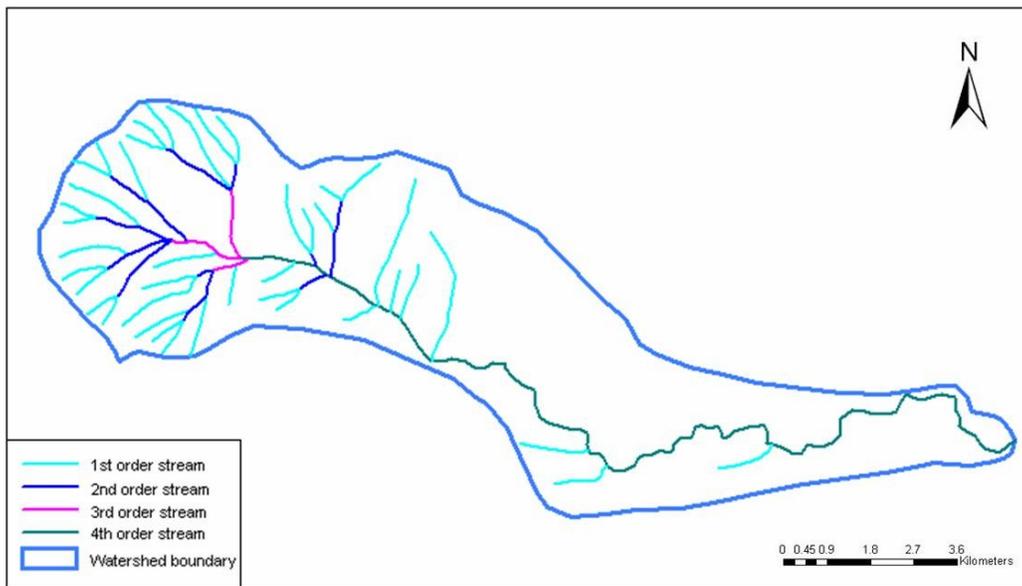
Figure 1. Drainage map of Deviar watershed

Figure 2. Contour map of Deviar watershed

Two major hydrological soil types were found to be present in this watershed. Type B and type C were predominant in this watershed. Of the total area, 75% was found to have C type soil and the remaining part was covered by B type soil. The digitized soil type map is shown in figure 3.
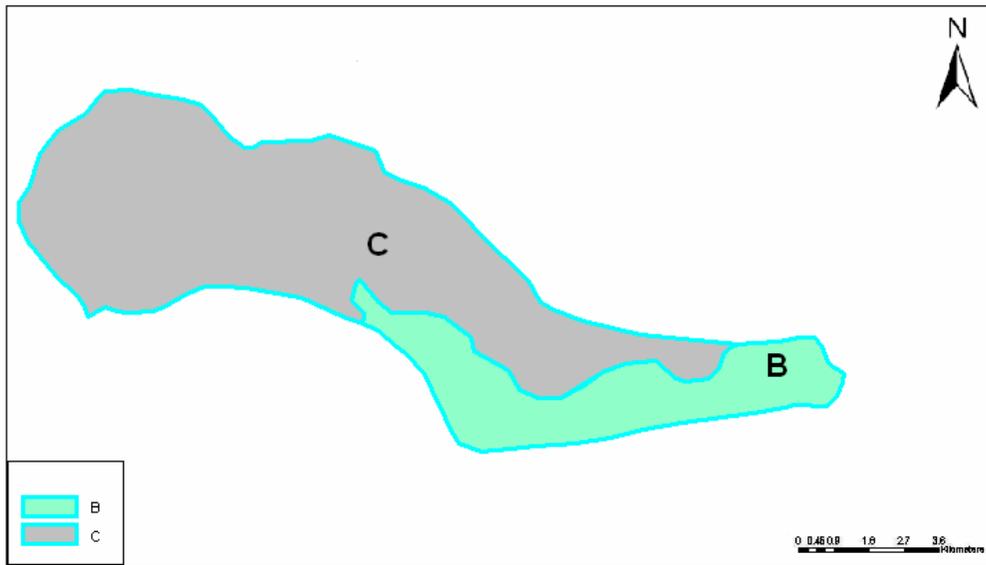
Figure 3. Soil type map of deviar watershed

The landuse map of Deviar watershed was prepared in digital. The landuse is categorized into two major types namely hill area and intensively irrigated area. Hill area is covered by 52% and the remaining portion in covered by intensively irrigated area. It is shown in figure 4.
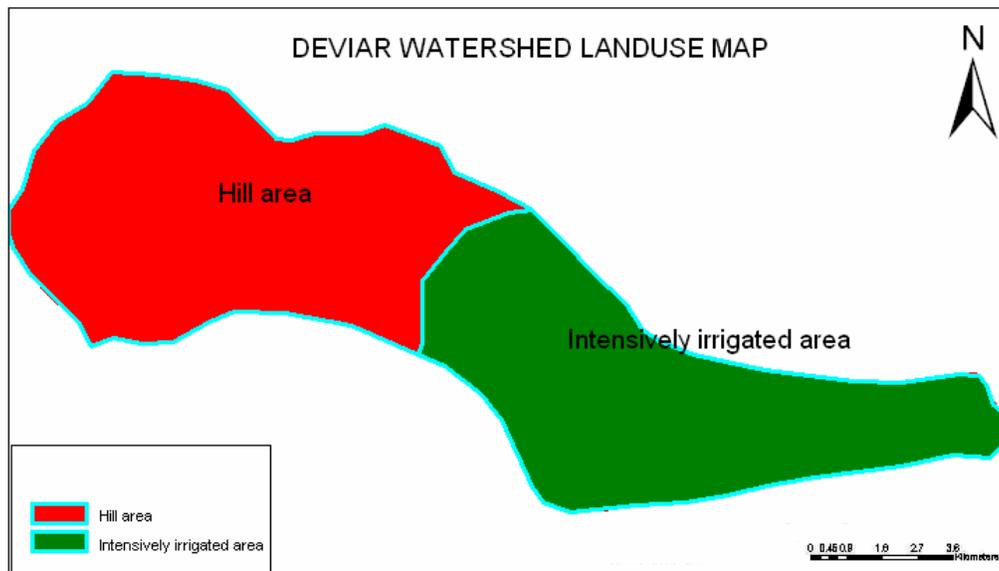

Figure 4. Landuse map of deviar watershed

DIGITAL ELEVATION MODEL

        A Digital Elevation Model corresponds to the 3 dimensional representation of the watershed. The Digital Elevation Model was prepared from the contour levels present in the Survey of India toposheet. From the Digital Elevation Model it is inferred that the North-western part of Deviar watershed is hilly and the South-Eastern part is almost flat. As the upper part has hilly terrains the travel time is less compared to the lower part which is flat. The Digital Elevation Model of Deviar watershed is shown in figure 5.
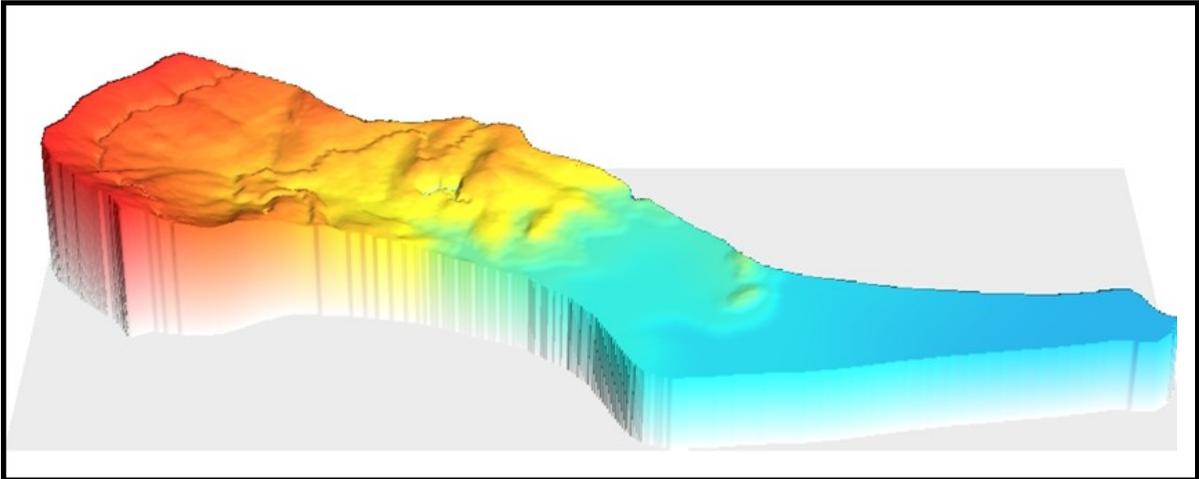

Figure 5. Digital Elevation Model of Deviar watershed

        The contour lines digitized from the base map is used as an input to create the Digital Elevation Model (DEM). The lines are converted into contour points and are fed into ArcGIS to create the DEM. The contour map is processed in ArcGIS 9.0 to derive the interpolated elevation map. The interpolation technique used in ArcGIS is Inverse Distance Weighting. The elevation map is used as a base to derive the flow direction map. From the flow direction map the flow accumulation map is generated. The stream network generated by the capabilities of ArcGIS is compared with the original stream network digitized from the toposheet. The generated stream network is found to match with the original, which implies that the analysis done is correct.

        The methodology is presented in the form of a flowchart in figure 6. Using SCS method the rainfall excess for a particular event of rainfall is to be found. The expression involved to determine the rainfall excess is shown in equation (1)

$$Q = \frac{(P-0.3*S)\char`\^2}{(P+0.7*S)} \qquad (1)$$

where Q is the actual direct runoff in mm, P is the total rainfall in mm and S is the surface retention or watershed storage in mm. **S** is related to curve number (**CN**) by the equation

$$S = \frac{25400}{CN} - 254$$

(2)

where CN represents the curve number of the watershed. Curve number is a dimensional parameter allied with the following factors such as hydrologic soil group and landuse. Weighted overlay analysis is to be performed for soil type and landuse maps created as a database. Overlay analysis is to be done in ArcGIS 9.0. The cumulative curve number for the watershed is to be found. The digitized land use and hydrologic soil group maps are to be overlaid. Each unique land use – soil

type polygon is to be identified and the area of each polygon is to be calculated. Each polygon is to be assigned with a curve number form the standard SCS curve number table.
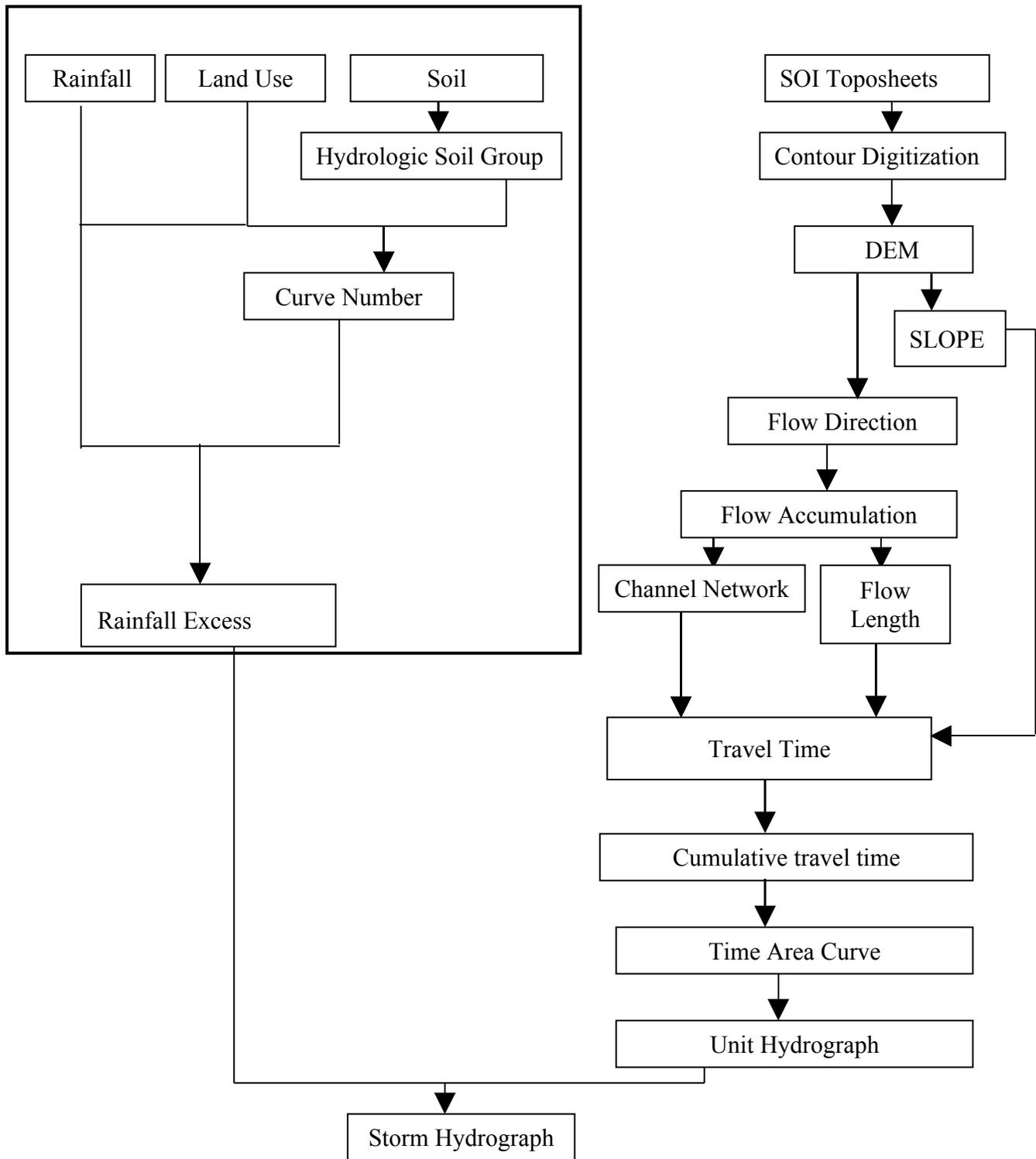
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┌─────────────────────────────────────────────────────┐
│  ┌──────────┐  ┌──────────┐  ┌──────────┐            │
│  │ Rainfall │  │ Land Use │  │   Soil   │            │
│  └──────────┘  └──────────┘  └──────────┘            │
│                              ┌────────────────────┐   │
│                              │Hydrologic Soil Group│  │
│                              └────────────────────┘   │
│                     ┌──────────────┐                  │
│                     │ Curve Number │                  │
│                     └──────────────┘                  │
│                                                       │
│        ┌──────────────────┐                           │
│        │ Rainfall Excess   │                          │
│        └──────────────────┘                           │
└───────────────────────────────────────────────────────┘
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Figure 6. Flowchart for methodology

The area weighted curve number is calculated using the relation given in equation (3).

$$CN_{aw} = \frac{\sum_{i=1}^{n}(CN_i * A_i)}{\sum_{i=1}^{n}A_i} \qquad (3)$$

Where CN_{aw} is the area weighted curve number of the watershed, CN_i is the curve number for each land use soil group polygon, A_i is the area for each land use soil group polygon and n is the number of land use soil group polygon in the watershed.

The rainfall for the year 2000 – 2001 was found to 75% dependable and hence one particular event was chosen from this year to find the rainfall excess. Weighted overlay analysis was performed for soil type and land use and the cumulative curve number for the watershed was found to be 79.56 Using SCS methods the rainfall excess for 75mm of rainfall of three hour duration on a particular day was found to be 26mm.

DERIVATION OF UNIT HYDROGRAPH FROM DEM

The prime factors involved in generating the slope map are the contour and the flow length map. From the slope map and the flow length map derived the isochrone map is derived for which the following relation is used.

$$V = 0.48*(S^{0.5}) \quad \text{(SCS method, NWS, Hydrologic training module)} \qquad (4)$$

The interpolated elevation map, flow direction map, flow accumulation map, flow length map are shown in figure 7, figure 8, figure 9 and figure 10 respectively.
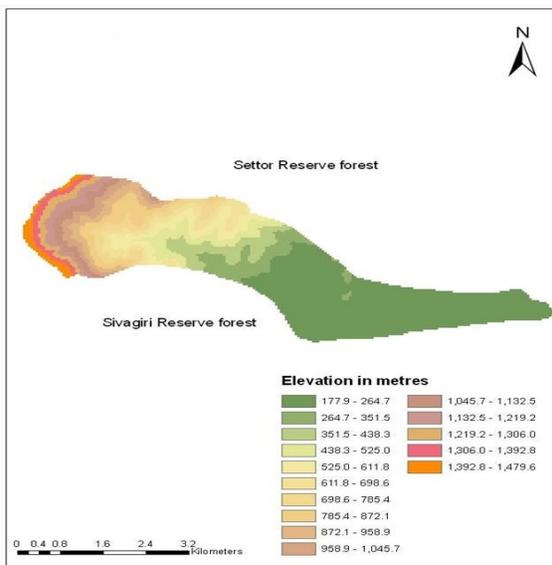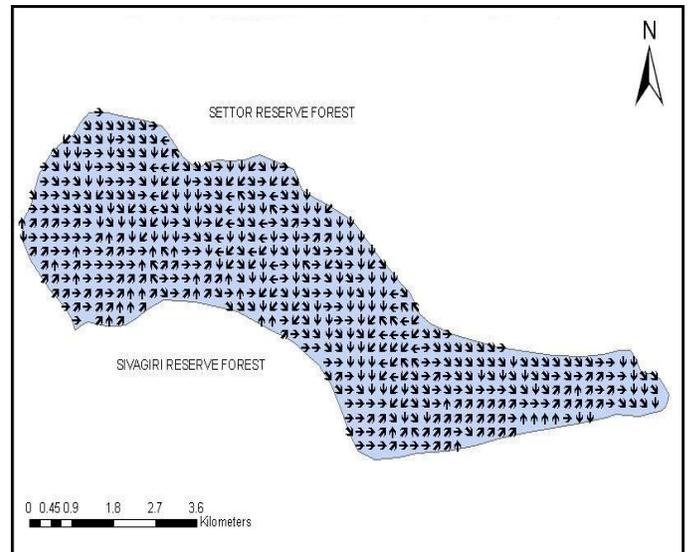

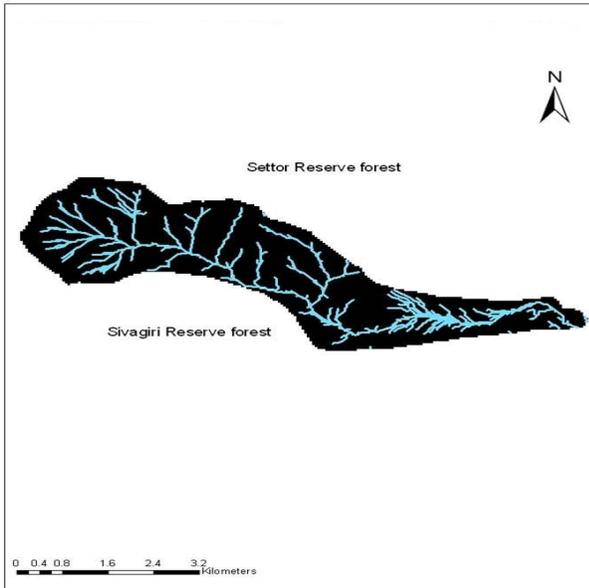Figure 7. Interpolated elevation map

Figure 8. Flow direction map

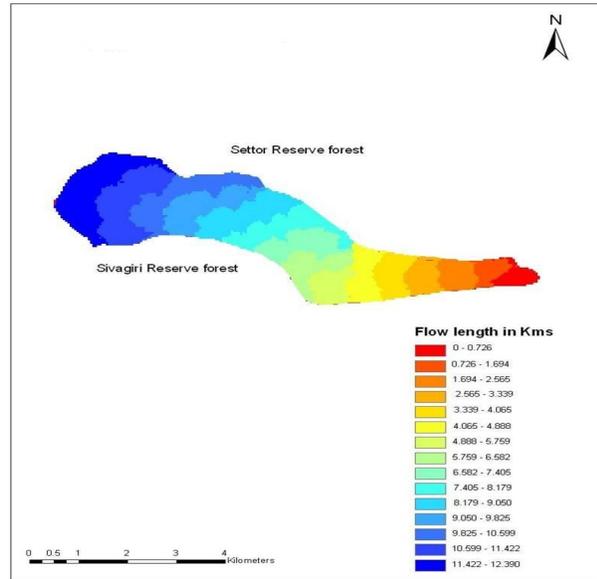Figure 9. Flow accumulation map

Figure 10. Flow length map

COMPARISON OF MODELLED AND NATURAL DRAINAGE

The stream networks derived by the capabilities of ArcGIS and the natural drainage network digitized from contour map are compared. The white line denotes the drainage network digitized from the contour map whereas the the red line denotes the stream network derived from ArcGIS 9.0. Both were found to be matching which indicates that the proceeding is correct. The map indicating comparison of natural drainage and stream network generated by ArcGIS 9.0 is shown in figure 11.
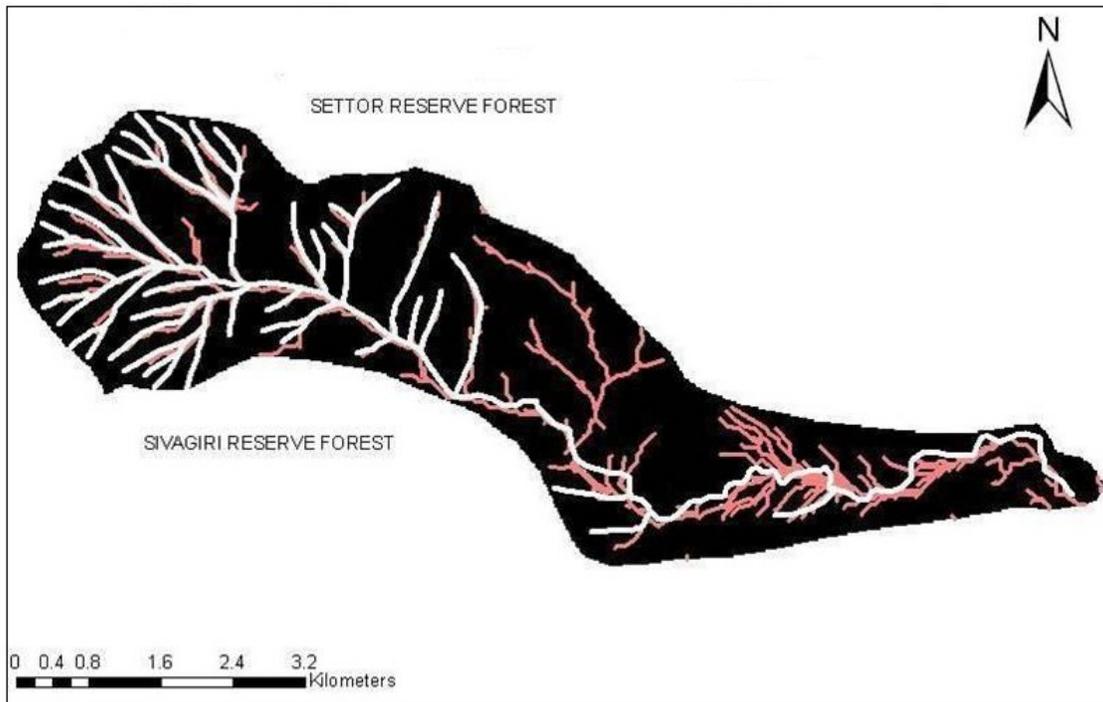
Figure 11. Comparison of natural and ArcGIS 9.0 generated stream network

Using the flow length and the slope map the travel time map is generated in ArcGIS 9.0. The slope map and the travel time map is shown in figure 12 and figure 13 respectively.
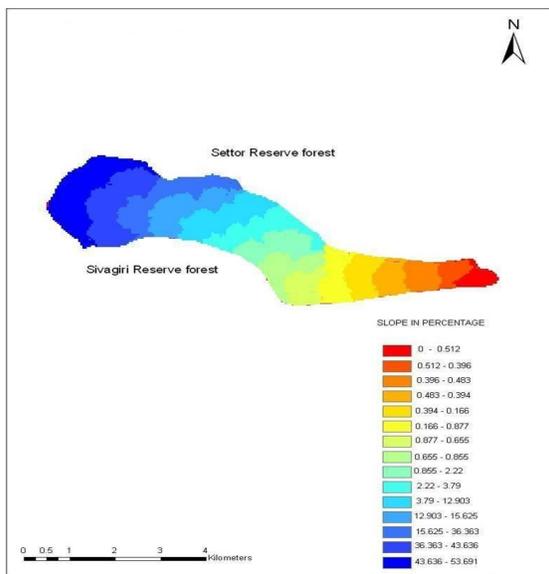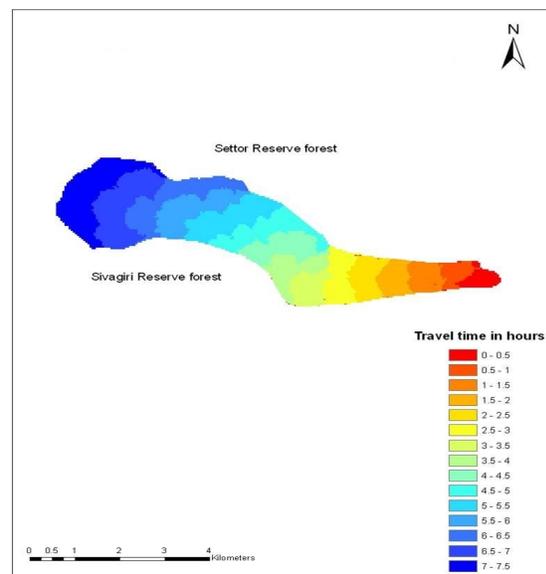

Figure 12. Slope map

Figure 13. Travel time map

From the isochrones derived the area under each isochrone was calculated in ArcGIS 9.0 and the Time - Area plot was done. The Time – Area plot done in MS Excel is shown in figure 14.
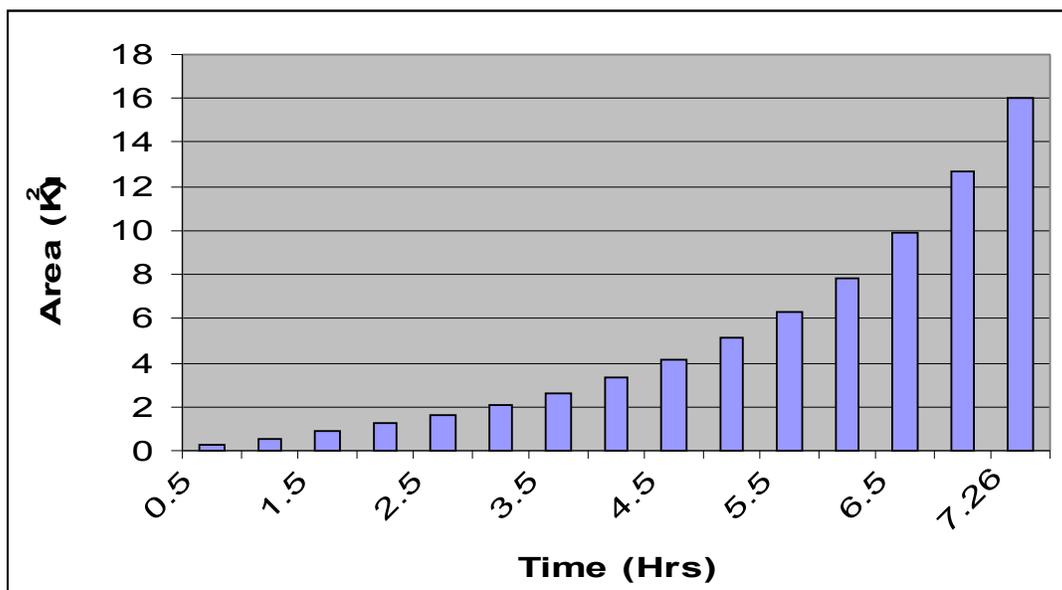
Figure 14 Time – Area diagram

Area routing method

A time-area method utilises a convolution of the effective rainfall hyetograph with the service of a time-area diagram. This diagram represents the progressive area contributions within a watershed as the time increases. By area routing technique, the ordinates for the Unit Hydrograph of different durations can be derived. The governing equation for this routing technique is

$$Qi = \sum_{j=1}^{i} aj * Ii - j \quad \text{(Rainfall runoff relationship, V.P Singh)} \tag{5}$$

Where a_i is the area enclosed by the ith isochrone and I_i is the intensity of effective rainfall in the ith interval. The unit hydrograph ordinates for three hour duration of rainfall was derived using time area routing method. The Unit hydrograph for three hour duration is derived The Unit hydrograph had a peak discharge of 5.59 m^3/s at duration of 7 hours 30 minutes. The shape of the watershed influences the time taken for water from the remote parts of the catchment to arrive at the outlet. Thus the occurrence of peak and shape of the hydrograph are affected by the basin shape. In this case the Unit Hydrograph is skewed to the right and the peak occurs with a relatively longer lag. Small watersheds behave different from large ones. In small watersheds the overland flow is predominant. In small watersheds the time taken for water to reach the outlet from the remotest parts plays a dominant role. Hence there is a relatively longer lag for the peak to occur.

Storm Hydrograph

The rainfall excess obtained using SCS method is distributed among the three hour Unit Hydrograph ordinates and the storm hydrograph was derived. The storm hydrograph had a peak discharge of 14.55 m^3/s at a duration of 7 hours 30 minutes. The three hour Unit Hydrograph and the consequent Storm Hydrograph are shown in figure 15 and figure 16 respectively.
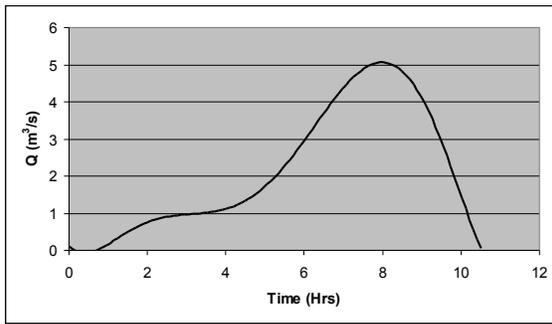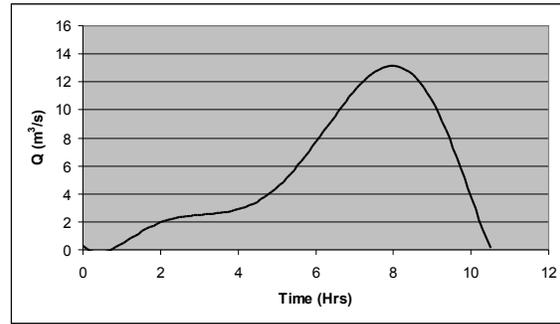
Figure 15. Three hour Unit Hydrograph

Figure 16. Three hour Storm Hydrograph

Summary and conclusions

Rainfall Runoff modeling is of prime importance considering any developmental activities in a particular basin. The key objectives of this study are to create a Digital Elevation Model in GIS, to derive the parameters required for rainfall runoff modeling from DEM and to generate the Unit Hydrograph and Storm Hydrograph for the watershed.

The study area chosen is Deviar watershed which has an area of about 15.95 Km^2. Soil Conservation Service method is used to find the rainfall excess for the basin and Time-Area routing method is used to derive the Unit Hydrograph. From the rainfall excess and Unit hydrograph, the storm hydrograph is derived for the watershed Creation of a Rainfall Runoff model involves dealing with a huge volume of data. GIS is found to very useful in the process of developing a Rainfall Runoff model. It has made the process much simpler when compared with doing it manually. The flow length map, isochrone map and flow direction map are derived in ArcGIS 9.0 which is impossible to derive manually. Time-Area routing is done to derive the Unit Hydrograph. Unit Hydrograph of any duration can be derived from the Time Area diagram. The coupling of GIS techniques with rainfall runoff model has resulted in a powerful tool for the assessment of water resources.

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