SIMULATION OF RUNOFF IN WATERSHEDS USING SCS-CN AND MUSKINGUM-CUNGE METHODS USING REMOTE SENSING AND GEOGRAPHICAL INFORMATION SYSTEMS

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Abstract

The Muskingum-Cunge flood routing procedure has been incorporated into the Natural Resources Conservation Service Technical Release 20 (TR-20) hydrologic model. The TR-20 model is an event watershed hydrologic model used to analyze impacts of watershed changes (land use, reservoir construction, channel modification, etc) on volume of runoff and peak discharge. Rainfall runoff modeling is very important in the planning and management of available water resources in a watershed. In this paper, a SCS-based unit hydrograph has been used to simulate the overland flow. Muskingum-Cunge hydrological routing method has been used for channel routing. Hydrologic processes such as infiltration losses and runoff are considered in the present model. Remote sensing and GIS techniques have been used to estimate the spatial variation of the hydrological parameters, which are used as input to the model. The runoff is considered as overland flow and channel flow. In the present work, Madikonda watershed, Warangal district, Andhra Pradesh is the study area. The geographical location of this watershed is in between North latitudes 17° 45'- 18° 00' and East longitude 79° 15'- 79° 30'. The watershed has an area of 35.9 Sq.Km. The complete watershed has been divided into six sub watersheds. The runoff from subwatersheds has been routed to the watershed outlet through channel network. The developed model is capable for simulating the event based runoff in the watersheds.

Keywords: *Channel flow, Curve number, Muskingum-Cunge routing, Overland Flow, Runoff.*

1. Introduction

The Muskingum-Cunge flood routing procedure has been incorporated into the Natural Resources Conservation Service (NRCS) Technical Release 20 (TR-20) hydrologic model. The Muskingum-Cunge method for channel flood routing has been documented in many textbooks, professional papers, and by Dr. Miguel Ponce in two reports delivered by contract to SCS in 1981 and 1983. The Corps of Engineers HEC added it as a flood routing option in the HEC-1 program (1990). Routing tests performed by Younkin and Merkel (1986, 1988) showed increased accuracy, consistency, and range of physical conditions when compared to both the Modified Att-Kin and Convex flood routing methods which had been used previously (NRCS, 1965 and 1983). The Muskingum-Cunge routing procedure was compared to the solution of the dynamic wave equations as formulated by St. Venant.

The term 'precipitaion'denotes all forms of the water that reach the earth from the atmosphere, and runoff means the draining or flowing off of precipitation from a catchment area though a surface channel after satisfying all surface and sub surface losses. (Dubayah, R., et al, 1997) Prediction of surface runoff is one of the most useful hydrological capabilities of a GIS.system. The prediction may be used to assess or predict aspects of flooding, aid in reservoir operation, or be used in the prediction of the transport of water born contamination (Jain, M.K., 1996). The type of models that have been applied with a GIS will be classified as lumped parameters, Physical based or some combination of the two. There has been a growing need to study, understand and quantify the impact of major land use changes on hydrologic regime, both water quantity and quality (Engman, E.T., et al, 1991). This is necessary to anticipate and minimize potential environmental detriment and to satisfy water resources requirements.

Hydrological modeling is a powerful technique of hydrologic system investigation for both the research hydrologists and the practicing water resources engineers involved in the planning and development of integrated approach for management of water resources (Schultz, G.A., 1993). Hydrologic models are symbolic or mathematical representation of known or assumed functions expressing the various components of a hydrologic cycle.(Beven, K.J.et al.,1979). Singh et al. (2007) presented a development of accurate surface runoff estimation techniques from ungauged watershed is relevant in Indian condition due to the non-availability of hydrologic gauging stations are another limited factors in India which leads to the use of surface runoff estimation techniques for ungauged watersheds. Das et al. (2004) was used Soil and Water Assessment Tool (SWAT) distributed parameter model for the simulation of runoff and was tested on daily and monthly basis for estimating surface runoff and sediment yield from a small watershed. Aggarwal (2001) discussed Infiltration losses, Unit hydrograph and river routing using Muskingum method.

2. Objectives of the Present Study

The aim of the present study is to develop a event based rainfall-runoff model using GIS and remote sensing techniques for a watershed. The objectives of the study are as follows:

- To develop a hydrological model to simulate runoff from subwatersheds using SCS curve number and unit hydrograph methods.

- To develop a hydrological model to route the runoff from subwatersheds to outlet of watersheds by Muskingum-Cunge method.
- To apply the developed model on a selected watershed

3. Methodology

The methodology to achieve the goals and objectives of the present study is discussed in this Figure 1.0 which shows the flow chart for the model development. The various steps involved in the model development are as follows:

- Data processing for the selected watershed.
- Preparation of the thematic maps of the watershed from the remotely sensed data.
- Formulation of model using C++ code.
- Testing and evaluation of the model for event based rainfall.

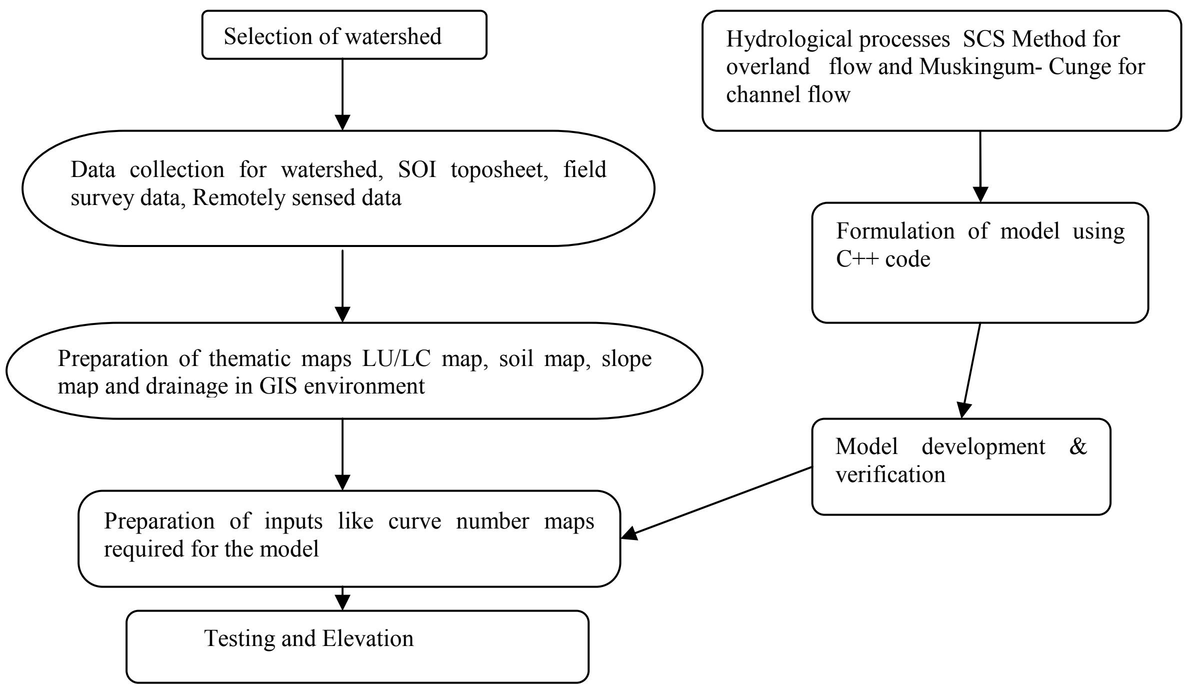

Figure 1.0 Flowchart for the Model Development

4. Governing Equations for Overland Flow

The Soil Conservation Service (SCS) (Chow, 1976) developed a method for computing effective precipitation from storm rainfall. For the storm as a whole, the depth of excess precipitation or direct runoff P_e is always less than equal to the depth of precipitation P; likewise, after runoff begins, the additional depth of water retained in the watershed, F_a, is less than or equal to some potential maximum retention S for which no runoff will occur, so the potential runoff is $P-I_a$.

The expression to estimate the effective rainfall is given as follows (Chow, 1976). Where P_e is effective rainfall from the continuity principle, I_a= initial abstraction, F_a=continuing abstraction.

$$P_e = \frac{(P-I_a)^2}{P-I_a+S} \quad (1)$$

This is the basic equation for computing the depth of excess rainfall or direct runoff from a storm by the SCS method. By the study of results from many small experimental watersheds, an empirical relation for initial abstraction is I_a =0.2S.The curve number (CN) and S are related by (Chow, 1976).

$$S = \frac{25400}{CN} - 254 \quad (2)$$

4.1.0 Time Distribution Of Scs Abstraction

By extension of the previous method, the time distribution of abstractions F_a within a storm can be found.

$$F_a = \frac{S(P-I_a)}{P-I_a+S} \quad (3)$$

4.1.2 Unit Hydrograph Method

Unit hydrographs were synthesized for the outlet of the watershed using SCS dimensionless unit hydrograph method. The parameters used in this method are Time of concentration -T_c, Lag time-T_{lag}, Duration of the excess Rainfall-D, Time to peak flow-T_p, Peak flow-Q_p. where, t_p, Q_p and T can be expressed as follows

$$t_p = C_t(L \times L_c)^{0.3} \quad (4)$$

$$Q_p = \frac{(2.78 \times C_p \times A)}{t_p} \quad (5)$$

$$T = 5\left(\frac{t_R}{2} + t_{pR}\right) \quad (6)$$

Where L is the length of the mainstream in km, L_c is the distance along the mainstream from basin outlet to a point on the stream which is nearest to the centroid of the basin in Km,C_t is a coefficient ranging from 1.36 to 1.66, t_p is the basin lag in hours, Q_p is the peak discharge in m^3/s, A is catchment area in km^2, C_p is a coefficient ranging from 0.56 to 0.69, T is the base width of unit hydrograph Standard duration D = $t_p/5.5$, D' is required duration, $t_{pR} = t_p + (D' - D)/4$. SCS Dimensionless Hydrograph has been used to generate unit hydrograph for event based rainfall. Where values of coefficients C_p and C_t have been taken as 0.625 and 1.51.

4.1.3 Dimensionless-Unit Hydrograph

Based on a study of a large number of unit hydrographs, dimensionless unit hydrographs are recommended by various agencies to facilitate construction of synthetic-unit hydrographs. A typical dimensionless unit hydrograph developed by the United States (US) SCS is shown in Figure 2 (Chow, 1976). In this the ordinate is the discharge expressed as ratio to the peak discharge (Q/Q_p) and the abscissa is the time expressed as a ratio of time to peak (t/t_{pk}).

4.1.4governing Equations For Channel Flow

Cunge, 1969 (Chow, 1976) proposed a method based on the **Muskingum method**, a method traditionally applied to linear hydrologic storage routing. Referring to the time space, the Muskingum routing equation can be written for the discharge at x= (i+1) Δx and t= (j+1) Δt.

$$Q_{i+1}^{j+1} = C_1 Q_i^{j+1} + C_2 Q_i^j + C_3 Q_{i+1}^j \quad (7)$$

Where, Q is flow rate , distance axis is laid out horizontally, i=1,2,3……..; while the time axis runs vertically ,j=1,2,3……..; Δt= time step and is taken as one hour. Where C_1, C_2 and C_3 are as defined in Eq (8) through Eq (10). K is storage constant having dimensions of time, and X is a factor expressing the relative influence of inflow on storage levels. The expressions for K and X are given as follows.

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X) + \Delta t} \quad (8)$$

$$C_2 = \frac{\Delta t + 2KX}{2K(1-X) + \Delta t} \quad (9)$$

$$C_3 = \frac{2K(1-X) - \Delta t}{2K(1-X) + \Delta t} \quad (10)$$

$$K = \frac{\Delta X}{C_k} = \frac{\Delta X}{dQ/dA} \quad (11)$$

$$X = \frac{1}{2}\left(1 - \frac{Q}{B C_k S_O \Delta x}\right) \quad (12)$$

Where C_k is the celerity corresponding to Q and B, and B is the width of the water surface. The right-hand side of Eq (11) represents the time propagation of a given discharge along a reach of length Δx. Cunge, 1969 (Chow, 1976) showed that for numerical stability it is required that $0 \le X \le 1/2$. Muskingum-Cunge routing is carried out by solving the algebraic Eq (7). The coefficients in Eq (7) are computed by using the Eq (11) and Eq (12) along with Eq (8) through Eq (10) for each time and space point of computation, since K and X both change with respect to time and space.

$$C_k = \left(\left(\frac{S_O^{\frac{1}{2}}}{n}\right)\left(\frac{5}{3}\right) y^{\frac{2}{3}}\right) \quad (13)$$

The expression for Y is given as follows:

$$y = \left(\frac{n * Q}{S_o^{1/2} * B}\right)^{3/5} \quad (14)$$

Where, n is the Manning's roughness coefficient is taken as 0.040 and S_o is the slope of the channel.

5. Model Development

Based on the above equations, Outflow of the subwatershed has been simulated using SCS dimensionless unit hydrograph method. The outflow of subwatersheds will be routed to watershed outlet by Muskingum-Cunge method. Code for the SCS dimensionless unit hydrograph and Muskingum Cunge model has been developed in C++ language.

5.1.0 Study Area and Database Preparation

a). Study Area

In the present work, Madikonda watershed, Warangal district, Andhra Pradesh is the study area. The geographical location of this watershed is in between North latitudes 17° 45′- 18° 00′ and East longitude 79° 15′- 79° 30′. The watershed has an area of 35.9 Sq.Km

b). Materials And Methods

The first part of the present work is to create the digital database using remote sensing and GIS techniques. Second part of work is to analyze digital database to calculate hydrological model parameters. ArcGIS and ERDAS Imagine software's have been used to prepare the database. Hourly rainfall data of NIT Warangal campus has been taken as the rainfall of the watershed.

C). Land Use Land Cover Map (Lu/Lc Map)

Supervised classification has been used to prepare the LU/LC map which has been shown in Figure 2.0 The study area has been identified into six major Land Use classes namely vegetation (35.24%), settlement (26.5%), Open scrub (26.9%), Agricultural land (9.23%), water body (1.05%), shallow water body (0.88%).

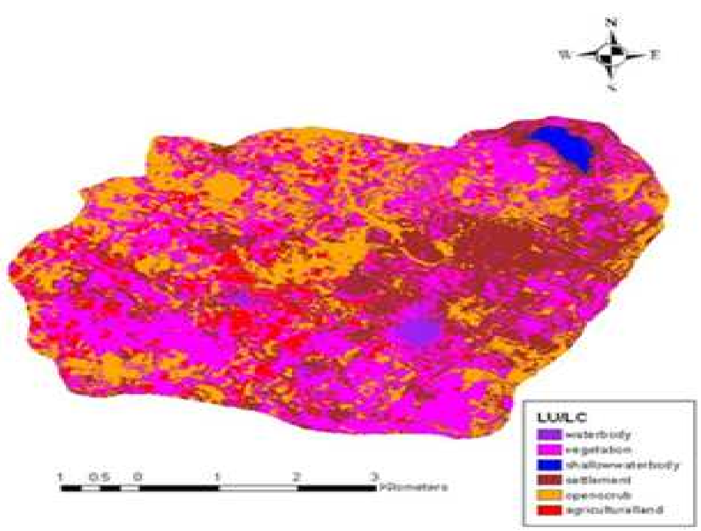

Figure . 2 Land use land cover map of watershed

d). Drainage Map

Watershed boundary and the drainage maps are digitized in ArcMap. Drainage pattern in the study area is dendritic. The watershed has been divided into six subwatersheds based on drainage and contours. Subwatershed map of watershed is shown in Figure 3.0

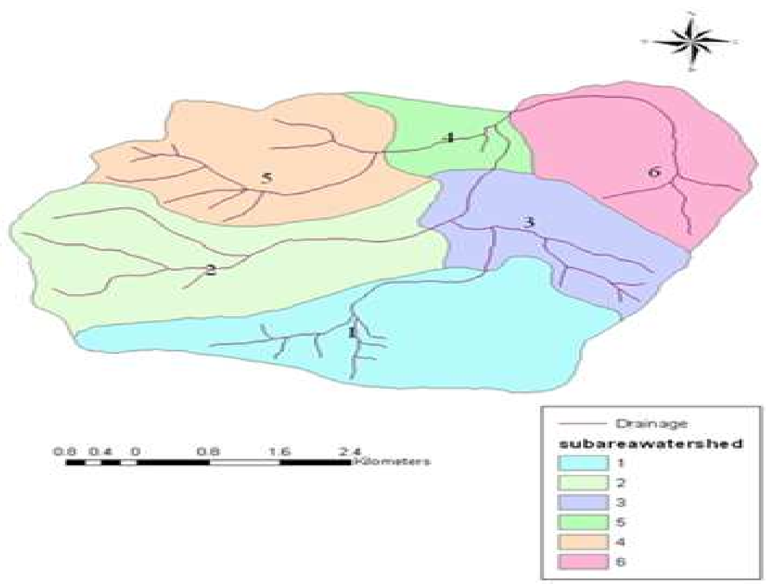

Figure . 3.0 sub watershed map of watershed

e). Soil Map

To prepare the soil map of the watershed, soil samples has been collected from the study area at six points. Sieve analysis test and hydrometer test have been conducted for the soil samples. With the help these values, the Textural Classification System (Triangular Classification System), the watershed is divided into two classes that are medium soil and fine soil. The soil present in watershed is sandy clay. Boundaries of different soil textures have been digitized in ArcGIS and the polygons representing various soils classes have been assigned and different for recognition in Figure 4.0

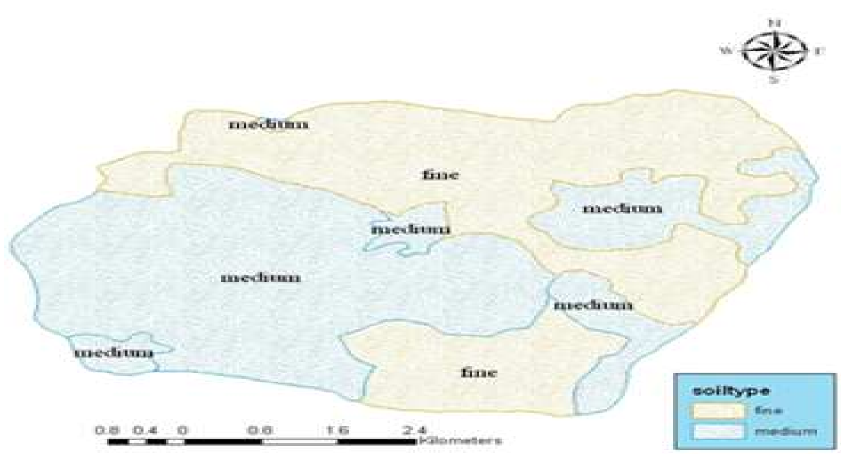

Figure . 4.0 Soil map of watershed

5.2.0 SCS Curve Number Maps of Watershed

Based on the hydrological soil group, the maximum area of study area has been observed to be under hydrological soil group A and C. Similarly, the study area was identified into six major land use classes. The curve number method assumes that

$$CN = \sum (CN_i * A_i)/A \tag{14}$$

There, CN_i = curve number from 1 to 100, A_i = area with curve number CN_i, A = the total area of the watershed. Based on the standard tables of curve number, curve numbers has been assigned to different LU/LC and soil classes of watershed. LU/LC classes, soil group and corresponding curve number of watershed are shown in table 1.0. By comparing the LU/LC map and soil map the curve number has been assigned to the each combination of land use and soil type. Weighted values of CN for each sub watershed have been found to be 62.70, 62.83, 60, 62.70, 61.03, and 61.58 respectively for AMC II condition

6. Results and Discussion

The developed model has been applied to three rainfall events of madikonda watershed. Initially the overland flow at outlet of subwatersheds has been estimated using SCS-based unit hydrograph method. The outflow of subwatersheds is routed to outlet of watershed by Muskingum-Cunge method.

6.1.0 Simulation of Runoff at Sub-Watershed Outlet

The procedure explained above has been used to simulate the flow at outlet of the watershed. The rainfall on August 29, 2008 occurred for 9 hrs has been simulated. With the help of this rainfall data cumulative rainfall (P), cumulative abstractions (I_a and F_a) and effective rainfall (P_e) have been estimated. Excess rainfall hyetograph values have been calculated by taking the difference of effective rainfall.

The dimensionless unit hydrograph discussed, has been used to interpolate with the calculated Q/Q_p and t/t_{pk} values to get discharge (Q) values. The Q values obtained have been multiplied with excess rainfall hyetograph to get discharge at outlet for sub watersheds. Hydrograph for sub watershed 1 is shown in Figure 5.0. Same procedure is applied to get the outlet hydrographs for other five sub-watersheds. The peak discharges, time to peak, base period of the outlet hydrograph of the rainfall events are shown in table 2.0.

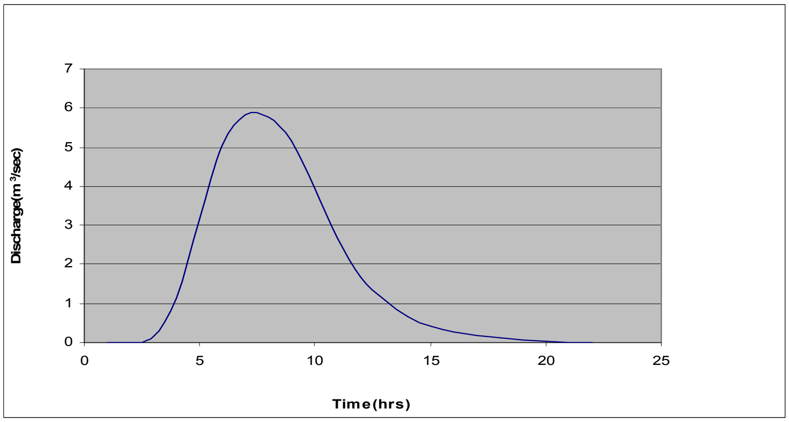

Figure 5.0 Hydrograph at Outlet of Subwatershed 1 for Rainfall Event of August 29, 2008

Table 2.0 Comparison of Time to Peak, Time Base and Peak Discharge of the Outlet

Subwatershed	Time to peak(Hr)	Peak Discharge (m^3/sec)	Time Base(Hr)	Curve Number (AMC-II)	Area (Sq Km)
1	7	5.836	15	61.70	8.40
2	8	6.651	18	62.83	8.80
3	8	2.382	15	60.00	4.70
4	7	5.274	15	62.70	6.42
5	6	1.425	11	61.03	1.96
6	8	3.602	16	61.58	5.54

6.1.1 Routing Of Runoff To Watershed Outlet

In the watershed six routing stations have been selected along channel network as shown in Figure 6. Initially flow at first sub watershed is routed to third routing point which is shown in Figure 7. The flow from second sub watershed is routed to the third routing point. Where the runoff from first and second sub watershed has been added and routed to the fourth routing point. The flow from fourth routing point is routed to sixth routing point and the flow from the sub-watershed fifth is routed to the sixth routing point. The flow from sixth routing point has been routed to the outlet of the watershed. The discharge from the fourth and sixth sub-watersheds has been added to the outlet discharge as shown in Figure 5.0. The results are shown in Table 3.0.

Table 3.0 Comparison of Time to Peak, Time Base and Peak Discharge of the Outlet for Different Rainfall Events

Rainfall event	Time to peak(Hr)	Peak Discharge (m^3/sec)	Time Base(Hr)	Volume of Runoff(m^3)
August 29, 2008	9	24.024	25	593513.95
September 17, 2007	7	92.518	29	2068342
July 28. 2007	11	108.68	29	2063449

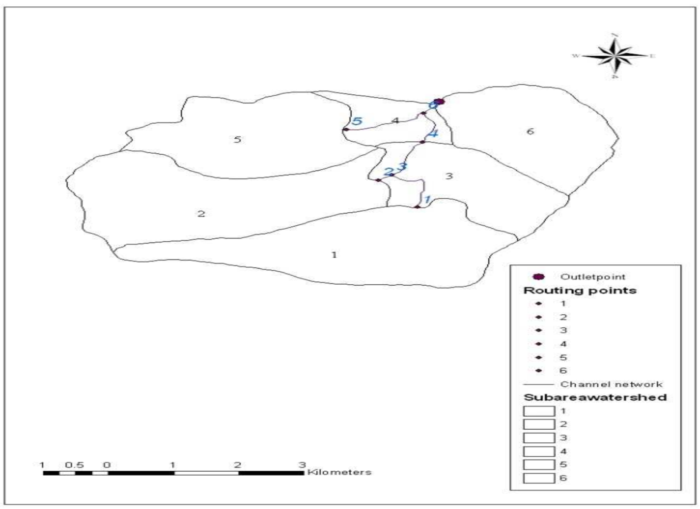

Figure 6.0 Routing Stations along the Channel Network Of Watershed

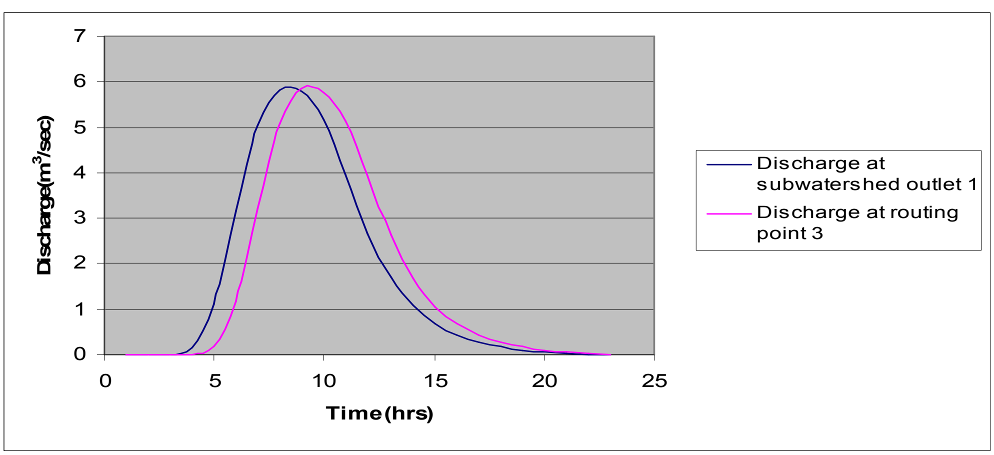

Figure 7.0 Hydrograph At Routing Point 1

7. Conclusions

In the present study, the objective is to develop a hydrological model for the simulation of runoff for the event based rainfall of a watershed. Infiltration losses, unit hydrograph and routing are the main model components. Remote sensing and GIS techniques have been used to estimate the spatial variation of the hydrological parameters, which are used as input to the model. SCS curve number and unit hydrograph methods have been used for the estimation of infiltration losses and to synthesis hydrograph respectively. The model has been applied for Madikonda watershed Warangal, Andhra Pradesh. The complete watershed was divided into six sub watersheds, where hydrographs are synthesized by routing the hydrographs along the channel. Muskingum-Cunge hydrological routing method has been used for channel routing. The model has been applied to three rainfall events of watershed. The developed model has reasonably simulated the hydrographs of runoff at the outlet of watershed. The developed model is useful in the simulation of hydrographs for small to medium type of watersheds. This approach could be applied in other Indian watersheds for planning of various conservation measures.

- The developed model has reasonably simulated the hydrographs of runoff at the outlet of watershed.
- Weighted values of CN for each sub watershed have been found to be 62.70, 62.83, 60, 62.70, 61.03, and 61.58 for AMC II conditions respectively.
- From the graphs, it is observed that the peak runoff has been found to be 20.88 m^3/sec, 92.51 m^3/sec and 108.68 m^3/sec and time at which peak runoff occurred at 9^{th} hr, 7^{th} hr and 11^{th} hr.
- From the graphs it is observed that for both hydrographs the peak runoff is same but the discharge for routing point is lagging by 1 hour to the discharge for the subwatershed.
- It is also observed that the peak runoff is same for both the cases but the discharge for routing point and subwatershed are flowing at the same time because the distance between subwatershed and routing point is less

In this paper, Hydrological model for the simulation of runoff for the event based rainfall of a watershed. The model has been applied to three rainfall events of watershed. The developed model is useful in the simulation of hydrographs for small to medium type of watersheds. This approach could be applied in other Indian watersheds for planning of various conservation measures. If the observed hydrographs of the watersheds are available, calibration and validation of developed model can be carried out.

References

[1] Aggarwal, S.P. (2001): Hydrological Modeling using Remote Sensing and GIS, Paper presented at the 22nd Asian Conference on Remote sensing, 5-9 November,

[2] C Chatterjee, R Jha, A K Lohani and R K Jaiswal. .Determination of SCS Curve Number and Landuse Changes for Hamidnagar Sub-basin of Punpun Basin, CS(AR) 14/96-97.. National Institute of Hydrology, Roorkee, 1997

[3] Choi, J., Engel, B. A., and Chung, H. W.: Daily stream flow modeling and assessment based on the curve-number technique, Hydrol. Process. 16(16), 3131–3150, 2002

[4] Dabral, P.P. and Pandey, A. (2004): Estimation of Runoff for Hilly Catchment Using Satellite Data, Journal of the Indian Society of Remote Sensing, Vol. 32, No.2, pp.35-240.

[5] Das, S.N. Tripathi, M.P. Shrivastava, P.K. (2004): Hydrological Modeling of a Small Watershed Using Satellite Data and GIS Technique, Journal of the Indian Society of Remote Sensing, Vol. 32, No.2, pp.145-157.

[6] Dingman, S. L.: Physical Hydrology Second Edition, Prentice-Hall, Inc., p. 409, 2002.

[7] European Soil Bureau: Soil geographical database of Eurasia at scale 1:1000000 version beta 5 25/09/2001 and Pedotransfer Rules 2.0, Dominant surface textural class (infered), JRC,online: http://eusoils.jrc.ec.europa.eu/ESDB Archive/ESDBv2/fr thema.htm, 2004.

[8] Geetha, K., Mishra, S. K., Eldho, T. I., Rastogi, A. K., and Pandey, R. P.: SCS-CN-based continuous simulation model for hydrologic forecasting, Water Resource. Manag., 22(2), 165–190, 2008.

[9] Hawkins, R. H.: Improved Prediction of Storm Runoff in Mountain Watersheds, J. Irrig. Drain.Div.-ASCE, 99, No. IR4, Proc. Paper, 10188, 519–523, 1973.