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Research Article

A GIS Based Variable Source Area Model for Large-scale Basin Hydrology

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Abstract: A geographic information system-based rainfall runoff model that simulate variable source area runoff using topographic features of the basin is presented. The model simulate the flow processes on daily time step basis and has four non linear stores viz. Interception store, soil moisture store, channel store and ground water store. Source area fraction is modelled as a function of antecedent soil moisture, net rainfall and pore capacity raised to the power of areal average topographic index (Λ). Source area fraction is used in conjuction with topographic index to develop linear relations for runoff, Infiltration and interflow. An exponential relation is developed for lower zone evapotranspiration and non-linear exponential relations to model macropore flow and base flow are proposed.

Keywords: DEM, GIS, runoff, topographic index, variable source area, wardha river basin

INTRODUCTION

Hewlett (1961a, b) put forward the variable source area concept of stream flow and storm flow mechanism. He concluded that the basin area contributing to stream flow changes with time and that the subsurface flow is the main source of base flow in vegetated basins. It has been observed that return flow (Hewlett and Hibbert, 1967) and Saturation excess overland flow (Dunne and Black, 1970) are the two important storm flow mechanisms in hill slope areas. Accumulation of interflow during rainy season at the bootom of hill slope is reported by scientiests (Frankenberger *et al*., 1999; Mehta *et al*., 2004). Spatial and temporal distribution of runoff producing source area's will be key to the future rainfall-runoff modelling (Maidment, 1993). Beven and Kirkby (1979) presented the most popular model amoung the hydrologist (TOPMODEL) with capablity to identify saturated source area's and simulate the basin discharge. Topography plays an important role in runoff genration and is central to TOPMODEL. Topogrphic index predicts sarface saturated source area's and help simulate the runoff during wet period when moisture distribution is predominantly driven by topography (Andrew and Günter, 1999). Use of DEMs and GIS for hydrological analysis and topograpic index based distributed rainfall runoff modelling has been investigated in recent studies.

MODEL DESCRIPTION

Interception model: In proposed VSA model we assumed the maximum interception storage (CEPMAX) as one of the model parameters. The daily interception (if any) is assumed to be based on current day rainfall, current day evaporation and previous day interception storage state:

Part (1)

$$\left.\begin{array}{c} PET_n > CEPMAX; EVP_{max} = CEPMAX \\ PET_n < CEPMAX; EVP_{max} = PET_n \end{array}\right\} \quad (1)$$

Part (1) determines the possible evaporation from interception store if the store is full and used in Part (2) of the interception model:

Part (2)

$$\left.\begin{array}{c} If,\ 0 \le intstore_{n-1} \le CEPMAX\ and \\ Case(1)\ If,\ rainfall_n \le \\ (CEPMAX - intstore_{n-1}) \\ intcep_n = rainfall_n \\ evp_n = \min\{(intstore_{n-1} + rainfall_n), \\ EVP_{max}\} \\ Case\ (2)\ If, rainfall_n \ge \\ (CEPMAX - intstore_{n-1}) \\ intcep_n = (CEPMAX - interstore_{n-1}) \\ evp_n = EVP_{max} \end{array}\right\} \quad (2)$$

Part (2) determines value of actual evaporation from interception store based on rainfall, maximum capacity of interception store and the status of previous day interception store:

Part (3)

$$intstore_n = intstore_{n-1} + intcept_n - evp_n \quad (3)$$

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Part (3) of interception model updates interception store based on values of daily interception and evaporation from interception store.

where,

- evp_n = The evaporation depth from interception store (mm)
- $intcep_n$ = The interception depth on n^{th} day (mm)
- $rainfall_n$ = The rainfall depth on n^{th} day (mm)
- $intstore_n$ = The interception store depth on n^{th} day (mm)
- CEPMAX = The maximum interception capacity (mm)
- EVP_{max} = Maximum value of evaporation from interception store (mm)
- PET_n = Potential evapotranspiration on n^{th} day (mm)

Net rainfall: The net rainfall is assumed to be the portion of rainfall that reaches soil matrix after subtracting losses due to interception. The Net rainfall is thus distributed as source area runoff and infiltration. It is known that if the rainfall intensity is lower than infiltration rate, the entire amount of net rainfall gets infiltrated. The net rainfall is thus calculated as follows:

$$rainnet_n = (rainfall_n - intcep_n) * canopy + rainfall_n * (1 - canopy) \tag{4}$$

where,

- $rainnet_n$ = The net rainfall (mm), on n^{th} day
- canopy = Fraction of catchment area covered with vegetation

Variable source area and source area runoff: Source area is formed due to saturation of soil and its variation depends upon antecedent moisture conditions, rainfall and duration of input. Volume of moisture that occupies pore spaces and saturate the soil matrix can be a part of antecedent soil moisture and rainfall.

Variable source area fraction is thus modelled as:

$$\left.\begin{array}{c} SAF_n = \frac{[SZWC1n + rainnet_n]^{\frac{1}{\Lambda}}}{SZPC} \\ chstore_n = chstore_{n-1} + SAF_n * rainet_n - saro_{n-1} \\ saro_n = LAG * chstore_n \\ LAG = (\Lambda - 1) \end{array}\right\} \tag{5}$$

where,

- SAF_n = The fractional source area on nth day, % of the total catchment area
- szwc1n = The soil moisture content on $(n - 1)^{th}$ day after losses (mm)
- SZPC = The soil zone pore capacity (parameter)
- Λ = The mean topographic index (approximated by a weighted average over the areas with the same hydrological similarity)
- $chstore_n$ = Runoff storage in channel on n^{th} day (mm)
- $saro_n$ = Source area runoff on n^{th} day (mm)
- LAG = Lag coefficient for source area runoff to occur in stream

Infiltration model: The amount of moisture already available in soil governs the rate of infiltration. An infiltration thus specify infiltration rate and is well linked with soil moisture model. A simple equation denoting the infiltration as rainfall falling on unsaturated area is proposed. This treats the infiltration and soil moisture interactively:

$$infil_n = (1 - SAF_n) * rainet_n \tag{6}$$

where,

$infil_n$ = The infiltration in mm on n^{th} day

Actual evapotranspiration:

Part (1)

EVP from interception model given by Eq. (2) (7)

Part (2)

Case (1) if, $SZWP \leq SZWC_n < SZFC$

EVP from Eq. (2):

$$\left.\begin{array}{c} uzet_n = (pet_n - evp_n) * \\ \left[\frac{(SZWC_n - SZWP)}{SZFC}\right]^{\left(1 - \frac{(SZWC_n - SZWP)}{SZFC}\right)} \\ lzet_n = (pet_n - evp_n - uzet_n) * e^{-LZC} \\ \mathrm{LZC} = (\Lambda + 1) \end{array}\right\} \tag{8}$$

Case (2) if, $SZFC \leq SZWC_n$

EVP from Eq. (2):

$$\left.\begin{array}{c} uzet_n = (pet_n - evp_n) \\ lzet_n = (pet_n - evp_n - uzet_n) * e^{-LZC} \end{array}\right\} \tag{9}$$

Part (3):

$$aet_n = evp_n + uzet_n + lzet_n \tag{10}$$

where,

- $uzet_n$ = The evapotranspiration (mm), from upper soil zone
- $lzet_n$ = The evapotranspiration (mm) from ground water store
- LZC = The constant governing evapotranspiration from lower zone (parameter)
- aet_n = Actual evapotranspiration on n^{th} day (mm)

Soil moisture storage: The proposed VSA model applies mass balance equation at each time step (i.e., daily) Soil moisture content is updated by following equation:

$$SZWC_n = SZWC_{n-1} + rainet_n(1 - SAF_n) - uzet_{n-1} - pflow_{n-1} - drain_{n-1} - saro_{n-1} \tag{11}$$

$$SZWC1_n = SZWC_{n-1} - uzet_{n-1} - pflow_{n-1} - drain_{n-1} - saro_{n-1} \tag{12}$$

where,

$SZWC_n$ = Soil zone water content (mm)
$SZWC_{n-1}$ = The previous day soil zone water content (mm)
$uzet_{n-1}$ = The previous day evapotranspiration from upper soil zone in mm
$pflow_{n-1}$ = The macro pore flow in mm
$drain_{n-1}$ = The drainage in mm
$szro_{n-1}$ = The interflow in mm

Interflow: For determination of interflow a linear relationship between the soil moisture properties such as Soil Moisture Content (SZWC), field capacity (SZFC), wilting point (SZWP) is assumed as interflow depends on moisture contents of the soil moisture zones. The interflow eventually merges with runoff. The model allows the interflow to occur till soil moisture content is above field capacity:

$$Interflow = szro_n = (SZWC_n - SZFC) * \left\{\frac{(SZWC_n - SZWP)}{SZWC_n}\right\} \quad (13)$$

Macro-pore flow: The soil forming factors such as non-capillary cracks or channels within soil matrix are responsible for macro-pore flow to occur. It depends upon various factors like rainfall intensity, pipe network, soil moisture condition, macro-pore size, catchment profile etc. The data regarding the pipe network, density of pipes, surface crack etc., is generally not available. In absence of such data a simple non-linear macro-pore flow model is assumed as follows:

$$Macropore\ flow = pflow_n = (SZWC_n - SZFC* \quad SZWCn-SZWPSZWCn*e- \quad \lambda \quad (14)$$

where,
$pflow_n$ = The macro pore runoff in mm
$szwc_n$ = The soil moisture in mm
SZFC = The field capacity in mm
$\bar{\lambda}$ = The average value of Ln (a/tanβ) distribution

Base flow: The ground water store is recharged by a part of water in excess of field capacity. The base flow is derived from ground water storage and sustains stream flow during dry period. The model assumes some initial Ground Water storage ($GZWC_n$) which serves as initial value for warm up period. A linear function of Ground Water Content ($GZWC_n$) and parameter GZK is assumed for base flow determination:

$$Base\ Flow = gwro_n = e^{-\Lambda} * e^{\left(\frac{gzwc_n}{GZK}\right)} \quad (15)$$

$$GZK = \frac{1}{0.01(\Lambda-1)}$$

Inflow to ground water store is drainage from upper soil layer. Out flow is mainly base flow and

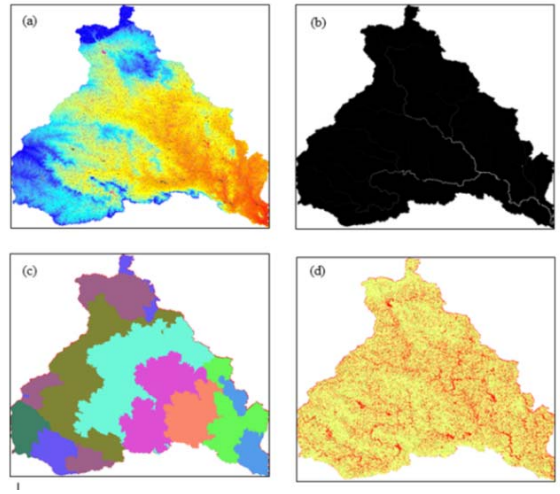

Fig. 1: DEM derivatives, (a) flow direction map, (b) flow accumulation map, (c) flow length map, (d) topographic index map

lower zone evapotranspiration. For daily updating of ground water store following equation is used:

$$gzwc_n = gzwc_{n-1} + drain_n - lzet_{n-1} - gwro_{n-1} \quad (16)$$

where,
$gwro_n$ = The ground water runoff in mm
$gzwc_n$ = The ground water store in mm
GZK = The ground water coefficient

APPLICATION TO WARDHA WATERSHED

Wardha is one of the right bank tributary of Pranhita river, which flows through Maharashtra and Andhra Pradesh states of India. The Wardha sub basin lies between latitude 19°18'N and 21°58'N and longitudes 77°20'E and 79°45'E. The major left bank tributaries of the Wardha are the Kar, the Wena, the Jam and the Erai and the right bank tributaries are the Madu, the Bembla and the Penganga. The drainage area of the Wardha River is 47985 km^2 upstream of gauge discharge station 'Dhaba' and throughout its course, the river flows through dense forests. The average annual rainfall for the entire sub-basin is 1,000 mm approximately.

Input data collection:

Topographic data: A high definition (30 m) digital elevation model is obtained via ASTER GDEM. Every pixel of DEM represents the average elevation of 30×30 m area. A GIS software was then used to interpret these elevations for producing various derivatives, one of which is to delineate watersheds. Figure 1 shows various DEM derivatives used for GIS based rainfall runoff modelling and calculation of topographic indices and Fig. 2 Shows delineated wardha watershed.

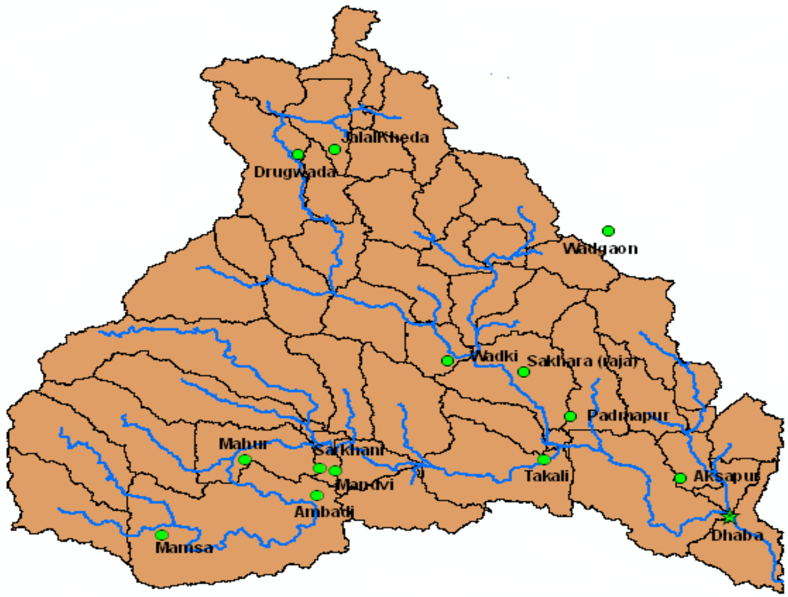

Fig. 2: Delineated wardha watershed

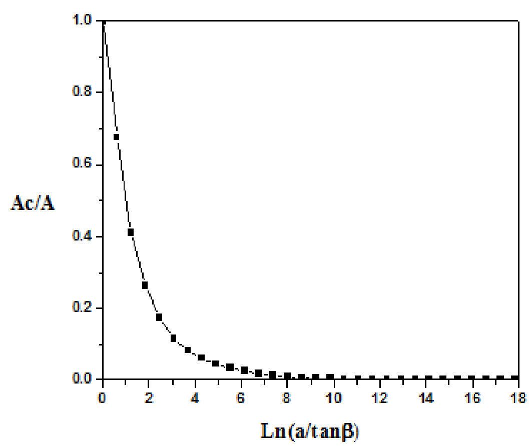

Fig. 3: Fractional contributing area A_C/A v/s Ln (a/tan/β) distribution

Mean area rainfall: The precipitation and evaporation data (2002 to 2010) collected for the fifteen weather stations of Wardha stream were obtained from Hydrological Data User Group (HDUG) Nashik, Maharashtra, India.

Observed stream flow: The stream flow data (from 2002 to 2008) for the basin outlet (Dhaba) was obtained from the HDUG. The observed stream flow is converted to units of depth, i.e., mm.

Potential Evapotranspiration (PET): In the present study air temperature based Hargreaves equation is used to calculate the potential evapotranspiration:

$$\mathrm{PET} = 0.0023 * \mathrm{R_{ext}} * \left(\mathrm{T_{avg}} + 17.8\right) * \left(\mathrm{T_{max}} - \mathrm{T_{min}}\right)^{0.5} \tag{17}$$

where,
PET = The potential evapotranspiration (mm/day)
R_{ext} = The daily extra-terrestrial radiation (MJ/m^2/day)
T_{max} = The daily maximum temperature (°C)
T_{min} = The daily minimum temperature (°C)
T_{avg} = The daily average temperature (°C)

Note: Radiation 1 MJ/m^2/day = 0.408 mm/day.

Model calibration: Topographic indices: Digital Elevation Model (DEM) of the study area was processed to obtain the various derivatives required for computing λ and distribution of ln (a/tanβ), with area, for each sub basin. The sinks in the DEM were filled and the filled DEM was then used to obtain flow direction map which is in turn used to obtain flow accumulation map. The spatial distribution of slope values and flow length map were then derived. Raster based calculations were performed to calculate tangent of slope radians and the distribution of ln (a/tanβ) with area. The data thus obtained was reclassified and processed for calculation of fractional area and thus areal mean topographic index (Λ). Figure 3 Shows variation of contributing area with topographic index.

Soil hydraulic parameters: Soil Hydraulic parameters are in principle, physically based and can be determined from knowledge of the catchment characteristics. For estimation of the soil hydraulic parameters (SZFC, SZPC and SZWP) onsite measurement of soil depth and saturated hydraulic conductivity can be preferred. Soil-survey data can also be used for estimation of these parameters.

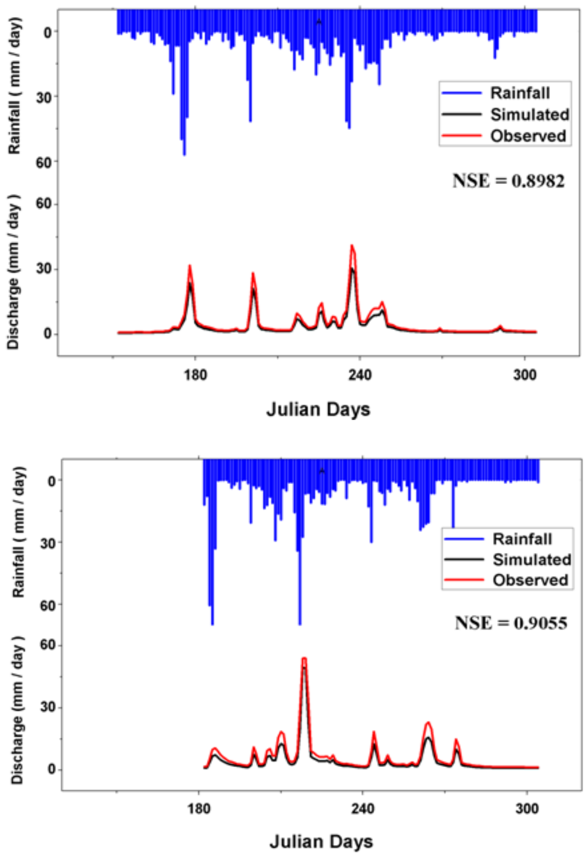

Fig. 4: Observed and simulated hydrographs of wardha watershed during calibration and validation period

HYDROGRAPH SIMULATION

The period from 2002 to 2004 was used for calibrating model parameters and the period from 2005 to 2008 was used for validation of daily stream flow simulation. For simulation of stream flow only the precipitation, evaporation and discharge data observed from June to October every year is used in the study, since other months are mostly dry. Nash-Sutcliffe efficiency is calculated to evaluate the performance of the proposed model, which express as:

$$NSE = 1 - \sum_i (Q_i - q_i)^2 / \sum_i (Q_i - Q)^2 \qquad (18)$$

where,
Q_i = The measured stream flow
q_i = The simulated stream flow
Q = The average measured stream flow

For calibration the model parameter 'SZWC' was varied keeping the value of parameter GZWC at initial value. The value of parameter 'SZWC' is set at one which yields the highest efficiency. Next the value of SZWC was varied to further enhance the efficiency. For best fit the other three criterions should move close to zero. These criterions are:

Sum of squared errors, $SSE = \sum_{i=1}^{n} (Q_i - q_i)^2$

Sum of squared log error, $SLE = \sum_{i=1}^{n} \{\log(Q_i) - \log\ (qi)2$

Sum of absolute error, $SAE = \sum_{i=1}^{n} |(Q_i - q_i)|$

The hydrographs thus obtained for the basin are shown in Fig. 4.

CONCLUSION

An alternative to curve number method for continuous simulation of variable source area based on concept of topographic index is proposed. The silent points about the efficacy of the model are:

- The model requires very few (6) parameters to be determined. The soil hydraulic parameters can be easily determined from catchment characteristics and topographic parameters can be calculated from the DEM analysis.
- The time marching model structure updates the source area fraction on daily basis.
- The model accounts for convective delay associated with source area runoff in flow routing algorithm.
- The model requires minimum data and can be used for ungagged catchments.

It is clear from Fig. 4 that, in terms of model efficiency (Nash-Sutcliffe) the model performs reasonably well as a continuous hydrograph simulator.

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