GRID-Based Storm Runoff Model (GRISTORM)

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1. Introduction

Understanding of nonpoint source pollutants is becoming increasingly important in establishing environmental protection plans for watersheds. It is necessary to find a way to predict temporal/spatial distribution and transport patterns of pollutants. During a hydrologic year, storm events are an important factor in pollutant transport. A hydrologic model which predicts surface and subsurface flows and their flowpaths to the stream is required.

Recently, several researchers have attempted to model the rainfall-runoff process with Geographic Information System. GIS has proven to be an efficient tool for spatial analyses and visualizing the results of hydrologic and water quality modeling.

In this paper, a grid-based subsurface and saturated overland/stream flow generation procedure is described. This approach predicts the temporal variation and spatial distribution of overland flow depth, discharge and soil moisture during a storm event. The procedure's applicability and its modification of the surface and subsurface kinematic modeling approach (Takasao and Shiiba, 1988) are described. The model runs on the GRASS and uses regular gridded data such as elevation, stream, land use and soil information. The data were previously developed and described in Frankenberger's Ph.D. thesis (1996). A storm runoff model coded in UNIX-C uses this information and displays the results on GRASS.

2. Model Description

Saturated overland/stream flow and subsurface flow model : In order to model the formation of variable source areas, we adopted the combined surface-subsurface kinematic modeling approach (Takasao and Shiiba, 1988). The continuity equation applied to each grid element can be written as in Equation 1.

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial \lambda}=\frac{rA_c}{L_c}+\frac{Q_\lambda}{L_\lambda} \quad \cdots\cdots (1)$$

where A = flow area (m^2), Q = discharge (m^3/sec), r = rainfall intensity (m/sec), A_c = grid element area (m^2), L_c = flow distance through the grid element (m), Q_λ = lateral discharge (m^3/sec), L_λ = lateral flow length (m), t = time (sec), λ = length (m).

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The finite difference form of Equation 1 is expressed as

$$A_4 + 2Q_4 \frac{\Delta t}{L_c} = A_1 - A_2 + A_3 + 2Q_2 \frac{\Delta t}{L_c} + \text{[illegible]}_c \frac{\Delta t}{L_c} + 2Q_3 \frac{\Delta t}{L_c} \quad \text{.................................(2)}$$

where Δt = time interval, A_1, A_3 = flow area at time t at the inlet and outlet of the grid element respectively, A_2, A_4 = flow area at time $t + \Delta t$ at the inlet and outlet of the grid element respectively.

To solve Equation 2, Brakensiek's four-point implicit scheme (1967) was adopted. The equation was rearranged to solve for flow depth (H), and Newton-Raphson method was used to calculate it at the outlet of the grid element after a given time interval.

Initial and boundary flow depth conditions of various shallow soil depths : The spatial distribution of initial flow depths in a watershed can be obtained from soil information maps describing porosity, field capacity and initial soil moisture conditions. At the watershed boundary, flow depth conditions at the beginning side of the grid element are assumed zero.

Overland flow pattern and its classification : We can choose a 3 by 3 grid to determine flow direction. Firstly, the flow direction from the center grid element is determined by calculating slopes to the neighboring eight grid elements. Secondly, the subsurface/surface flow depth at the outlet of center grid is calculated by Equation 2 for a given time increment. Thirdly, the water of the grid element flows in the steepest direction. This means that a single output flowpath is chosen but the inflow to a grid element can come from multiple sources. If overland flows meet a stream, they are converted to lateral flow in the stream.

Model structure and implementation : A schematic flow diagram of the GRISTORM model is shown in Figure 1.

3. Model Application

Watershed, soils, land use and storm events : The model was tested on the Crowe Road watershed located in the Northern Catskill region of New York State. The watershed area is 170 ha and the elevation ranges from 580 m to 732 m. The watershed soils are classified as inceptisols or entisols. The surface layer of most soils is shallow and permeable with a high percentage of rock fragments. Soil depths ranged from 28 cm to 150 cm and the percentage of rock fragments was between 10 % and 40 %. The impeding layers are composed of bedrock, fragipan and clay. Saturated hydraulic conductivity in the surface layer is about 2 m/day. Average porosity and field capacity values without rocks are 0.6 and 0.37 respectively. Precipitation and stream flow data were measured at 10-minute intervals at the watershed outlet by the New York State Department of Environmental Conservation. Six storm events from July and August, 1994, were chosen for model calibration and verification.

Map data from GRASS : Seven maps containing information on elevation, stream, soil, land-use and soil parameters-porosity, field capacity and initial soil moisture condition-were used for input data. Elevation data were obtained from the USGS quadrangle vector map.

Stream locations were obtained from maps supplied by the New York City Department of Environmental Protection. The soil map was rasterized from the vector DLG file. The land-use map was obtained from the Natural Resources Conservation Service. These base maps were adapted by Frankenberger (1996) to fit grid dimensions of 10 m by 10 m. Soil parameters were obtained from 'A GIS-Based Variable Source Area Model' developed by Frankenberger (1996). Daily soil moisture distribution maps generated by Frankenberger's model were used as the initial soil moisture conditions for the selected storm events. These maps form 151 rows by 174 columns ASCII-formatted map data.

Comparing predicted and observed streamflow at the watershed outlet : Three storm events (July 2, July 22, August 18) were used for model calibration. In the model calibration, the initial soil moisture distribution before the storm event proved to be the most sensitive parameter affecting stream flow at the watershed outlet. The second most sensitive parameter was Manning's roughness coefficients for overland areas and streams which affected the time and magnitude of the peak stream flow. Table 1 shows the calibrated parameters for all three storm events.

The model was verified using the calibrated parameters from Table 1 (except the soil moisture adjustment factors which differ for each storm-event/soil-group combination) to predict stream flows at the watershed outlet for three new storms (August 14, August 17, August 21). A summary of model verification is given in Table 2. The average Nash-Sutcliffe efficiency R^2 (Nash and Sutcliffe, 1970) for the model was 0.72. The total runoff was underestimated for three events. This error may be caused by the simplification of subsurface flow. Preferential flow through macro-pores in the soil can contribute to stream flow as a subsurface lateral flow. Other sources of error may arise from the uncertainty of initial soil moisture condition and lumping parameters within each 10 m by 10 m grid element.

Temporal variation and spatial distribution of saturation overland flow : Knowing only the stream flow at the watershed outlet, we cannot determine where the overland flow originated and how much water each source area contributed. GIS can provide this information which is important for investigating the loss of soil due to erosion and the transport of non-point source pollutants.

Figure 2 shows the predicted temporal and spatial distribution of saturated overland flow depths for the July 2 storm. After the storm started at the time of 23:24 hr, the overland flow areas initially occurred around the areas of the main stream. These areas have mild slopes and higher initial soil moisture content than other areas. The source area for overland flow increased from the start of rainfall to the time of 23:54 hr and decreased gradually after that time. But the peak flow reached at the time of 0:40 hr. This shows that the overland/subsurface flows delayed the transport of water to the watershed outlet causing a lag time.

4. Conclusions

Grid-based storm runoff model was developed. This model generates the flow depth, discharge and soil moisture of subsurface flow and saturated overland flow on a variable source area with shallow soil depths. The model uses regular gridded ASCII-formatted data from GRASS to predict the temporal variation and spatial distribution of saturation overland flow areas.

The model was tested on a small watershed located in the Northern Catskill region of New York State with 10 m by 10 m grid dimensions. For model calibration and verification, the observed stream flows measured at watershed outlet were compared with values predicted by the model. The spatial distributions of saturated overland flow areas for several storm events were successfully modeled and displayed with GRASS. The calculated overland flow areas coincided with the areas which had high initial soil moisture contents. Temporal variation of those areas showed that the overland/subsurface flows attenuate and causes lag in the stream flows. This model can be used on other raster-based GIS if ASCII-formatted grid data are available.

5. References

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Table 1. Summary of model calibration and its parameters.

Storm event	Total rainfall (mm)	Manning's n					Hydraulic conductivity (m/day)		Initial soil moisture adjustment ratio		Total runoff (mm)		Peak discharge (m^3/sec)	
		Stream	Forest	Grass /Alfalfa	Corn	Farm -stead	high SMA	low SMA	stony	silt loam	observed	predicted	observed	predicted
7/02/94	24.02	0.03	0.15	0.14	0.17	0.09	1.20	0.80	1.066	1.072	1.72	1.64	0.234	0.235
7/22/94	24.76	0.02	0.26	0.20	0.23	0.12	2.00	0.80	0.520	0.560	1.17	1.00	0.236	0.230
8/18/94	22.62	0.04	0.20	0.14	0.17	0.09	1.20	0.80	0.610	0.690	5.99	5.54	0.276	0.267
Mean		0.03	0.20	0.16	0.19	0.10	1.47	0.80						

Note) SMA : soil moisture area

Table 2. Summary of model verification.

Storm event	Total rainfall (mm)	Initial soil moisture adjustment ratio		Total runoff (mm)		Peak discharge (m^3/sec)		Nash-Sutcliffe efficiency R^2
		stony	silt loam	observed	predicted	observed	predicted	
8/14/94	25.80	1.180	1.230	2.30	1.94	0.209	0.201	0.754
8/17/94	17.68	1.071	1.076	2.04	1.83	0.172	0.186	0.742
8/21/94	14.64	1.066	1.072	3.18	2.90	0.256	0.242	0.653

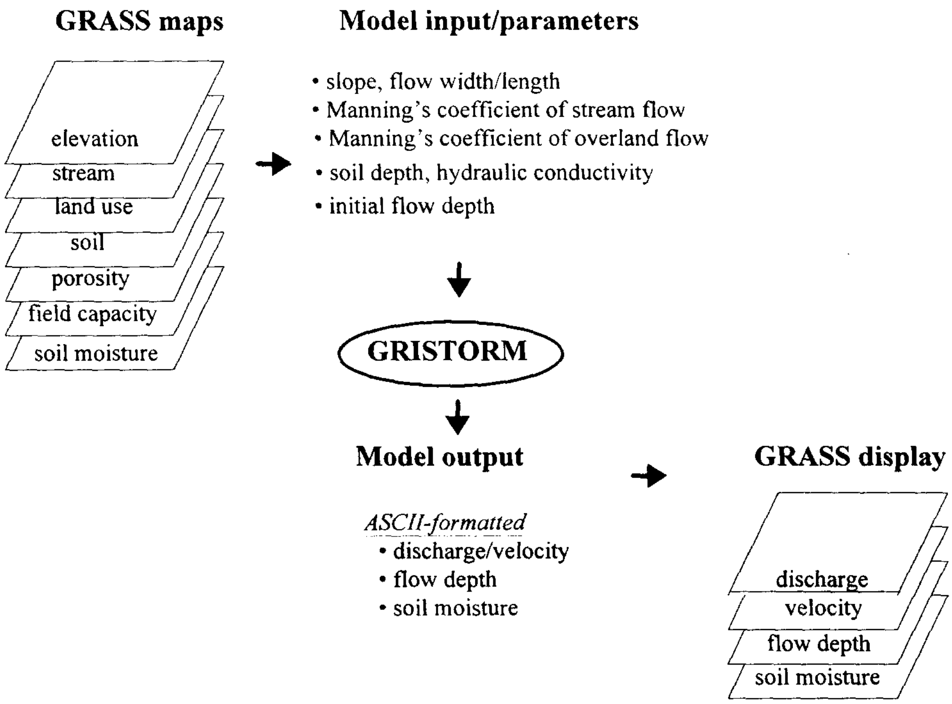

Figure 1. Schematic diagram of GRISTORM.

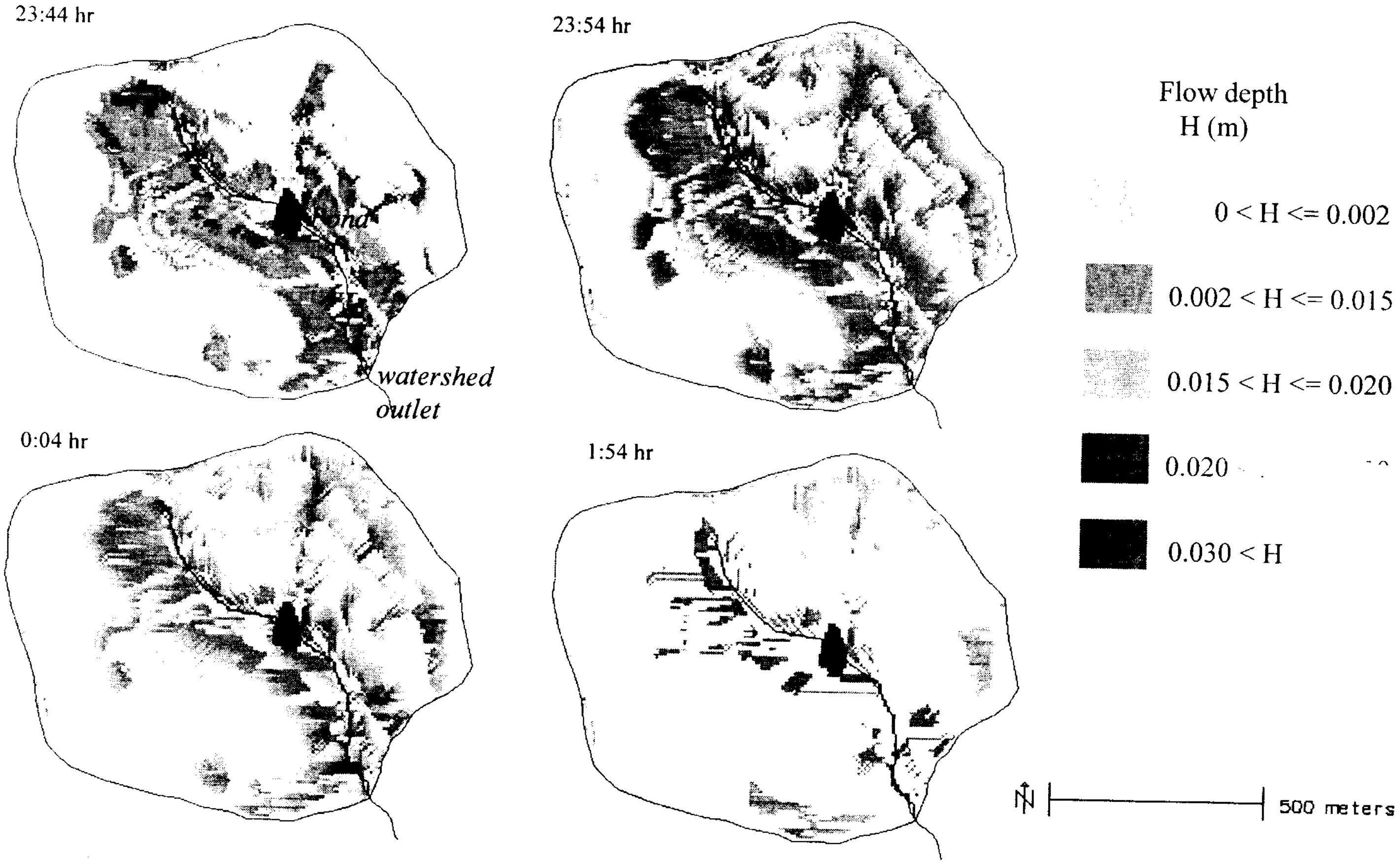

Figure 2. Temporal variation and spatial distribution of overland flow depth (July 2, 1994 at Crowe Road watershed)