GRID-Based Soil-Watei Erosion and Depoistion Model (GRIEROM)

김성준

1. Introduction

Erosion prediction is the most widely used and most effective tool for soil conservation planning and design (Laflen, 1991). Geographic Information System can provide a practical solution for handling the detailed spatial variability within a watershed. GIS also can preserve the spatially oriented data structures and operations to maintain the physical meaning at any point in the modeling process (Zollweg, 1994).

Erosion in a variable source area with shallow soils is a big problem. The loss of soil due to surface runoff as well as the pollution in runoff, seepage or percolation from agricultural management activities is one of the major problems in modern agricultural management.

Almost all erosion models are based on the concept that runoff occurs when the rainfall intensity is larger than the infiltration rate of the soil. Runoff in a variable source area does not occur in areas where the soil has high infiltration rate which are in excess of rainfall intensity. Runoff only occurs under the circumstance where the soil profile is filled with water and there is place for the water to infiltrate. The soil loss equation such as developed by Rose et al. (1983) should equally apply independent of the mechanism that determines the runoff as long as the quantity and velocity of the water flow is predicted correctly. A factor-based soil erosion model is not suitable for extrapolation beyond the limits of the data set. A physically-based model of soil erosion processes has the capacity to extrapolate and generalize beyond the database used to check its utility (Rose, 1993). It also can simulate sediment movement accurately with little or no calibration of parameters (Bingner, 1990).

A mathematical model of soil-water erosion and deposition developed by Rose et al. (1983) was adopted in this study. It represents mathematically the rates of rainfall detachment, sediment deposition and soil entrainment by overland flow. It uses the concept of stream power in representing the entrainment processes. It expresses the conservation of mass of sediment to an ordinary differential equation which can be solved analytically. The solution gives sediment concentration at any time as a function of distance down the plane.

한국수자원공사 수자원연구소 선임연구원

The objective is to develop an event-based soil erosion model in areas where the saturation excess overland flow is the mechanism that generate runoff. A grid-based soil-water erosion and deposition procedure is described. This approach predicts the temporal variation and spatial distribution of sediment transport areas and their concentrations during a storm event. The applicability and its modification of physically-based soil erosion model (GUEST) by Rose and Hairsine (1988) are described. The model runs on GRASS with a regular gridded data such as elevation, stream, land use and soil informations. The data were previously developed and described in Frankenberger's Ph.D. thesis (1996). A soil-water erosion and deposition model coded by UNIX-C uses these informations and displays the model results on GRASS.

2. Model description

Saturation overland flow and subsurface flow model : The combined surface-subsurface kinematic modeling approach (Takasao and Shiiba, 1988) was adopted for hydrologic process. The continuity equation applied to each grid element can be written as Equation 1.

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

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 = grid element length (m).

Soil-water erosion and deposition model : The source of power available from the flow to either entrain or reentrain sediment is the rate of working of the shear stress called the "stream power" (Ω) by Bagnold (1977). The stream power using the kinematic approximation for the mean shear stress per unit area of wetted surface is given by,

$$\Omega = \rho g S R_h V \quad \text{(2)}$$

where Ω = stream power (W/m^2), ρ = water density (kg/m^3), g = gravitational constant (m/sec^2), S = grid element slope (m/m), R_h = hydraulic radius, V = mean velocity (m/sec).

After calculation of sediment concentration at each outlet of the grid element, the following continuity equation for one-dimensional flow is applied to determine sediment discharge at a given time and space.

$$\frac{\partial c}{\partial t} + V\frac{\partial c}{\partial \lambda} = c_{\lambda} \qquad (3)$$

where c = sediment concentration (kg/m^3), c_{λ} = lateral sediment discharge per unit time ($kg/m^3/sec$).

Model structure & implementation : The schematic flow diagram of the model is shown in Figure 1.

3. Model application

Watershed, soils, land use and storm events : The model was applied to 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 soils are classified as inceptisols or entisols. Surface layer of most soils is shallow and permeable with a high percentage of rock fragments. Soil depths are ranged from 28 cm to 150 cm and their percentage of rock fragments are 10 % - 40 %. The impeding layers are composed of bedrock, fragipan and clay. Saturated hydraulic conductivity is about 2 m/day. Average porosity and field capacity values are 0.6 and 0.37 without rocks respectively. Land use data for the watershed by Frankenberger (1996) were used. Precipitation, stream flow and sediment concentration data which were measured at the watershed outlet by the New York State Department of Environmental Conservation, were used. Four storm events from July and October, 1994, were chosen for model test.

Map data from GRASS : Seven maps which are elevation, stream, soil, land use and soil parameters-porosity, field capacity and initial soil moisture condition-were used for input data. These maps were prepared as grid data (151 rows by 174 columns) which were converted to ASCII-formatted data using GRASS.

Hydrologic simulation : Prior to soil-water erosion simulation, hydrologic simulation was completed using the 'GRID-Based Variable Source Area Storm Runoff Model' (Kim and Steenhuis, 1996). A summary of model results for hydrologic simulation is given in Table 1.

Soil-water erosion and deposition simulation : An example of the observed versus predicted sediment concentration at the watershed outlet is shown in Figure 2 for September 8 storm. A summary of model parameters and results is given in Table 2. Temporal and spatial distribution of sediment transport areas by concentration (kg/m^3) is shown in Figure 3 for September 8 storm.

4. Conclusions

A physically-based soil-water erosion and deposition model was developed. 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. The model successfully generated the temporal and spatial distribution of sediment transport areas by concentration and flux respectively. This model can be used to a raster-based GIS if ASCII-formatted grid data are available.

5. References

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Table 1. Summary of GRISTORM hydrologic model results.

Storm event	Total rainfall (mm)	Manning's n					Hydraulic conductivity (m/day)		Total runoff (mm)		Peak discharge (m^3/sec)	
		Stream	Forest	Grass /Alfalfa	Corn	Farm -stead	high SMA	low SMA	observed	predicted	observed	predicted
7/30/93	9.1	0.025	0.20	0.11	0.17	0.09	0.80	0.20	0.019	0.014	0.0057	0.0057
8/02/93	11.2	0.025	0.20	0.14	0.17	0.09	0.50	0.10	0.023	0.019	0.0065	0.0067
9/08/93	24.4	0.026	0.20	0.14	0.17	0.09	1.00	0.50	0.285	0.287	0.0768	0.0829
10/21/93	23.1	0.030	0.30	0.24	0.27	0.19	1.20	0.80	0.576	0.575	0.1140	0.1115
Mean		0.027	0.23	0.16	0.20	0.12	0.88	0.40				

Note) SMA: soil moisture area

Table 2. Summary of soil ero[illegible]n model parameters and results.

Storm event	N	η high	η low	φ	F	J	ε	c_{min}	λ_O	C_g Forest	C_g Grass /Alfalfa	C_g Corn	C_g Farm -stead	Max. concentration (kg/m³) observed	Max. concentration (kg/m³) predicted	Sediment yield (kg) observed	Sediment yield (kg) predicted
7/30/93	1	1.0	0.9	3×10^{-5}	0.1	20	9.1	1.0	1.0	1.0	0.8	0.65	0.0	4.62	20.32	44.4	52.0
8/02/93	1	1.0	0.9	5×10^{-4}	0.1	20	9.1	1.0	1.0	1.0	0.8	0.65	0.0	2.39	2.39	28.6	18.3
9/08/93	1	1.0	0.8	0.043	0.1	20	9.1	1.0	1.0	1.0	0.8	0.65	0.0	4.93	5.02	695.7	587.3
10/21/93	1	1.0	0.6	0.100	0.1	20	9.1	1.0	1.0	1.0	0.8	0.65	0.0	1.41	1.52	574.9	306.4

Note) N: rill density (rills/m), η: erodibility, φ: depositability (m/sec), F: fraction of stream power effective in erosion,

J: specific energy of entrainment (J/kg), ε: value of exponent in assumed relationship $\tau_{SS} / \tau_S = (1 - C_g)^{\varepsilon}$,

C_{min}: minimum sediment concentration due to vegetation (kg/m³), λ_O : downslope distance at $c=c_{min}$ (m),

C_g : fraction of sufrace cover.

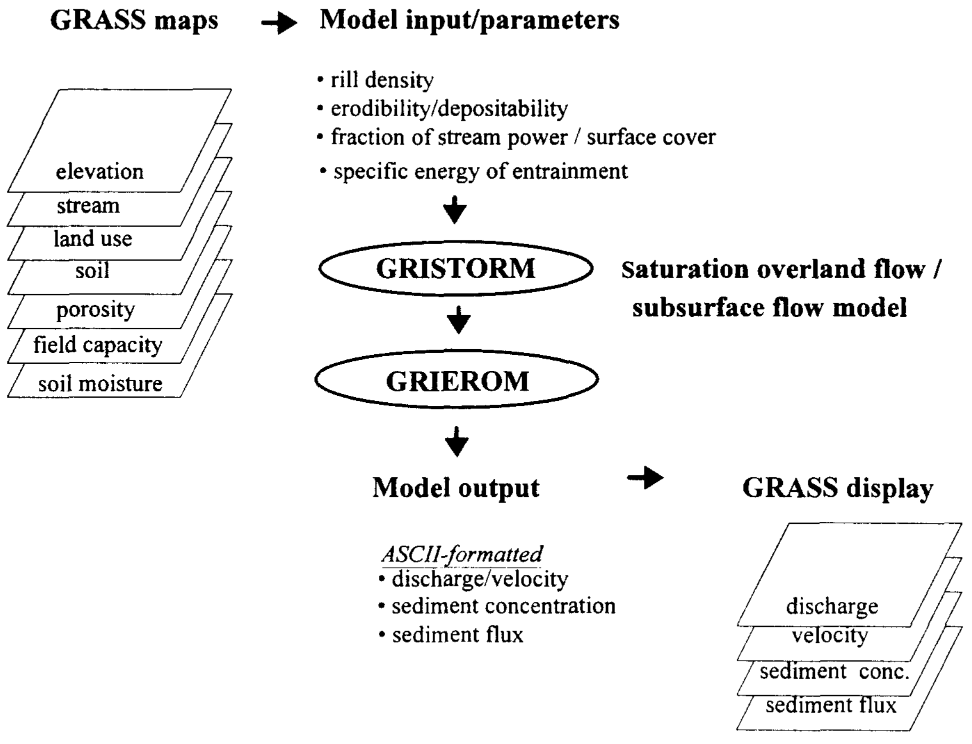

Figure 1. Schematic diagram of GRIEROM

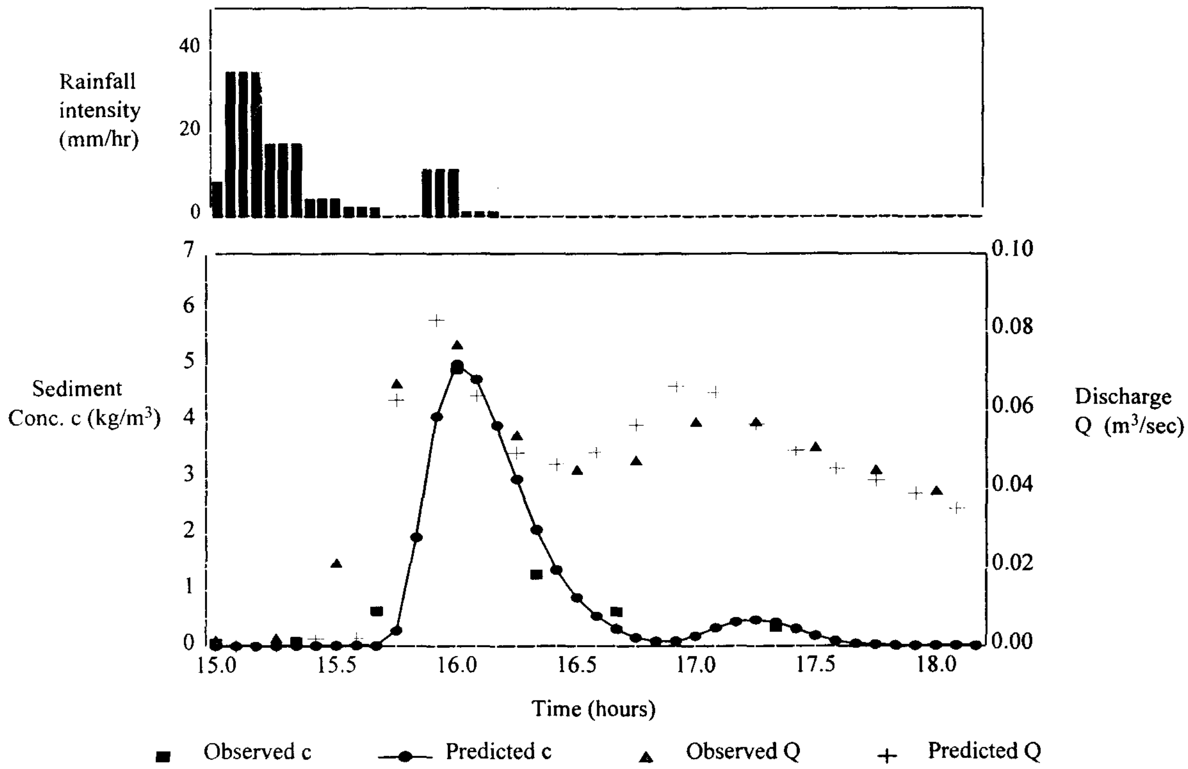

Figure 2. Comparison of observed and predicted sediment concentration (September 8, 1993 at Crowe Road watershed)

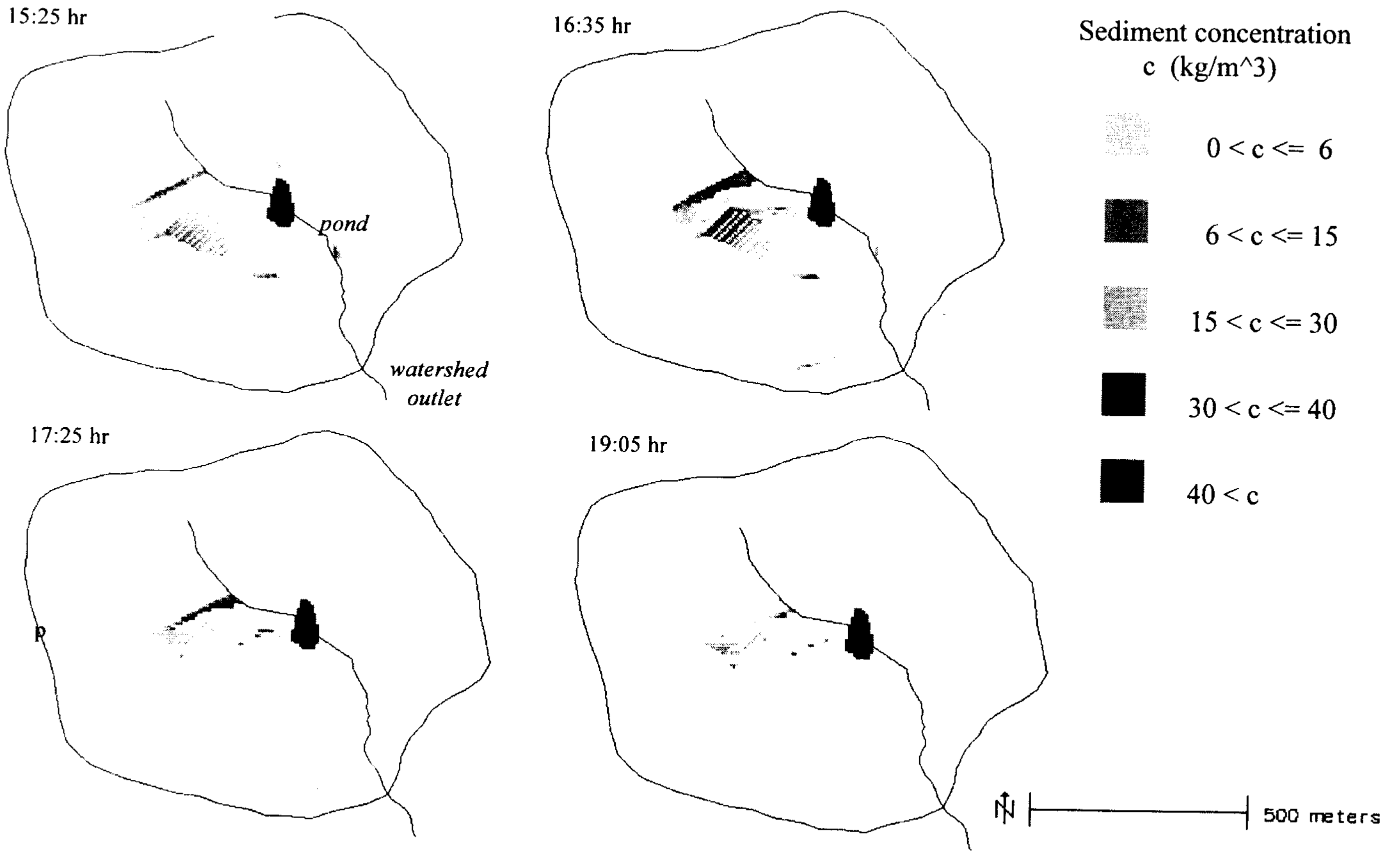

Figure 3. Temporal variation and spatial distribution of sediment transport by concentration (September 8, 1993 at Crowe Road watershed)