Application of Grid-based Kinematic Wave Storm Runoff Model

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ABSTRACT: The grid-based KIneMatic wave STOrm Runoff Model (Kim, 1998; Kim, et al., 1998) which predicts temporal variation and spatial distribution of saturated overland flow, subsurface flow and stream flow was evaluated at two watersheds. This model adopts the single overland flowpath algorithm and simulates surface and/or subsurface water depth at each cell by using water balance of hydrologic components. The model programmed by C-language uses ASCII-formatted map data supported by the irregular gridded map of the GRASS (Geographic Resources Analysis Support System) GIS and generates the spatial distribution maps of discharge, flow depth and soil moisture of the watershed.

1. INTRODUCTION

The representative distributed models are ANSWERS (Beasley, et al., 1980), TOPMODEL (Beven, et al., 1979, 1984), SHE (Abbott, et al., 1986a, 1986b), DBSIM (Cabral, et al., 1990), THALES (Grayson, et al., 1992). The detailed description of the models at a glance can be found in the book "Computer Models of Watershed Hydrology" (Singh, 1996). Recently, Inspired by the rapid increasing power of computers and the Geographical Information Systems (GIS) and digital terrain maps, distributed models in hydrology have been developing rapidly since the first outline of a physics-based distributed model published by Freeze and Harlan in 1969 (Beven, 1996).

Allen (1987) developed SWHAM (Small Watershed Hydrologic Analysis Model) using GIS. The model is an overland flow model composed of a one-dimensional groundwater hydrologic model, stream flow model and digital map. Input data were extracted from soil, land use/cover and contour map. Stuebe and Johnston (1990) applied GIS to all phases of the SCS (Soil Conservation Service) modeling processes, including watershed delineation and routing of runoff to estimate the outlet runoff volume. Stuebe and Johnson's work demonstrated the use of GRASS to estimate runoff via the SCS Runoff Curve Number Model. Famiglietti (1992) used grid data extracted from a GIS and developed a GIS model using grid-based water balance and flow equation. Zollweg (1994) developed SMoRMod (Soil Moisture-based Runoff Model) using a series of GRASS commands. The model is a grid-based rainfall-runoff model which is composed of a daily soil moisture balance and subroutines which calculate runoff generation/transport at 30-minute intervals. The initial condition for the runoff generation is provided by daily soil moisture balance. The model has a tendency to either over- or under-predict the recession part of hydrographs. Kim and Steenhuis (1998) developed GRId-based STOrm Runoff Model (GRISTORM) which predicts temporal variations and spatial distributions of subsurface flow and saturated overland flow with shallow soil depths in a variable source area. The model adopted the combined surface-subsurface kinematic modeling approach (Takasao and Shiiba, 1988), and uses ASCII-formatted map data supported by the regular gridded map of the GRASS-GIS and generates the temporal and spatial distribution of discharge, flow depth and soil moisture in overland flow areas.

Kim (1998) and Kim, et al. (1998) developed grid-based KIneMatic wave STOrm Runoff Model (KIMSTORM) which predicts temporal and spatial distributions of overland flow, subsurface flow and stream flow in a watershed. The model adopts the single overland flowpath algorithm and simulates surface and/or subsurface water depth at each grid element by using grid-based water balance of hydrologic components with

Hortonian flow condition. In this paper, the applicability of KIMSTORM (Kim, 1998) is described. The model coded in C language runs on the GRASS using regular gridded data such as Digital Elevation Model (DEM), stream and flow direction, land cover, soil texture and Thiessen network with ASCII-formatted map data. The results are generated as ASCII-formatted map data, and displays on GRASS-GIS.

2. MODEL DESCRIPTION

2.1 Drainage network and inflow/outflow directions

The drainage network is made up of a set of subaerial topographic surfaces which are contiguous with uphill slopes on all sides except in the direction of water flow. This set of surfaces may be covered with water either temporarily or permanently (Deffontaines and Chorowicz, 1991). An automated drainage network extraction process by using DEM can be easily found in many GIS softwares such as GRASS (U.S. Army CERL, 1993) or ARC/INFO. We can consider 3 ×3 window grid permitting the water to flow to one of its eight neighbor cells as shown in Fig. 1(a). By taking a grid of DEM, examine the eight neighbor elevations with respect to center elevation, and determine the direction of steepest descent downhill numbering to the center cell from 1 to 8 which eventually generates flow direction grid. By using the generated grid, the outflow from the center cell such as overland/subsurface flow can be delivered to the determined neighbor cell by referencing the flow direction number. But the inflow to the center cell may be over one, thus 3 ×3 mirror window was adopted as shown in Fig. 1(b) (Chung et al., 1995). If the flow direction number of neighbor cell matches with that of mirror window, then the cells are treated as inflow.

3	2	1
4		8
5	6	7

Fig. 1. (a) 3 ×3 window grid for outflow

7	6	5
8		4
1	2	3

(b) 3 ×3 mirror window grid for inflow

2.2 Water balance components in a cell

The schematic representation of water balance components in a cell is shown in Fig. 2.

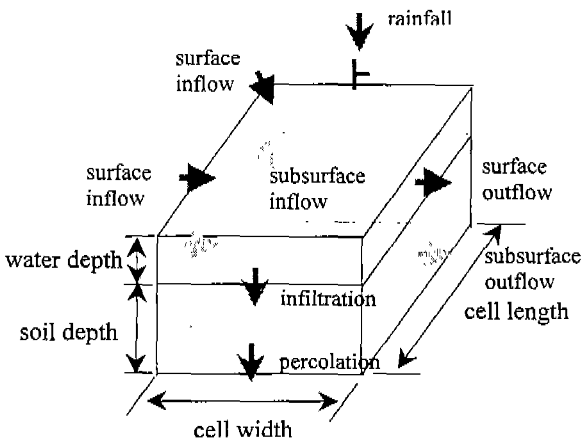


Fig. 2. Grid-based water balance components

2.3 Surface runoff

The kinematic wave equation for saturation overland/stream flow are obtained by the Manning equation:

$$Q = \alpha R^{m1} A^{m2} \tag{1}$$

where Q = discharge (m^3/sec); $\alpha = n^{-1} W^{-2/3} \tan^{1/2}\beta$ for overland flow, $n^{-1} \tan^{1/2}\beta$ for stream flow; n = Manning's roughness coefficient; W = cell width orthogonal to streamline (m), β = cell slope (degree), R = H for overland flow as a shallow sheet flow, $\gamma A^{1/2}$ for stream flow; H = flow depth (m); γ = 0.354 for rectangular channel (Moore and Foster, 1990; Moore and Burch, 1986); A = cross sectional flow area (m^2); m1 = 0 for overland flow, 2/3 for stream flow; m2= 5/3 for overland flow, 1.0 for stream flow.

2.4 Suburface flow

Lateral saturated subsurface flow equation approximated by the kinematic assumption (Beven, 1982; Sloan and Moore, 1984) was adopted.

$$Q_{sub} = K_s A \sin\beta \tag{2}$$

where Q_{sub} = subsurface discharge; K_s = saturated hydraulic conductivity (m/sec).

2.5 Infiltration and Percolation

Huggins and Monke infiltration equation (Beasley, et al., 1980) was adopted, and the percolation rate was applied when the soil moisture is over the field capacity.

$$f = f_c + f_i (SM_r / PO_e)^b \qquad 3)$$

where f = infiltration rate (mm/hr); f_c = final infiltration rate (mm/hr); f_i = initial infiltration rate (mm/hr); SM_r = available storage capacity (m^3/ m^3); PO_e = effective porosity (m^3/m^3); b = constant coefficient.

2.6 Initial flow depth condition

The spatial distribution of initial subsurface flow depths in a watershed can be obtained from soil information maps describing porosity, field capacity and initial soil moisture conditions. The initial flow depth for each cell can be calculated by

$$H_i = \begin{cases} D_c (SM_i - F_c) /(PO_e - F_c), & F_c < SM_i < PO_e \\ = D_c, & SM_i \geq PO_e \\ = 0, & SM_i \leq F_c \end{cases} \tag{4}$$

where H_i = initial flow depth in cell (m); D_c = soil depth above the impeding layer (m); SM_i = initial soil moisture content (m^3/m^3); F_c = field capacity (m^3/m^3).

2.7 Grid-based water balance for overland and stream flow

Water balance in a cell is sequentially calculated beginning from the most upper left cell to the lowest right cell. The calculated outflow delivered to the neighbor cell by flow direction is stored and used as inflows of the cell at the next time step. The water balance equation for overland flow and stream flow is,

$$\frac{dSi}{dt} = P(t)i - F(t)i + \sum Q_{in.i} - Q_{out.i} \qquad \text{for overland flow}$$

$$\frac{dSi}{dt} = P(t)i - F(t)i + \sum Q_{in.i} + \sum Q_{sub.in.i} - Q_{out.i} \qquad \text{for stream flow} \tag{5}$$

where i = cell address; S_i = cell storage (m^3); P_i = rainfall (m^3/sec); F_i = infiltartion (m^3), $Q_{in\,i}$ = inflows to the cell (m^3/sec); $Q_{out\,i}$ = outflow from the cell (m^3/sec); $Q_{sub\,in.i}$ = subsurface inflows to the cell (m^3/sec); t = time (sec). The soil moisture routing equation is,

$$\frac{dSMi}{dt} = F(t)i + \Sigma Q_{sub.in.i} - Q_{sub.out.i} - DP(t)_i \qquad (6)$$

where SM_i = soil moisture content in the cell (m^3); $Q_{sub\,out\,i}$ = subsurface outflow from the cell (m^3/sec); DP_i = Deep percolation to the groundwater (m^3).

2.8 Model structure and implementation

A schematic flow diagram of the KIMSTORM model is shown in Fig. 3. As input data for the model, the six GRASS regular gridded maps which are elevation, stream and flow direction, land use, soil, Thiessen network are converted into ASCII-formatted map data using GRASS command r.out.ascii. The model uses this data to generate discharge, flow depth and soil moisture at each cell outlet for a given time interval. Stream flow at the watershed outlet and ASCII-formatted discharge maps, flow depth maps, and soil moisture maps were generated for 1-hr intervals while the calculation time step is 1 minute. The ASCII-formatted map data were converted into GRASS maps using GRASS command r.in.ascii.

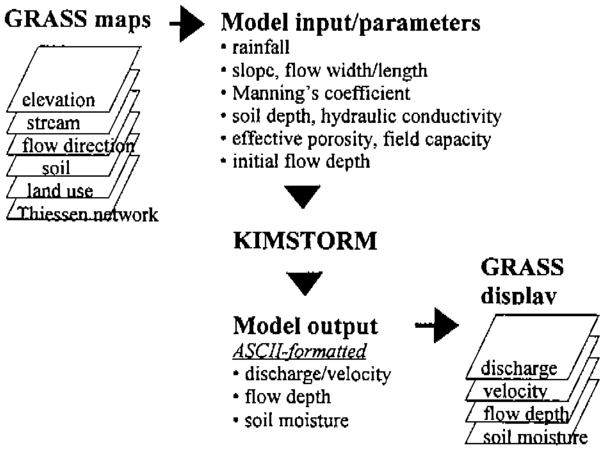


Fig. 3. Schematic diagram of KIMSTORM model.

3. MODEL APPLICATION

3.1 Watershed, soils, land use, storm events and stream flow data

The model was tested at two watersheds; Hongbo and Ipyunggyo located in Hongseong-Boryung tideland reclaimed area and Bocheong river basin in Korea. The watershed areas are 218.3 km^2 and 75.6 km^2, and elevations range from 0 m to 772 m and from 144 m to 491 m, respectively. The 3 arc-second spacing DEM from the Defense of Mapping Agency of United States was used. The DEM of Hongbo has the grid of 226 rows and 296 columns, and that of Ipyunggyo has the grid of 114 rows and 200 columns with cell size 75 m in width and 95.5 m in length, forming a rectangle (Fig. 4). By using DEM as input data, the stream and flow direction maps were generated with GRASS 'r.watershed' command.

The soil map was rasterized from ARC/INFO vector file. The watershed soils of Hongbo and Ipyunggyo are classified by 5 textures of which 62.6 % and 85.2 % is clay and clay loam, respectively. The surface layer of most soils is permeable with soil depths ranged from 50 cm to 150 cm. To obtain the land cover map, Landsat image (Nov. 25th 1996; path 116 / row 35) merged by SPOT panchromatic image (Nov. 15th, 1997; path 304 / row 277) for Hongbo watershed and six Landsat TM images (Jan. 11th, April 1st, May 3rd, June 20th, Oct. 10th, Nov. 27th, 1995; path 115 / row 35) for Ipyunggyo watershed were used, respectively. Land cover for the watershed was classified by using maximum likelihood method. Forest is more than 73.6% and 69.0 % and the lower slopes are mainly paddy fields with 16.3 % and 15.0 %, respectively. Thiessen network maps were also rasterized from valued point vector file.

A strom event (September 11, 1990) for Hongbo watershed and two storm events (July 11, August 31, 1995) for Ipyunggyo watershed were used for model test. Stream flow data were obtained from the hydrological survey report by Ministry of Agriculture and Forestry, and the annual report of International Hydrological Program (IHP) accomplished by Ministry of Construction and Transportation, Korea.

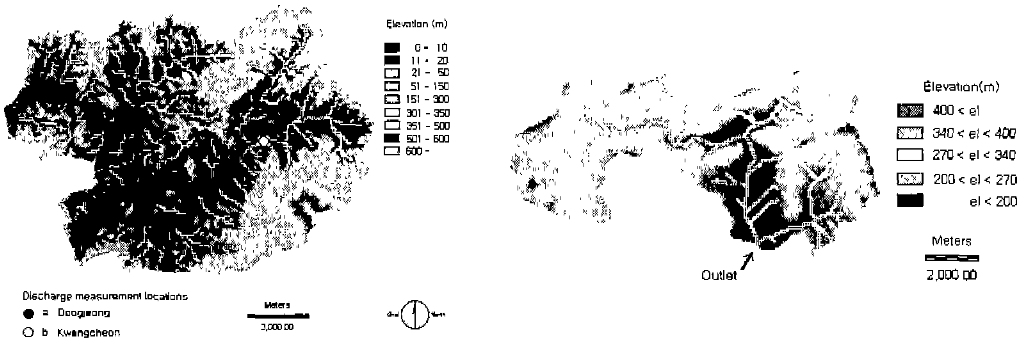


Fig. 4. DEM and generated stream map of (a) Hongbo and (b) Ipyunggyo watershed

3.2 Comparing predicted and observed streamflow at the watershed outlet

Soil parameters are effective porosity, field capacity and saturated hydraulic conductivity which were adopted from Rawls et al. (1982). In the model calibration, the Manning's roughness coefficients proved to be the most sensitive parameter for overland areas and streams which affected the time and magnitude of the peak stream flow. The next sensitive parameters were the initial and final infiltration rate affecting the magnitude of the peak stream flow. Fig. 5 shows the observed versus predicted stream flow at two locations (a: Dukjeong, b: Kwangcheon marked in Fig. 4) of Hongbo watershed for September 11 storm. Fig. 6 shows the results of Ipyunggyo watershed outlet for July 11 and August 31 storms. The predicted runoff agreed well with the observed values. Table 1 shows the calibrated parameters and summary for three storm events.

The average Nash-Sutcliffe efficiency R^2 (Nash and Sutcliffe, 1970) for the model was 0.64. The peak discharge showed a time gap between observed and predicted streamflows ranging from 1 hour to maximum 3 hours. This error may be caused by Thiessen averaged rainfall with abrupt polygon boundaries and by the simplification of subsurface flow. Spatially interpolated rainfall, for example, by using spline or distance-weighted average method would improve the results. 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 soil depth, initial soil moisture condition and lumping parameters within each grid element.

Table 1. Parameters used and calibrated for the storm events.

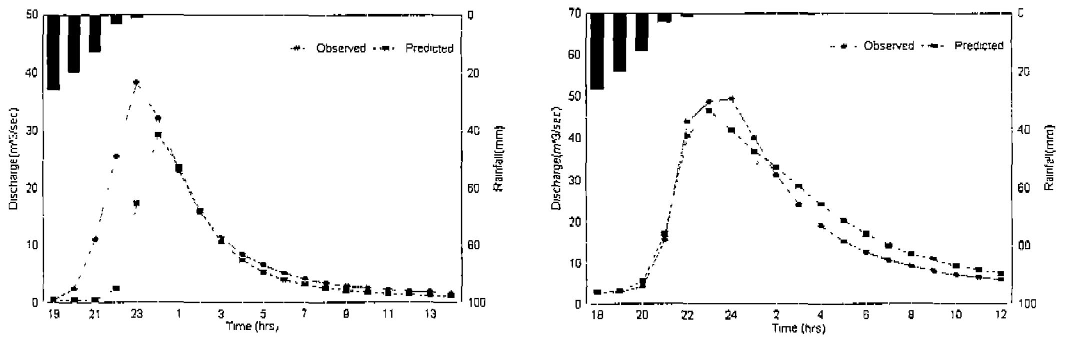
Storm Event	Total rainfall (mm)	Manning's n				Ave. infiltration (mm/hr)			Ave. K_s (m/day)	Total runoff (mm)		Peak discharge (m^3/sec)		Nash-Sutcliffe efficiency R^2
		Stream	Forest	Cultivated	Settlement	f_c	f_i	b		Obs.	Pre.	Obs.	Pre.	
9/11/90	62.7	0.052	0.38	0.55	0.26	1.0	7.0	0.65	2.0	20.3	14.4	38.4	29.2	0.53[a]
										36.1	38.3	49.5	46.5	0.95[b]
7/11/95	52.3	0.060	0.15	0.72	0.10	5.0	20.0	0.65	2.0	27.4	24.4	22.3	21.5	0.40
8/31/95	157.0	0.065	0.15	0.72	0.10	2.0	20.0	0.65	2.0	68.6	61.4	61.9	61.6	0.69

Note) a: Dukjeong (22.0 km^2), b: Kwangcheon (35.5 km^2)

3.3 Temporal variation and spatial distribution of overland/stream flow

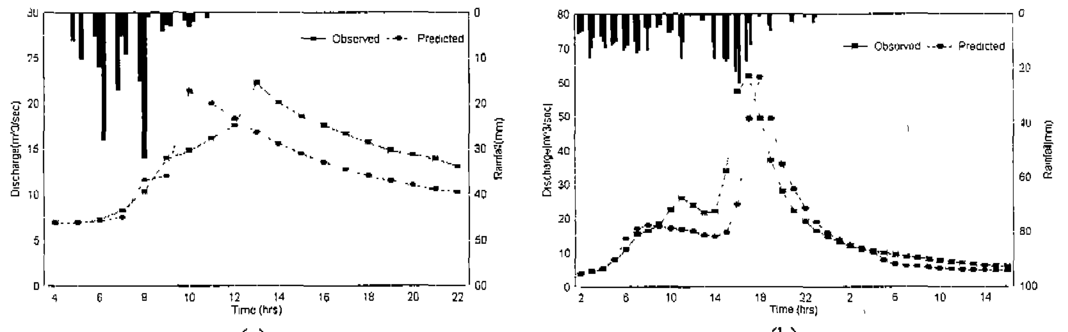
Knowing only the stream flow at the watershed outlet, we cannot determine where the overland flow originated and how much water at each source area contributed. GIS can also provide the information which is important for investigating the loss of soil due to erosion and the transport of non-point source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

Fig. 7 shows the predicted temporal and spatial distribution of saturated overland/stream flow depths for the September 11 storm of Hongbo watershed. After the storm started, the overland flow areas initially occurred around the areas of the main stream. These areas have mild slopes and higher soil moisture content than other areas. The source area for overland flow increased from the start of rainfall to the end of rainfall, and decreased gradually after that time. Also we can find the overland flow areas contributing to stream flows after the peak discharge shown in Fig. 7(c). This shows that the overland/subsurface flows delayed the transport of water to the watershed outlet causing a lag time.



(a) Dukjeong (b) Kwangcheon

Fig. 5. Observed versus predicted stream flow at two locations of Hongbo watershed for September 11 storm



(a) (b)

Fig. 6. Observed versus predicted stream flow at the watershed outlet of Ipyunggyo watershed for (a) July 11 and (b) August 31 storms.

4. CONCLUSIONS

The model was tested on two watersheds; Hongbo (218.3 km^2) and Ipyunggyo (75.6 km^2) located in Hongseong-Boryung tideland reclaimed area and Bocheong river basin in Korea. GRASS regular gridded maps which are elevation, stream and flow direction, land use, soil, Thiessen network were prepared for model inputs. The observed stream flows measured at watershed outlet were compared with the values predicted by the model. The spatial distributions of saturated overland flow areas for three storm events were successfully modeled and displayed on GRASS. This model can be used on other raster-based GIS if ASCII-formatted grid data are available.

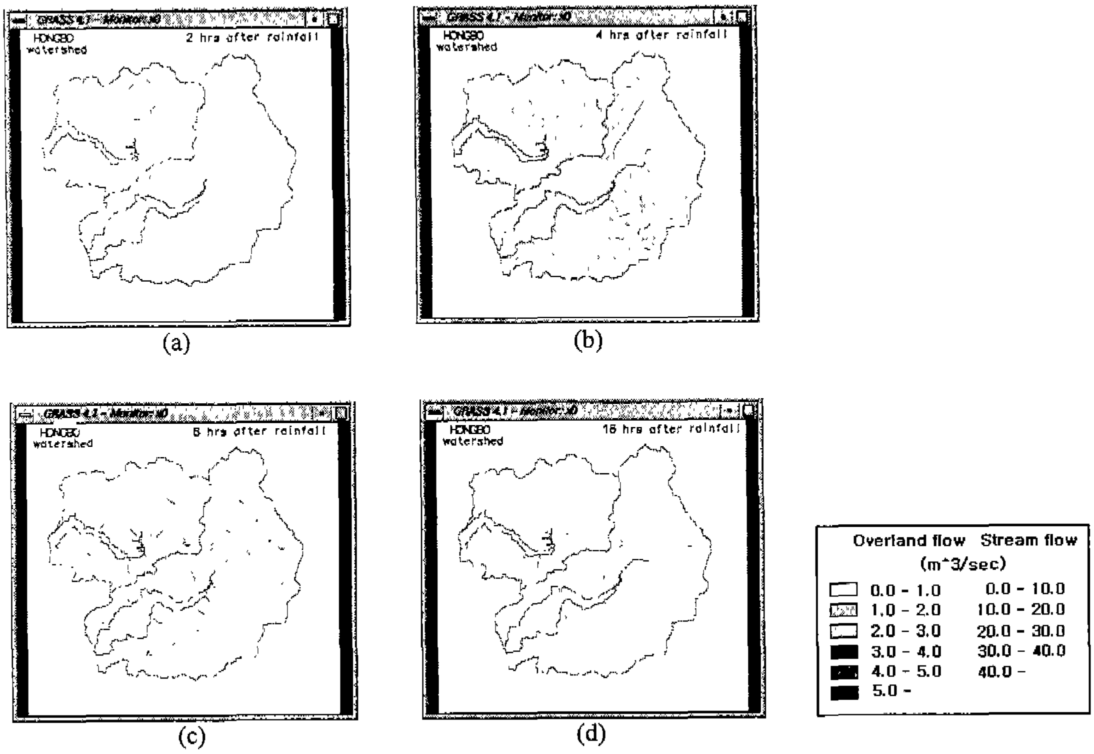


Fig. 7. Spatial distribution of surface and channel runoff after (a) 2 hrs, (b) 4 hrs, (c) 8 hrs, (d) 16 hrs of storm event (September 11 storm, Hongbo watershed)

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