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Grid-based dam inflow prediction on a large river basin using Thiessen polygon and spatially-distributed rainfall data

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Abstract The surface runoff and streamflow responses between Thiessen average rainfall controlled by rainfall stations (T) and spatially distributed rainfall that is cell by cell units (R) would be different from each other. To identify the effects quantitatively, the grid-based kinematic wave storm runoff model (Kim, 1998; Kim *et al.*, 1998) was adopted. The model was tested for the above rainfall conditions on Yeoncheondam watershed (1875 km^2) in South Korea. There were big temporal and spatial surface runoff/discharge differences between T and R when the rainfall is moving in a north to south direction rather than moving in an east to west direction because the watershed width is relatively narrow in shape.

Key words grid-based; kinematic wave; spatial rainfall; storm runoff; Thiessen

INTRODUCTION

Rainfall is a key input for all hydrological/water quality (H/WQ) models because it activates flow and mass transport. Chaubey *et al.* (1999) mentioned that large uncertainty in the model outputs could be expected if the spatial variability of rainfall is not properly taken into account.

The distributed storm runoff model, KIMSTORM (Kim, 1998; Kim *et al.*, 1998) described here was developed to predict temporal and spatial distributions of overland flow, subsurface flow, and streamflow in a watershed. The model coded in C language uses several GRASS (US Army CERL, 1993) grid data and the results are generated as ASCII-formatted map data, and displayed on GRASS–GIS. There are two grid-based hydrological models available with the GRASS distribution. *r.water.fea* (Vieux *et al.*, 1990) is an interactive program that allows the user to simulate stormwater runoff analysis using the finite element numerical technique. *r.hydro.CASC2D* (Saghafian, 1993) is a physically-based, distributed, raster hydrological model which simulates the hydrological response of a watershed subject to a given rainfall field. These models are fully embedded in GRASS. On the other hand, KIMSTORM just uses model input and generates model output as GRASS format.

The objective of this research is to study the effect on runoff when using point-averaged rainfall by Thiessen polygon and spatially-distributed rainfall interpolated by using point value rainfall using KIMSTORM. This study attempts to quantify the dam inflow due to rainfall spatial variability considering moving direction when applied to a large watershed (1875 km^2) with a loose network of four raingauges. The study watershed is in a special situation because part of the watershed belongs to North Korea, thus the hydrological data have not been collected in good condition.

MODEL (KIMSTORM) DESCRIPTION

The watershed is divided into regular cells and the schematic representation of water balance components in a cell is shown in Fig. 1. We can choose a 3 × 3 grid filter to determine lateral flow direction. The flow direction from the centre grid cell is determined by identifying the steepest slope to the eight neighboring grid cells using elevation data. The direction of the steepest descent downhill, numbering 1–8 to the centre grid cell, eventually generates flow direction. The water of the grid cell flows in the steepest direction. Single output flowpath is chosen in this study, but the inflow to a grid cell can come from multiple sources. To deal with multiple lateral inflows, the eight neighbouring grid cells are treated as inflows only if the flow direction number among them matches the already determined flow direction grid. If flows drain into a stream, then they are treated as lateral flow to the stream.

The kinematic wave equation for saturation overland flow/streamflow is obtained by the Manning equation:

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

where Q is discharge ($\mathrm{m}^3\ \mathrm{s}^{-1}$); $\alpha = n^{-1} W^{-2/3} \tan^{1/2}\beta$ for overland flow, $\alpha = n^{-1} \tan^{1/2}\beta$ for streamflow; n is Manning's roughness coefficient; W is cell width orthogonal to streamline (m), β is cell slope (degree), $R = H$ for overland flow as a shallow sheet flow, $\gamma \cdot A^{1/2}$ for streamflow; H is flow depth (m); $\gamma = 0.354$ for rectangular channel (Moore & Foster, 1990; Moore & Burch, 1986); A is the cross-sectional flow area (m^2); m1 = 0 for overland flow, 2/3 for streamflow; and m2 = 5/3 for overland flow, 1.0 for streamflow. The lateral saturated subsurface flow equation approximated by the kinematic assumption (Beven, 1982; Sloan & Moore, 1984) was adopted:

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

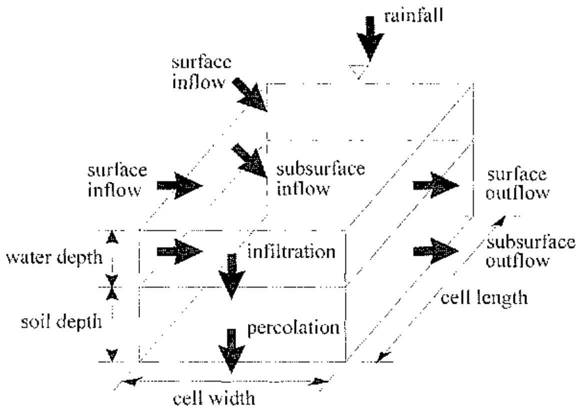

Fig. 1 Grid-based water balance components.

where Q_{sub} is subsurface discharge; K_s is saturated hydraulic conductivity (m s^{-1}). The Huggins and Monke infiltration equation (Beasley *et al.*, 1980) was adopted, and the percolation rate was applied when the soil moisture content is above the field capacity:

$$f = f_c + f_i (SM_r / PO_e)^b \tag{3}$$

where f is infiltration rate (mm h^{-1}); f_c is final infiltration rate (mm h^{-1}); f_i is initial infiltration rate (mm h^{-1}); SM_r is available storage capacity (m^3 m^{-3}); PO_e is effective porosity (m^3 m^{-3}); and b is a constant coefficient. 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:

$$\begin{aligned} H_i &= D_c (SM_i - F_c)/(PO_e - F_c) && F_c < SM_i < PO_e \\ &= D_c && SM_i > PO_e \\ &= 0 && SM_i \le F_c \end{aligned} \tag{4}$$

where H_i is initial flow depth in cell (m); D_c is soil depth above the impeding layer (m); SM_i is initial soil moisture content (m^3 m^{-3}); and F_c is field capacity (m^3 m^{-3}). Water balance in a cell is sequentially calculated beginning from the uppermost left cell to the lowest right cell. The calculated outflow delivered to the neighbouring 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 streamflow is:

$$\frac{dS_i}{dt} = P_i - F_i + \sum Q_{in.i} - Q_{out.i} \text{ for overland flow} \tag{5}$$

$$\frac{dS_i}{dt} = P_i - F_i + \sum Q_{in.i} + \sum Q_{sub.in.i} - Q_{out.i} \text{ for streamflow}$$

where i is cell address; S_i is cell storage (m^3); P_i is rainfall (m^3 s^{-1}); F_i is infiltration (m^3), $Q_{in.i}$ is inflows to the cell (m^3 s^{-1}); $Q_{out.i}$ is outflow from the cell (m^3 s^{-1}); $Q_{sub.in.i}$ is subsurface inflows to the cell (m^3 s^{-1}); and t is time (s). The soil moisture routing equation is:

$$\frac{dSM_i}{dt} = F_i + \sum Q_{sub.in.i} - Q_{sub.out.i} - DP_i \tag{6}$$

where SM_i is soil moisture content in the cell (m^3); $Q_{sub.out.i}$ is subsurface outflow from the cell (m^3 s^{-1}); and DP_i is deep percolation to the groundwater (m^3).

A schematic flow diagram of the model is shown in Fig. 2. As input data for the model, six GRASS regular grid maps that are elevation, stream and flow direction, land use, soil, Thiessen or spatial rainfall data are converted into ASCII-formatted map data using the GRASS command r.out.ascii. Streamflow at the watershed outlet, and ASCII-formatted discharge map, flow depth map, and soil moisture map were generated for 1-h interval while the calculation time step is 1 min. The ASCII-formatted map data were converted into GRASS maps using the GRASS command r.in.ascii.

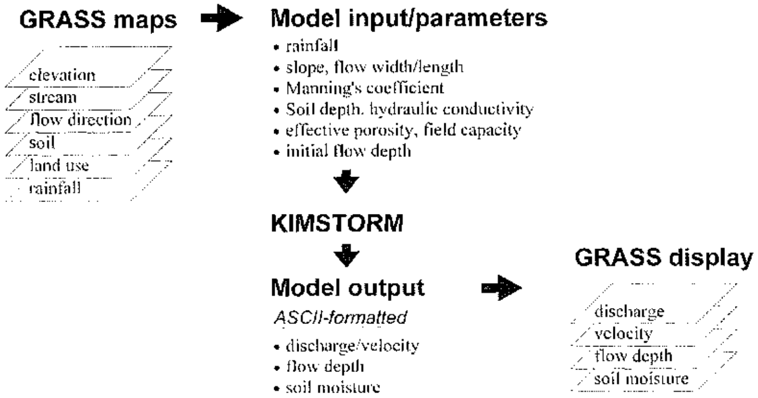

Fig. 2 Schematic diagram of the model.

MODEL APPLICATION

Watershed, soils and land-use data

The model was tested on Yeoncheondam watershed located in the north of South Korea. About one third of the watershed belongs to North Korea. The latitude ranges from 37°45′ to 38°33′. The watershed area is 1875 km^2 and the elevation ranges from 73 to 1171 m. Watershed location, elevation, and the streams are shown in Fig. 3. The subsurface unsaturated layer of most soils is permeable with soil depths ranging from 50 to 150 cm. Clay loam dominates covering 56.7% of the watershed. As soil information of North Korea was not available, it was assumed as clay loam. More than 52.3% is forested and 30.2% of lowland is paddy fields. The remaining area is dry field farming (11.3%) and farm village (0.6%) scattered between forest and paddy.

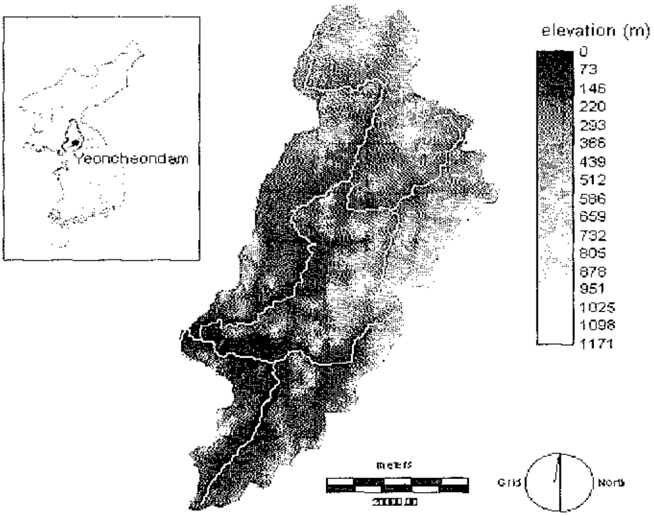

Fig. 3 Watershed location, main streams and topography.

Map data preparation

Elevation data was rasterized from the vector map of 1:5000 scale supplied by the Korea National Geography Institute. The flow direction map and flow accumulation map were generated using elevation data with the GRASS r.watershed command. Soil data were rasterized from the vector map of 1:50 000 scale supplied by the Korea Rural Development Administration. The land-use map was prepared using Landsat TM image of 2 June 1992 supplied by RESTEC (Remote Sensing Technology of Japan). Land cover analysis was achieved through the maximum likelihood classification with overall accuracy of 95.6%. The Thiessen polygon network was rasterized from the point vector data of geometric coordinates of four rainfall gauges. The Spatial rainfall map was generated from the valued point vector files using distance-weighted average interpolation. These maps were prepared to have a 400 × 400 m cell size.

Dam inflow prediction by Thiessen polygon network and spatially distributed rainfall data

Simulation by T (Thiessen polygon rainfall data) and R (spatially-distributed rainfall data) was conducted in four moving directions [NS (north to south), SN (south to north), EW (east to west), and WE (west to east)] with 2 h duration of arbitrary rainfall. Table 1 shows the applied rainfall conditions. Figures 4 and 5 show the predicted dam inflows by NS/SN direction, and EW/WE direction for T and R, respectively. Table 2 summarizes the predicted statistics of each case.

Table 1 Applied 2 h rainfall characteristics for each condition.

Rainfall type		Thiessen					Spatial distribution	Remarks
		Kim-hwa	Dong-song	Yeon-cheon	Po-cheon	Total/Mean		
Area (km^2)		839.9	522.3	123.3	389.2	1874.7	1874.7	2 h rainfall
Rainfall Intensity ($mm\ h^{-1}$)	ⓐ	90	70	40	15	65.6	72.9	ⓐ+ⓑ: NS
	ⓑ	70	90	120	145	94.4	86.5	ⓑ+ⓐ: SN
	ⓒ	90	50	10	45	64.3	68.3	ⓒ+ⓓ: EW
	ⓓ	70	100	130	110	90.6	90.0	ⓓ+ⓒ: WE

Table 2 Summary of predicted dam inflows by NS/SN direction, and EW/WE direction for T and R.

	NS:		SN:		EW:		WE:	
	R	T	R	T	R	T	R	T
Peak discharge ($m^3\ s^{-1}$)	1216.1	3572.1	1605.0	3550.2	3536.6	3307.1	3470.8	3350.1
Time to peak (h)	12	7	8	7	9	9	8	8
Total discharge ($10^6\ m^3$)	100.7	207.4	125.4	207.8	204.5	198.2	204.9	199.0

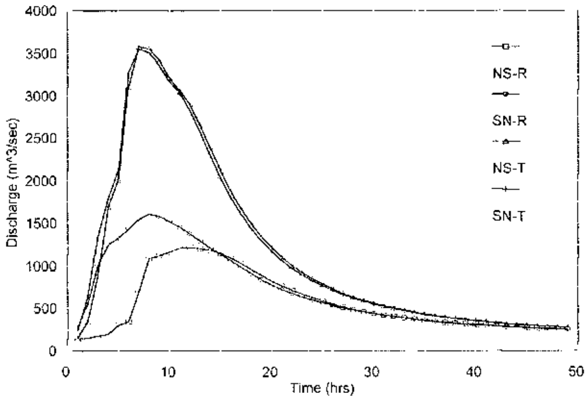

Fig. 4 Predicted dam inflows by NS and SN direction for T and R.

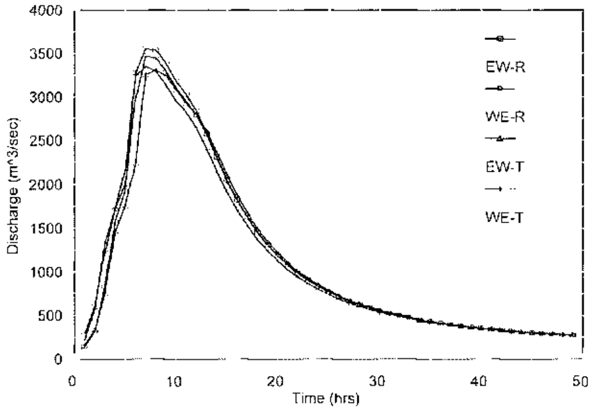

Fig. 5 Predicted dam inflows by EW and WE direction for T and R.

Runoff volume and peak flow rate of NS-R were 48.6% and 34.1% compared with those of NS-T, and the time to peak flow was delayed by 5 h. The runoff response of NS-R was slower than that of NS-T. This is because the first 1 h rainfall in the downstream areas of the watershed is relatively low to contribute as a streamflow and the produced runoff at the upstream areas needs time to reach to the watershed outlet. Runoff volume and peak flow rate of SN-R were 60.3% and 45.2% comparing with those of SN-T, and the time to peak flow was delayed by 1 h. The simulated results of under-produced runoff volume and peak flow by R application indicate the reflection of the spatial variations of rainfall to runoff. The results also suggest that the rainfall stations of this watershed are not sufficient to represent the areal average rainfall of the watershed as a well-designed Thiessen network. The simulated results by EW/WE direction for T and R showed little difference in the hydrograph. This is because the watershed is elongated to the north and south, and the rainfall by T and R did not give considerable difference from each other.

SUMMARY AND CONCLUSIONS

An analysis of the effect of rainfall by Thiessen polygon and spatial distribution map on runoff by using distributed storm runoff model (Kim, 1998; Kim *et al.*, 1998) was accomplished. The model was applied to a 1,875 km^2 watershed with a loose network of four raingauges. It revealed that the hydrograph generation is strongly related to the spatial variations in the rainfall, moving direction of the rainfall, and the shape of a watershed. Simulated results imply that the watershed needs more raingauge stations or other rainfall detection methods such as radar techniques to represent spatial variations of rainfall for the whole watershed. We can infer a result that if the watershed has a dense network of raingauges enough to represent spatial variations of rainfall, then the runoff difference by Thiessen polygon and spatially distributed rainfall will decrease.

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