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GIS-Based 1-d Diffusive Wave Overland Flow Model

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Abstract

This paper presents a GIS-based 1-d distributed overland flow model and summarizes an application to simulate a flood event. The model estimates infiltration using the Green-Ampt approach and routes excess rainfall using the 1-d diffusive wave approximation. The model was designed to use readily available topographic, soils, and land use/land cover data and rainfall predictions from a meteorological model. An assessment of model performance was performed for a small catchment and a large watershed, both in urban environments. Simulated runoff hydrographs were compared to observations for a selected set of validation events. Results confirmed the model provides reasonable predictions in a short period of time.

Introduction

A key component of flood prediction, planning, and mitigation is numerical modeling of rainfall-runoff. Physically-based approaches have developed rapidly the past decade with the increase in the development and availability of the required spatial datasets. Distributed models have also experienced substantial progress as computational and data availability limitations have been reduced. They demand intensive data, data handling and computational abilities. The advent of digital technology has eliminated this limitation. Distributed, physically-based modeling is viewed as the most appropriate for large-area applications not only because of the reduction in previous limitations, but also because of advances to modeling approaches and integration with geographic information systems (GIS) (Vieux, 2001).

In this research, a distributed hydrologic model was built and tested for use in large area extreme rainfall event simulation. The model would be able to input readily available spatial datasets downloadable from the internet, capitalizing the spatial analysis capabilities of GIS. The model was optimized to perform analysis for rapid-response and decision making.

Methodology

A GIS-based 1-d Distributed Hydrologic Model (DHM) was developed through a collaborative effort between researchers at the University of Utah and Los Alamos National Laboratory. The DHM is part of a flood prediction and damage assessment framework designed to rapidly simulate flooding from extreme events of national importance (e.g., hurricanes, tropical storms) and assess damage and operational impacts to infrastructure systems (communications, transport, hospital, power *etc.*) (Judi *et al.*, 2007). The overall tool and the DHM were developed as extensions to the ESRI® ArcGIS™ 9.1 software in a Microsoft® VB.NET environment. The DHM generates runoff hydrographs using the following readily available datasets downloadable from the Internet (Figure 1):

- Digital elevation model (DEM) from the United States Geological Survey (USGS)
- State Soil Geographic (STATSGO) database from Natural Resources Conservation Service (NRCS)
- Land use / land cover from the USGS
- Watershed boundaries from the National Hydrography Dataset
- Gridded rainfall data from meteorological simulation or radar or rain gauge observations

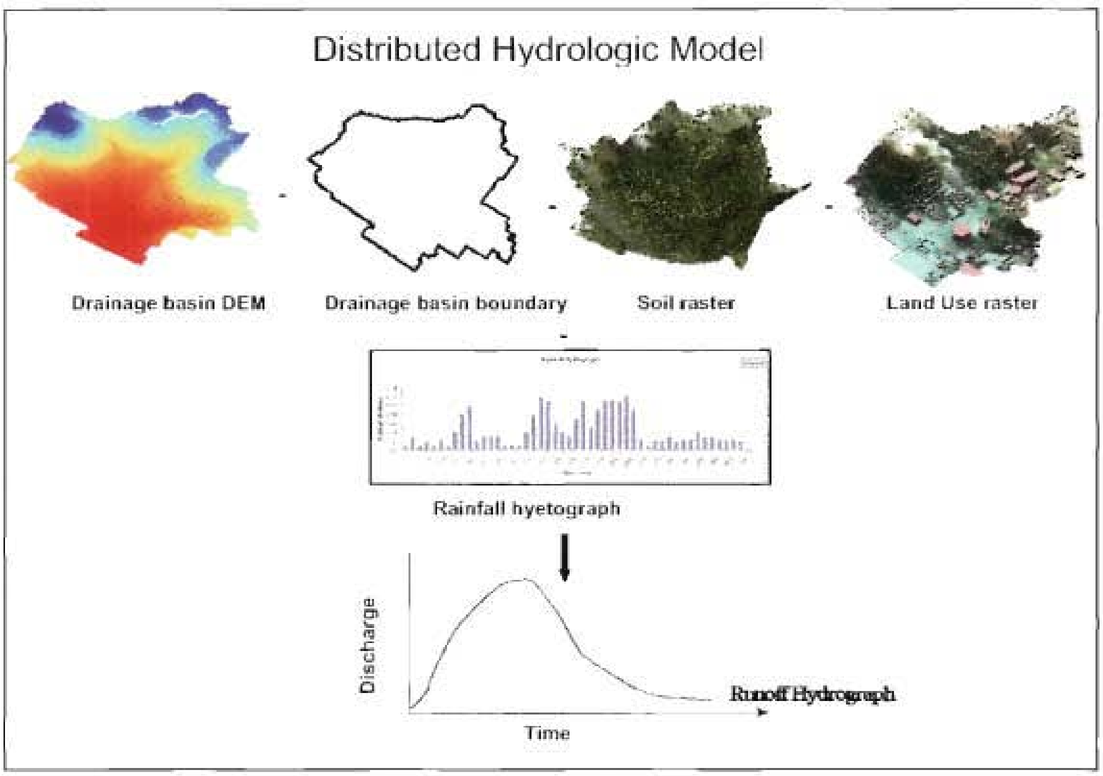

Figure-1 Illustration of structure of distributed hydrologic model

The distributed, physically-based model predicts infiltration using the Green-Ampt (GA) approach. The infiltration excess is used to compute overland flow depth at each cell, which is routed to the outlet of the drainage basin based on the diffusive wave approach, a simplified form of the Saint Venant equations. However, the model does not account for impervious areas, base flow and detention storage, and maintains a simple architecture. Details of the infiltration and routing are provided in the following two sub-sections.

Infiltration:

The GA equation is a simplified representation of the infiltration process in the field, describing the infiltration rate as an implicit function of time as shown in the following equation.

$$f(t) = K_s\left(1 + \frac{\psi_{mf} \cdot \Delta\theta}{F}\right)$$

It assumes a homogeneous soil profile and a uniform antecedent soil moisture distribution. It also assumes the water movement in the soil to be in the form of an advancing wetting front, and the diffusion of soil moisture in the lateral direction to be negligible. Even with somewhat limiting assumptions, the model is considered one of the best available to describe infiltration over a wide range of rainfall events (Chu, 1978). While the GA model is considered more accurate than other relatively simple models feasible to apply over wide areas (e.g., curve number), there is an increased data requirement to estimate the necessary parameters (Van Mullem, 1991). In one of the most comprehensive studies conducted, Rawls *et al.* (1983) provided average values of the GA parameters after their analysis of nearly 1200 different soils covering 34 states across the U.S. The DHM uses the STATSGO database (Soil Survey Staff, 2006) from Natural Resources Conservation Service (NRCS) to define the soil texture class and then uses data collected by Rawls *et al.* (1983) to define the GA parameters (Table 1). The values of the GA parameters are defined at the center of the grid cell and the cumulative infiltration depth is computed using the Newton-Raphson procedure (Smith, 1993; Chow *et al.*, 1988).

Table1- GA parameters for selected soil texture classes (Rawls *et al.*, 1983).

Soil Texture Class	Hydraulic Conductivity K_s (mm/h)	Wetting Front Suction, ψ (mm)	Volumetric Moisture Deficit (Normal Condition) θ (Dimensionless)
Loamy Sand/Sand	30	61	0.3
Sandy Loam	10	110	0.25
Loam	6.4	89	0.25
Silty Loam	3.8	168	0.25
Silt	2.5	191	0.15
Sandy Clay Loam	1.5	218	0.15
Clay Loam	1.0	208	0.15
Silty Clay Loam	1.0	274	0.15
Sandy Clay	0.51	239	0.1
Silty Clay	0.51	292	0.1
Clay	0.25	315	0.05

Overland flow routing:

One of the common representations of the flow over planes and land surfaces or in channels is Saint Venant (SV) equations (Zhang and Cundy, 1989; Tayfur *et al.*, 1993; Jin and Fread, 1997; Singh *et al.*, 2005). They are obtained by integration of the three-dimensional Navier-Stokes equations over depth, with the assumption that the vertical hydrostatic pressure distribution is negligible (Garcia and Kahawita, 1986). They are a set of continuity and momentum equations shown below in partial derivative form in the x-direction:

Continuity Equation : $$\frac{\partial h}{\partial t}+\frac{\partial q_x}{\partial x}=R_e$$

Momentum Equation : $$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+g\left(\frac{\partial h}{\partial x}-S_o+S_f\right)=0$$

where h is the height of water head above the ground surface [L]; q_x is the unit discharge [L^2/T]; R_e is the rainfall excess [L/T]; V is the depth averaged flow velocity in the x-direction [L/T]; S_f is the friction slope [L/L]; S_o is the bed slope [L/L]; g is the acceleration due to gravity [L/T^2]; t is time [T]; x is the distance [L] along the surface. q_x is the flow rate per unit width, i.e., the flow coming in and going out at a location in the domain. R_e is the rainfall excess and it is a lateral inflow after deducting the infiltration.

The SV equations are generally classified into kinematic, diffusive and dynamic wave approximations based on the simplification level of the momentum equation. The simplest form of SV equations is the kinematic wave approach (KWA), followed in complexity by the diffusive wave, and then the dynamic wave. The diffusive wave approach was selected for the model described here because it performs better than the kinematic wave approach for many cases, and is more straightforward to implement than the dynamic wave (Govindaraju *et al.*, 1988).

The DHM is subject to upstream, downstream and initial conditions. The initial condition for the overland flow problem is a dry drainage basin surface. After diffusive wave simplification, the 1-d continuity and momentum equations are.

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} = R_e$$

$$S_f = S_o - \frac{\partial h}{\partial x}$$

A relationship between the unit flow discharge, flow depth and the friction slope is required to solve this set of equations. The Manning equation is used for this purpose:

$$q_x = \frac{1}{n_x} h^{5/3} \sqrt{S_f}$$

where n_x is the manning's roughness coefficient. In the DHM, Manning roughness coefficients are estimated based on the land cover designated by the National Land Cover Dataset (NLCD) 1992.

The numerical approach used in the overland flow computation is a backward difference explicit finite difference technique. The continuous partial derivatives of the equation are replaced by finite differences on grid points. Thus, a set of algebraic equations are formed with all the variables and parameters defined at the centers of the grid cells. These equations are solved using the values of the dependent variables from the initial and boundary conditions. The solutions at a particular time step become the dependent variables for the solution in the next time step. This process is iterated until reaching the required number to obtain the final solution of the problem (Singh, 1996).

Chow *et al.* (1988) suggested that although the explicit method is convenient, it may be less efficient and not suitable for longer duration calculations. It can however be used by applying certain stability criteria. The scheme may be stable if the errors generated from discretization, are not propagated to the future time steps. A necessary but insufficient condition for stability of an explicit scheme is the Courant condition (Liggett and Woolhiser, 1967). The courant condition as used in this study for the solving the diffusive wave equations is represented by the following equation.

$$\Delta t = C_n\left(\frac{\Delta x}{u_{\max}}\right)$$

where, C_n is the Courant number; u_{max} is the maximum velocity in any cell including the diffusive wave celerity 'c', $u_{max} = max(u) + c$.

Model Testing and Validation

The model predictions were tested for a small watershed (~ 3 km^2) located in Fayetteville, Arkansas. Simulated peak discharges from six rainfall-runoff events were compared to observed peak discharges. On average the model over predicted the peak discharge by 90%. However, the shapes and timing of the observed and simulated hydrographs were similar suggesting the model was sound, and performance might be improved through calibration.

Following the preliminary testing for the Fayetteville watershed, a more comprehensive assessment of the DHM was performed. Specifically, a sensitivity analysis was conducted, and an iterative calibration-validation process was completed. The model assessment was performed using a 60-km^2 sub-basin of the Greens Bayou watershed located in the Houston, Texas metropolitan area.

The sensitivity analysis involved systematically varying the input parameters (list the parameters) one at a time and then quantifying the change in output. Sensitivity of the DHM to input parameters occur in the following order listed from most sensitive to least sensitive: Manning roughness coefficient, soil hydraulic conductivity, wetting front depth, and moisture content. The model was calibrated in a bulk sense (all grid cells adjusted identically) for three storm events. Initially, the DHM was under predicting peak discharges of two of three storms by 45% (4 April 1995 and 27 March 2001), while the peak discharge for the third event (23 May 1993) was over predicted by 50%. This discrepancy suggested the assumption of an initial dry basin might be the problem because rainfall occurred in the days leading up to the 4 April and 27 March events. To test this hypothesis, a bulk calibration was performed by adjusting the model input parameters to represent wetter watershed conditions (Manning roughness adjusted slightly and hydraulic conductivity reduced substantially). DHM predictions improved, although it proved difficult to obtain a coordinated match for all three storm events (Table 2).

Table 2- Statistics before and after calibration

Storm Event	**% Diff. in Peak Discharge**		**RMSE (cfs)**		**Vol. Change (acre-foot)**		**% Diff. in Time to Peak**	
	Before	After	Before	After	Before	After	Before	After
May 23, 1993	52	109	32	63	7	67	-1	-3
April 4, 1995	-46	-5	79	38	-122	-24	13	6
March 27, 2001	-41	-25	391	349	-710	-605	-5	-6

Final validation of the model was performed with two additional storm events (4 February 1991 and 9 March 1994). Results of the validation indicate the model predicts reasonably well (Table 3; Figure 2).

Table 3- Post-validation statistical comparison statistics.

Storm Event	% Diff. in Peak Discharge	RMSE (cfs)	Bias (cfs)	Volume Change (acre-foot)	% Diff. in Time to Peak
4 Feb 1991	36	28	-1	1	-4
9 Mar 1994	12	29	15	48	-24

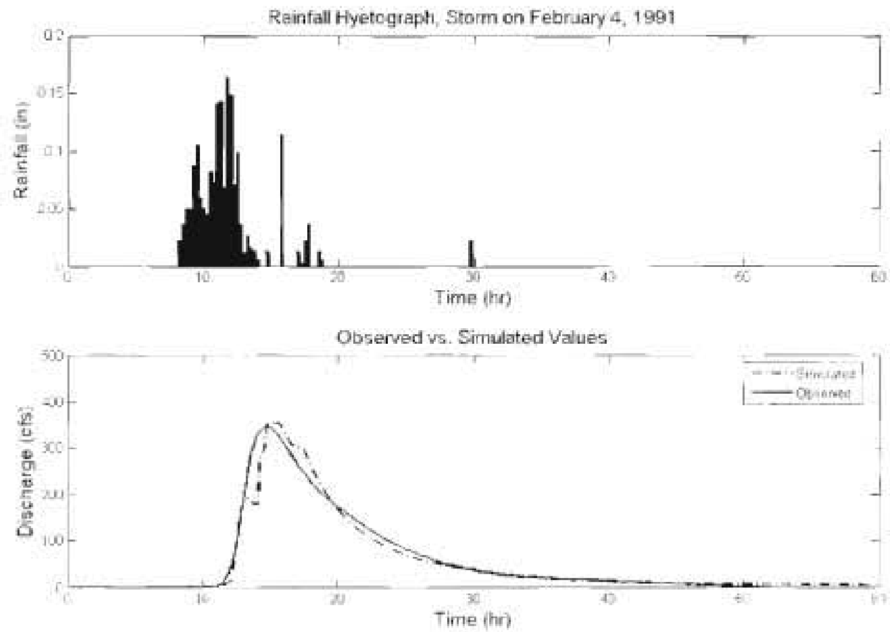

Figure 2- Validation results for 4 February 1991 event

Summary

This paper presented a GIS-based 1-d distributed hydrologic model. The model is physically-based, estimates infiltration using the Green-Ampt approach, and models overland flow using the diffusive wave approach. The model was designed for fast deployment to a new region (numerous river basins) and rapid prediction and assessment. To meet this need, the model uses readily available national datasets for topography, soils, land use/land cover, and watershed boundaries and was created using a hybrid combination of computer codes (VB.NET and Fortran) to permit interfacing with GIS and an existing graphical user interface. A parameter sensitivity analysis of the model indicated the Manning roughness coefficient and hydraulic conductivity are the most important parameters. A calibration and validation step was performed for a large urban watershed and the model was found to provide very reasonable results given the rapid deployment and limited data requirements.

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