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DEM-based modelling of surface runoff using diffusion wave equation

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Abstract

A digital elevation model (DEM)-based overland flow routing model was developed for computation of surface runoff for isolated storm events. The model operates on a grid or cell basis and routes the rainfall excess generated over the cells, following the DEM-derived drainage paths, to the catchment outlet. The rainfall excess for each cell of the catchment was computed using the Philip two-term infiltration model utilizing the physical properties of the cell. The overland flow was described by a finite volume-based numerical solution of the diffusion wave approximation of the St Venant equations. The cell physical properties, such as topographic characteristics, land use, soil, etc., were extracted from published maps for discretized cells of the catchment using a Geographic Information System. The results of model application indicate that the model satisfactorily predicted the runoff hydrograph. The cell-based structure of the model allowed for generation of spatially distributed catchment information in terms of the model-computed variables, such as the depth of flow and discharge.

Keywords: Digital elevation model; Diffusion wave routing; Distributed model; GIS; Overland flow; Rainfall runoff modelling; Watershed model

1. Introduction

The generation of runoff from a catchment results from a complex interaction of climatologic and catchment characteristics, and this interaction influences the spatial and temporal variability of runoff. The catchment characteristics influencing the generation of runoff include morphology (area, width, shape, slope, and channel network), soil, vegetation cover, and underlying geology. The knowledge of spatial and temporal variation of model inputs and controls and their use in a distributed modelling enhances our understanding and capabilities to simulate complex hydrological processes. The remote sensing and Geographic Information System (GIS) technologies are now well-established tools for generation and interpretation of spatially distributed information required for use in distributed hydrological models (Julien et al., 1995; Schultz and Engman, 2000; Vieux, 2001). The GIS offers new

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opportunities for the collection, storage, analysis, and display of spatially distributed hydrological data.

The rainfall-runoff process is generally investigated with the aid of mathematical models. These models integrate existing knowledge into a logical framework of rules and relationships (Moore and Gallant, 1991) and can be used to (1) improve our understanding of environmental systems, that is, as a tool for hypothesis testing, and (2) provide predictive tools for management (Beven, 1989; Grayson et al., 1992). Recently, there have been attempts to take advantage of GIS capabilities for runoff modelling. Hydrological models with a spatial structure based on digital terrain models have been developed by Beven and Kirkby (1979), Beasley et al. (1980), Abbott et al. (1986), Moore et al. (1988), Young et al. (1989), Grayson et al. (1992), Palacios-Velez and Cuevas-Renaud (1992), Wigmosta et al. (1994), Vieux and Gaur (1994), Julien et al. (1995), Bouraoui and Dillaha (1996), Wang and Hjelmfelt (1998), Johnson et al. (2000), Fortin et al. (2001), Jain (2002), and Karssenberg (2002), and others. New models compatible with remote sensing and GIS data have also been developed recently (Leavesley and Stannard, 1990; Schultz, 1990; Wigmosta et al., 1994; Julien et al., 1995; Desconnets et al., 1996; Dupont et al., 1996; Olivera and Maidment, 1999; Fortin et al., 2001; Karssenberg, 2002). In most of these models, the grid-based catchment discretization procedure was followed and the same has been adopted for present study.

Comprehensive reviews of past efforts and current trends in using digital terrain models and GIS to perform hydrological analyses are available in Vieux (1991), DeVantier and Feldman (1993), Moore et al. (1993), Singh and Fiorentino (1996), and Vieux (2001). Singh and Woolhiser (2002) have presented a historical perspective of hydrological modelling and new developments and challenges in watershed models. In Singh (1995) and Singh and Frevert (2002a,b) are included a slew of models based on GIS and digital elevation models (DEMs).

In most process-based distributed models reported in the literature, mathematical relations describing processes, such as interception, infiltration, evaporation, surface and sub-surface flow, etc. are generally used depending on the purpose and the complexity of the model. The use of kinematic wave approximation of the Saint Venant equations is common for describing overland flow of water (Singh, 1996). However, in a grid-based catchment discretization, the cells with zero gradient of the terrain is a common occurrence in flat areas. These cause discontinuities in the solution based on the kinematic wave approximation, because the terms discarded may have afforded a complete solution while their absence causes mathematical discontinuities. Generally, a special treatment is required to obtain the solution to the kinematic wave representation for runoff on a spatially variable surface (Vieux, 2001). This difficulty may be overcome by using the diffusion wave analogy. Mathematically, the diffusion term smoothens out numerical discontinuities that occur due to the change in parameters typical of most natural catchments. Therefore, for the present study the diffusion wave analogy was adopted for the purpose of flow routing.

The objective of this study was to develop and test a DEM-based overland flow routing model for computation of surface runoff from isolated storm events using the diffusion wave approximation. Spatially distributed information for model inputs, such as topography, soil, land use, etc. for each of the discretized cells of the catchment was provided through a GIS. The catchment DEM was utilized to derive the flow direction and the computational sequencing for flow routing for each of the discretized cells of the catchment represented as a proper hydrologic cascading system. A finite volume-based numerical solution of the diffusion wave approximation of the St Venant equations for DEM-derived overland flow and channel flow was developed. Using the Philip (1969) infiltration model, infiltration was computed on a cell basis. The model produces in spatial and temporal domain the flow discharge, depth, and velocity due to isolated rainfall events on a catchment.

2. Model formulation

For developing a DEM-based surface runoff model, the catchment was represented as a matrix of cells formed through discretization of the catchment using square grids as shown in Fig. 1. Each discretized cell of the catchment had eight possible flow