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Distributed Catchment Modelling with Efficient Computation of Unsaturated Flow

Graduate School University of Tokyo Student Member Guangheng NI
I.I.S. University of Tokyo Member S. HERATH
I.I.S. University of Tokyo Member K. MUSIAKE

1. INTRODUCTION

In hydrologic modelling, soil moisture flow in unsaturated zone is of particular importance because it connects surface flow and groundwater flow by controlling infiltration, surface runoff and recharge to groundwater. Due to the high nonlinearity of governing equations and soil parameters, the simulation of unsaturated zone takes a lot of computation time. Therefore proper treatment of unsaturated zone is critical to the model formulation. In this study, a distributed catchment model is established by coupling hydrologic models for surface flow, subsurface flow, and groundwater flow. The subsurface flow simulation is carried out by applying Richards' equation only to the top soil zone and adopting an efficient simplified process model for the soil moisture flow in the underlying zone. The catchment model is applied to a small experimental basin with all the parameters determined from observed data or published references.

2. MODEL DESCRIPTION

The catchment model consists of mainly three parts, surface flow component, subsurface flow component and groundwater flow component, as presented in Figure 1. For simulation, the whole catchment is discretized into rectangular grids of equal size in horizontal direction and each grid has a top soil zone, a deep soil zone and a groundwater zone in vertical direction. By carrying out computations of surface flow and subsurface flow grid by grid, and numerical approximation of groundwater flow in the solution domain, catchment simulation can be realized.

In the model, the flow direction of both surface and subsurface are assumed to be consistent with the topography and is computed using ARC/INFO GIS software.

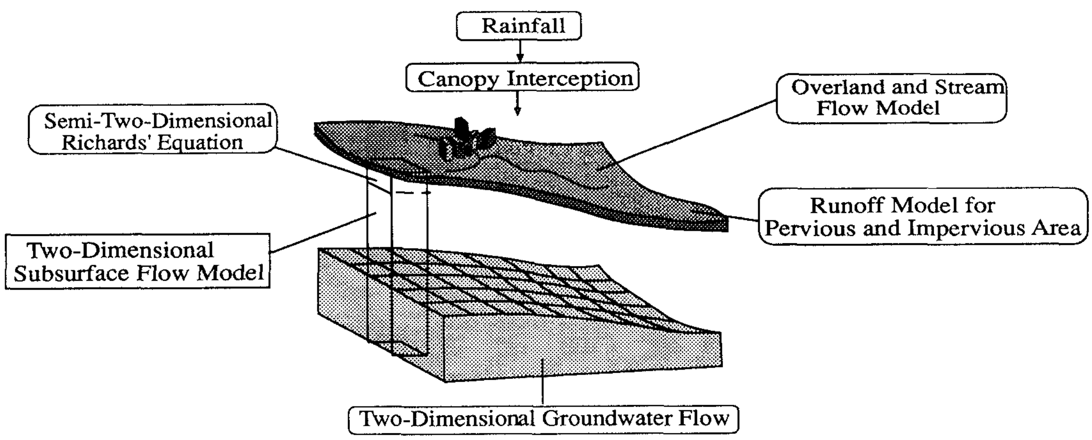

Figure 1: Schematic Representation of the Catchment Model

2.1 Surface Flow Component. Surface runoff generated when rainfall rate exceeds the infiltration capacity of soil, or generated when groundwater rises up and prevents further infiltration, is routed down either as overland sheet flow or as channel flow, depending upon whether there is a stream flowing through. The kinematic wave method is used to simulate the over land and stream water routing.

2.2 Subsurface Flow Component. To make it computationally easier while maintaining the physical flow characteristics, the subsurface flow component is further divided into two parts, top soil zone and deep soil zone, based on the observations and numerical simulation results. For the top soil zone, one-dimensional Richards' equation is used and for the deep soil zone a simple storage-discharge equation is adopted to simulate the flow process through it.

Flow in top soil zone The water head h-based one-dimensional Richards' equation is adopted and the simulation is made semi-two-dimensional by introducing the lateral flow exchange with its neighbor grids which are calculated by equation 1. The thickness of the top soil zone depends on hydrological and soil conditions and usually a thickness between $1.0m - 2.0m$ is adequate.

$$q_L = k(h) * Slope \tag{1}$$

where q_L is lateral flow, k is soil hydraulic conductivity, h is water pressure, *Slope* is the land slope of grid.

Flow in deep soil zone In this zone, soil moisture is assumed to change gradually and soil moisture flow is principally in vertical direction. For simulation, the deep soil zone is discretized into a few layers, and for each layer the relation between the flux out of the layer, average conductivity, and the storage changes are written as,

$$V\_out(j) = k(S) \tag{2}$$

$$\Delta S(j)/\Delta t = V\_in(j) - V\_out(j) \tag{3}$$

where $V\_in(j)$ and $V\_out(j)$ are flux into and out of layer j respectively. $k(S)$ is averaged conductivity for the simulation time step (Δt) and is calculated from storage S. The flux from the top soil zone is taken as input to the deep soil zone and the flux out from the last layer in the deep soil zone is the recharge to groundwater. After each calculation of the groundwater component, the depth of deep soil zone is adjusted according to the groundwater head.

2.3 Groundwater Flow Component. In this study the groundwater is treated as a multi-layered two-dimensional horizontal flow, where each layer could be either a homogeneous or a heterogeneous aquifer, with shifting conditions between unconfined and confined condition. The spatial and temporal variation of the hydraulic head is described mathematically by the nonlinear Boussinesq equation. Leakage is included as a vertical flow through aquitard and the amount of leakage depends on the hydraulic gradient across the aquitard, thickness and vertical hydraulic conductivity of the aquitard. The governing equation of groundwater flow is given as equation 4,

$$S_s \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}[T\frac{\partial h}{\partial x}] + \frac{\partial}{\partial y}[T\frac{\partial h}{\partial y}] + R - W + L_{in} - L_{out} \tag{4}$$

where $S_s(x, y)$ is specific storage or specific yield; $h(x, y, t)$ is phreatic surface level; T is transmissivity. $R(x, y, t)$ is vertical recharges into groundwater;W is withdraw; L_{in} and L_{out} are leakage from above aquitard and leakage out of low aquitard respectively. The simulation domain is discretized into quadrangular elements and finite element approximation is used to solve the governing equation numerically.

3. MODEL APPLICATION AND RESULT

The established catchment model was applied to a small experimental basin which is of a area of 12 ha for verification. After discretizing the area into grids of 25.0-meter size, the soil map was overlaid on it. All the parameters used in simulation were determined either from measured data or from published references, without any fitting.

No data for initial condition was available and instead, the simulation result of one year with a small flux input at the upper boundary was used. A good agreement between observed and simulated hydrograph was obtained. In addition to discharge, the model can provide a lot of information on hydrologic processes, like soil moisture, evaporation, groundwater table distribution over the basin. Simulation was carried out for the rainy season of 1988 and the soil moisture distribution at the end of simulation is shown in Figure 2 as an example of model output.

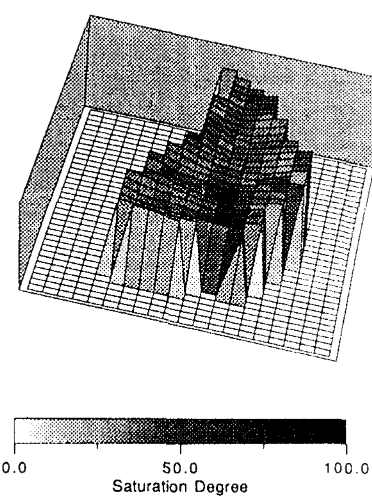

Figure 2: Moisture Distribution Draped on Topography

REFERENCE

NI, G., HERATH, S. and MUSIAKE, K.: Numerical Simulation of Hillslope Infiltration and Discharge into River, 38th Japanese Conference on Hydraulics, pp.191-196 (1994).