Accumulation of Streamflow in Complex Topography by Digital Terrain Models

복잡한 지형에 있어서 디지털 지형모델을 이용한 유출량계산

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요 약

본 연구에서는 지표면유출과 중간유출의 수문학적과정을 함께 모의발생 시키는 합성 유역모델이 제시되었다. 본 모델은 디지털지형모델과 상호 연결되도록 하였으며 지형이 복잡한 지역에서도 유출이 시간과 공간적으로 누가계산되어 이 분야의 조사연구에 필요한 정보를 제공할 수 있다. 본모델을 이용 유역의 불투수층 위에 분포해있는 토양의 중간유출과 토양수분의 계산 및 침투/용탈의 과정을 모의 발생시킬 수 있다.

I. Introduction

1. Model Purpose

The past decade or two has seen a wealth of watershed model development, ranging from single lumped parameter linear response models to complex parametric or deterministic nonlinear models. These latter models attempt to simulate the surface and subsurface movement of water in great detail. Much argument has been heard concerning the utility of the more complex models in practical applicative capability as compared to the more simple models. An infinite number of factors influences the accumulation of flow on real watersheds. No existing model would be of practical use if it were not due to the fact that the net result of all of these factors is a retardation of the progress of individual water particles, arriving as precipitation, in their journey to the watershed outlet. Fortunately, the infinite variety of flow paths result in a combined outflow that is effectively an weighted average measure of this infinite variety at any instant in time, or for short segments of time. If all of these flow paths behave in the same way, independent of time, then lumped parameter linear models would be the best choice. As everyone knows, real watersheds are highly nonlinear

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in their runoff response. This nonlinearity is due to a vast number of factors. Some factors are more important than others. The purpose of the research effort, and hence the model being presented herein, is to investigate the relative influence of some of the more important nonlinear factors.

The model presented herein is referred to as a synthetic model in an attempt to differentiate it from practical models. It is not intended for practical application, but only to investigate the effects of space and time variant surface runoff, soil moisture, interflow of shallow groundwater flow, and infiltration exfiltration over real topographic surfaces. The only real world data to be used are digital terrain data.

The digital terrain modeling technique is illustrated in Fig. 1. Rectangular grid digital terrain data is first contoured using an automated contouring package. The contour interval is chosen small enough to adequately represent the changing hillside slope, showing slope breaks and divides. The resulting digital contour point strings are next edited, removing excess points, and then stitched together with a triangulated mesh as shown in Fig. 1. The reason for selecting an irregular triangulated network digital terrain model is to provide a geometrically more precise representation of a complex surface. The movement of water downslope corresponds to the gradient direction of each triangle lying along the flow path. The combined surface-subsurface model treats each triangle as an equivalent rectangle with equal area and aspect ratio, thereby producing a sequential series of plane surfaces downslope, culminating in a stream segment. The stream segments then accumulate the flow as a drainage tree until the watershed outlet is reached.

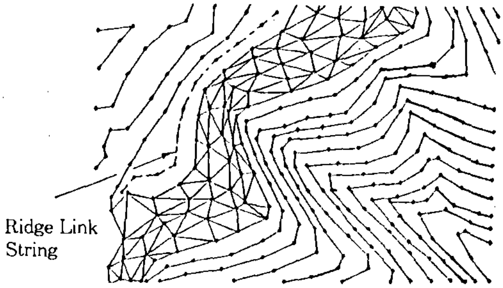


Fig. 1. Partial triangulation of a Watershed Segment using Contours

2. Background

Most popular watershed models often used by hydrologists have utilized a Hortonian concept of runoff generation, which state that runoff can be generated when the rate of rainfall exceeds the absorptive capacity, or infiltration rate of the soil. Ground water flow is treated as baseflow, which will respond after a long delay, a few days of weeks after, but not during the storm. Actual observations of rainfall-runoff events, in many cases, contradict this approach showing a subsurface response within a delay as short as a few minutes, or a fraction of an hour. It appears to be evident that rainfall which exceeds the infiltration rate of the soil will run off, but quick runoff responses are infiltration caused by relatively light rainfalls that are much lower than the infiltration rate. Therefore, the Hortonian concept can not be generally true and at best draws a partial picture of the mechanisms involved in the rainfall-runoff process.

The mechanisms in the generation of

streamflow have been traditionally identified as overland flow, interflow which is saturated near surface flow, and ground water flow which displacement of stored water from upslope[5,8,10]. Overland flow may occur when the rainfall intensity exceeds the infiltration rate of the soil in Hortonian concept, or when the saturation of near surface zone leads to seepage flow which is exfiltration. Hortonian overland flow predominates on those soils having low infiltrability. The upland watershed of hilly area, which is of major interest here, is likely to have high infiltration rates feeding a shallow subsurface interflow. Therefore, simulating runoff by accounting for only overland flow is not appropriate in this situation. It has been suggested that, in the small upland catchments, the interflow along soil layers should be taken into account[5,8].

The variable source area concept proposed by Hewlett[1] may be a better way to interpret and explain runoff accumulation from upland watersheds. Many current rainfall-runoff modeling techniques are based on the assumption that a watershed is lumped hydraulics system. In other words, that streamflow is generated by processes which operate uniformly over the catchment surface, and therefore the catchment has a source area equal to the basin area. Although popular models such as TR-20 of Soil Conservation Service and HEC-1 of Corps of engineers discretize the watershed into several subwatersheds, each subwatershed is still a large lumped hydraulic system that is still not small enough to demonstrate the concept of variable source flow component. Shanholtz et al.[6] have developed a rainfall-runoff model using smaller subareas which are individual elements in a finite element solution technique. Without the capability of accounting for the interflow, the model can only best describe the overland flow, but not the variable source area. The information contained in the digital terrain model can be used to discretize the watershed into many very small finite elements as shown in Fig. 1. Each element can be treated as a contributing source area. This paper proposes a synthetic rainfall-runoff model which can account for both overland flow and interflow, and the infiltration exfiltration process between the two. It utilizes the complex topographic information provided by high resolution digital terrain models.

II. General Descriptions of the Model

Each triangular element in the digital terrain model is assumed to maintain hydrologic and topographic homogeneity within its boundary.

The orientation of flow direction, slope, hydrologic and topographic characteristics of the element are stored in the digital terrain model files. Therefore, the contributing elements to each stream segment can be established. By suitable transformation as explained earlier, the contributing elements can be treated as a series of planes over of through which the flow passes. Thus the water is routed continuously through a combination of overland flow and interflow from the uppermost plane element down to the stream segment.

Kinematic wave routing is used when overland flow occurs, while interflow occurs according to Darcy's law. The storage-discharge history of the entire hillslope system of rectangular elements is based on a water balance i.e. mass continuity.

An expandable and shrinkable interflow zone is assumed to adequately represent subsurface flow. The zone thickness will increase or decrease depending on the availability of water supply and the rate of soil moisture draining downslope, which is equivalent to the mass balance principle. The vertical profile of the element is shown in Fig. 2. It is assumed that the maximum extension rate of the interflow zone is a function of its thickness and the initial hydraulic conductivity which is equivalent to the infiltration rate of the soil as follows:

$$f = f_0 \exp(-kH) \cdots\cdots\cdots\cdots (1)$$

where f = extension rate of interflow zone, m/min, f_0 = extension rate of interflow zone when its thickness is equal to zero, m/min, k = a constant which corresponds to initial hydraulic conductivity), and H = the thickness of interflow zone, m.

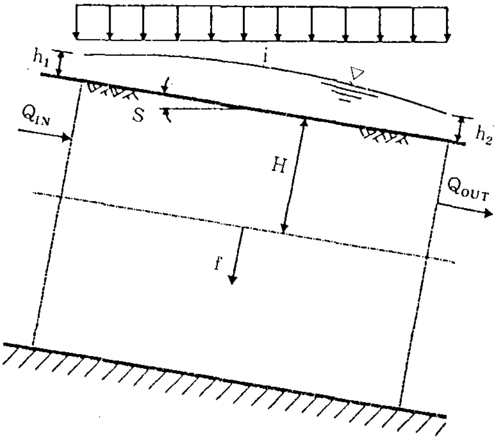


Fig. 2. Vertical Profile of Element

The upper bound of the zone is the soil surface and the lower bound is the wetting front which will vary with time. The movement of subsurface water downslope follows Darcy's law which states that the interflow rate will depend on the saturated thickness, soil horizontal hydraulic conductivity, and the surface slope, or hydraulic gradient as follows:

$$Q = KSH \cdots\cdots\cdots\cdots (2)$$

where Q = interflow rate along the slope, K = hydraulic conductivity along the slope, and S = surface slope.

The possible sources of water input to the subsurface system of each element are the subsurface flow from the upslope element, and availability of overland flow or rainfall for infiltration, which treated as lateral inflow. Exfiltration flow and interflow to the adjacent downslope element are sources of water output. The governing water balance in the subsurface system will determine whether the interflow zone of the present element should extend or shrink, thus determining the lateral inflow rate term on the surface.

The surface flow is described by the well-known Saint-Venant hydrodynamic continuity and momentum equations. The equation of continuity in conservative form can be expressed as follows:

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} + \frac{\partial u}{\partial x} = q \cdots\cdots\cdots\cdots (3)$$

and the equation of momentum is also expressed as follows:

$$\frac{1}{g}\frac{\partial u}{\partial x}+\frac{u}{g}\frac{\partial u}{\partial x}+\frac{\partial h}{\partial x}=S-S_f-\frac{q}{gh}(u-u_x)\cdots(4)$$

where q=lateral inflow per unit length of flow plane, t=time, x=distance along downslope direction, H=depth of overland flow, u=velocity, u_x=x component of the velocity of the lateral inflow, g=acceleration due to gravity, S=surface slope, and S_f= friction slope.

However, to solve the complete equations, one will encounter a system of non-linear hyperbolic partial differential equations. Due to the complexity and difficulty of solving the full equations, the kinematic wave approximation was applied to the momentum equation. The justification of this procedure is well documented in the literature[2,3,7,9]. The kinematic wave approximation requires that there has to be a balance between the gravitational and frictional forces involved in the momentum equation and it can be represented by a uniform flow equation such as Manning's equation as follows:

$$u=\frac{1}{n}h^{\frac{2}{3}}S^{\frac{1}{2}} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

where n=Manning's n, then the continuity equation can be rewritten as follows:

$$\frac{\partial h}{\partial t}+\frac{5}{3}ah^{\frac{2}{3}}\frac{\partial h}{\partial x}=q\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (6)$$

where. $a=\frac{1}{n}S^{\frac{1}{2}}$.

The non-linear hyperbolic Equation(6) can then be solved by applying backward finite difference scheme in time t and distance x. The scheme is shown in Fig. 3, and the difference equation of becomes as follows[6]:

$$h_{m,n}=\frac{1}{1+\lambda\alpha}[h_{m,n-1}+\lambda\alpha h_{m-1,\,n}+q_{m,n}\Delta t] \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (7)$$

where $a=\frac{5}{3}\alpha_m h^{\frac{2}{3}}_{m,n-1}; \lambda=\frac{\Delta t}{\Delta x}$

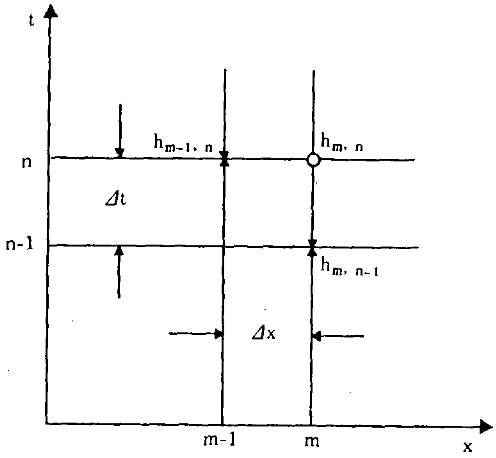


Fig. 3. Finite Difference Scheme

The linear stability of the scheme is unconditionally stable, which is easily proved by the method of Von Neumann[4]. Since the initial conditions and boundary conditions of the utmost element are known, the depth of flow on the present element at the current time can be directly computed from the depth of flow on the element at previous time step and the depth of flow on upstream element at current time step. Therefore, the solution can be obtained by propagating downstream. The overland outflow of the element is then calculated by using Manning's equation.

Before propagating to the next element, the mass balance is checked for the present element, including both overland flow with lateral inflow, and interflow. If an error correction is required it is needed distributed over the whole element.

The computations continue and advance to the adjacent downslope element until the stream segment is encountered. The accumulation of the streamflow is determined as the sum of the outflows of overland flow and interflow of the last element. The whole procedure is then repeated in the next time step until the maximum time specified. Fig. 4 shows the schematic flowchart of the model.

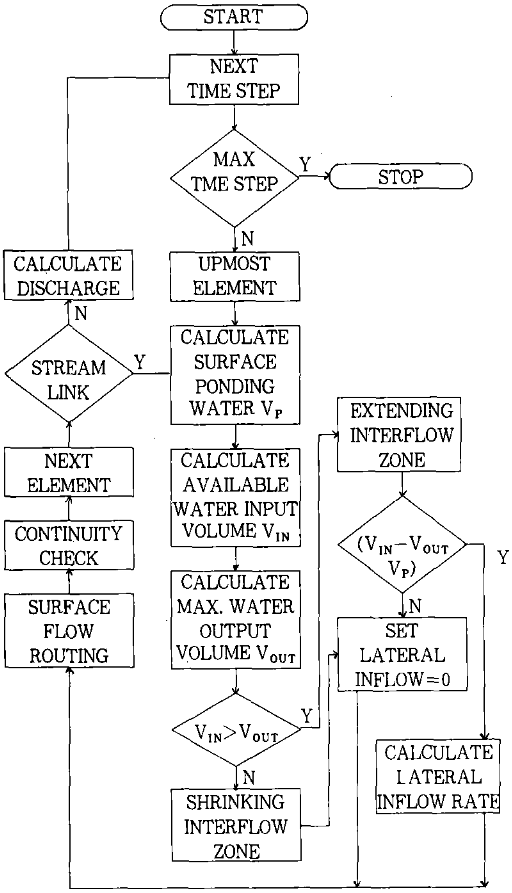
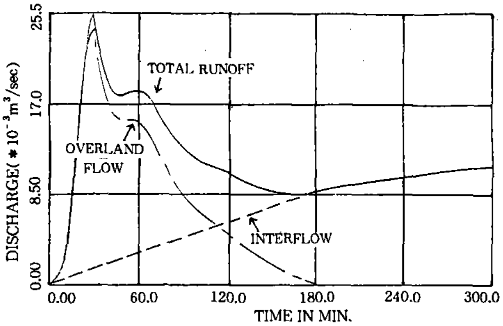


Fig. 4. Schematic Flowchart of the Model

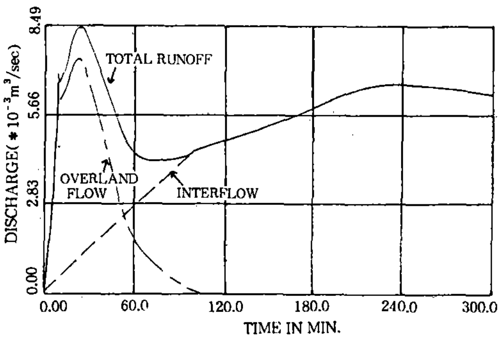
III. Results and Discussions

A synthetic series of ten planes has been used to test the performance of the model. Two cases of spatial uniform rainfalls are exercised. One of them is a temporal uniform rainfall of 10cm/hr(4inch/hr) intensity with duration of 20 minutes, the other is a time varied rainfall which has a intensity of 10cm/hr(4inch/hr) in the first 20 minutes, 15cm/hr(6inch/hr)in the next 20 minutes followed by 10cm/hr(4inch/hr) in the last 20 minutes. The total duration is 60 minutes. The resulting hydrographs of the streamflows are shown in Fig. 5 which indicates a significant contribution of the interflow to the streamflow.

Fig. 6 shows the saturation history of the sloping soil exaggerating in the vertical scale.



TIME VARIED RAINFALL



TEMPORAL UNIFORM RAINFALL

Fig. 5. Hydrographs of Streamflows

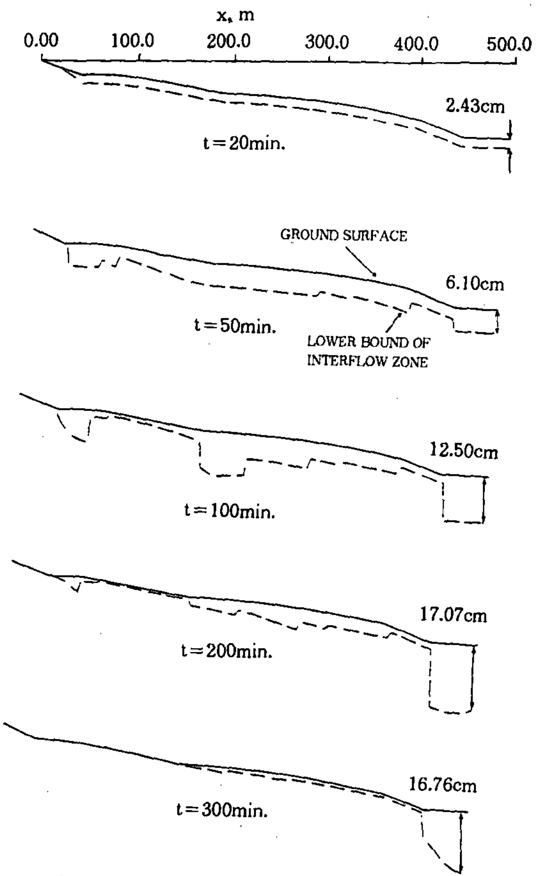


Fig. 6. Time Variation of Soil Moisture

As shown in Fig. 6, the pocket and band saturations of soil on the hillslope, stated by Hewlett[1], are produced by the model. It should be noted that the saturated conditions are reached first at the concave slope transitions, producing local exfiltration, equivalent to hillside springs observed on real watersheds.

Ⅳ. Conclusions

A synthetic rainfall runoff model which can account for both overland flow andinterflow, and the infiltration-exfiltration process between the two is proposed. The adaptation of the model is tested using a synthetic series of ten planes and two cases of spatial uniform rainfalls.

From the present investigation, the following conclusions have resulted;

- Rainfall which exceeds the infiltration rate of the soil will run off, but quick runoff responses are sometime caused by relatively light rainfalls that are much lower than the infiltration rate.
- In the small upland catchment, the interflow along soil layers should take into account.
- The model demonstrated the ability to simulate the detail flow behavior observed in actual upland watershed.
- The model also demonstrated the ability to display both spatial and temporal variation.

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