QUASI-PHYSICALLY-BASED DISTRIBUTED RAINFALL-RUNOFF MODEL INCORPORATING GIS DATA

- MODEL STRUCTURE DEVELOPMENT -

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ABSTRACT: DISCAS model(DIStributed CAScade model)was developed to correlate the input and output of basin by taking into account of the spatial variations of the physical characteristics of the catchment and also the time-space variations of relevant meteorological data. Model divides the catchment area into various small square subcatchments, each small subcatchment has own precipitation-receiving area which equals to the area of square grid and the physical characteristics are assigned corresponding with its conditions. GIS(Geographical Information System)data such as elevation, landcover, soil type and channel route is utilized to be the data base of the catchment for such model.
Keywords: DISCAS, distributed cascade, spatial variations, time-space variations, precipitation-receiving area, GIS

INTRODUCTION

Hydrologic mathematical models have been used widely to transform basin input to be output by incorporating a set(lumped model) or sets (distributed model) of appropriate parameters. Lumped parameter model trends to misinterpret the runoff phenomena of large scale watersheds which their physical characteristics vary from point-to-point over whole basin, instead of that, distributed model has been introduced by dividing the catchment area into many small subcatchments. **Sugawara et al.**(1984) introduced conceptual distributed tank model by dividing into zonal subbasins and different sets of model parameters are assigned to each zone. **Hata**(1976) proposed a series of distributed linear storage tanks in which their parameters are derived from kinematic wave model for both surface and subsurface flows, the sets of such physically-based parameters are estimated for all tanks . **Onstad and Jamieson** (1970) modeled the whole catchment into two subcatchments and for each subsystem, all runoff components are considered. The coefficients of linear storage functions are determined by considering landuse and soil conditions. **Gupta and Solomon**(1977)s' model accounts for the spatial distribution of physical characteristics of large scale watersheds and includes the time-space variation of basin input, the catchment is allocated into a number of small uniform square grids and within each grid, those characteristics are assumed homogeneous but may differ from the other grids. **Abbott et al.**(1986) introduced full physically-based SHE model, the model distributes watershed into many small gridded subcatchments and the parameters of each grid are estimated as the functions of landcover and soil conditions. Flow processes are formulated by the partial differential equations of continuity and momentum or by empirical formulae obtained by experiments.

PROPOSED MODEL STRUCTURE

The proposed model as shown in Fig.1 includes all components of hydrological processes such as interception, infiltration, overland

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flow, channel flow, root zone and groundwater components. These components except groundwater are considered as distributed system by dividing whole catchment into many small square subcatchments and each cell is considered separately. Within each grid the physical characteristics are assumed to be uniform over that grid area but may differ from the others. Land phases and soil types are assigned to every cell by using GIS data file KS202 and KS156 respectively. The parameters of interception and infiltration components are valued corresponding with landcover and soil types respectively and both types are used to define the appropriate parameters for root zone component. Overland and channel flow components, flow resistance coefficients are distributed to every grid by assuming depend only on landcover types and the slopes of flow planes are calculated by adopting elevation data file KS110. The flow directions of interception and infiltration components are considered only for vertical direction but for overland and channel flow components, horizontal flow direction is prominent leading to neglect the other directions, both directions are considered in root zone component. Horizontal grid flow directions are drawn by using maximum descend method and elevation data file KS110. Obtained drainage networks form the flow pattern of cascade planes which have the lengths equal to flow path lengths and widths are equivalent to constant grid area divided by their flow path lengths as shown in Fig.2. Groundwater component is considered as lumped model.

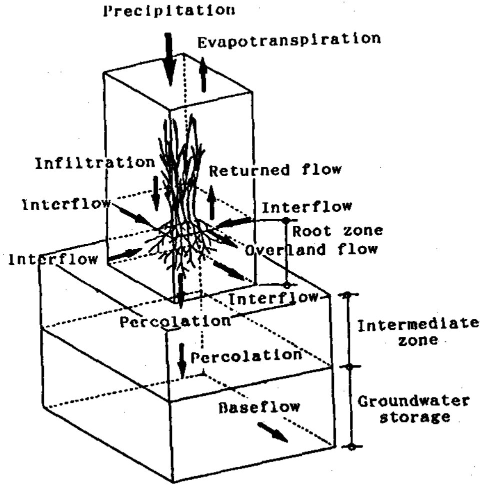

Fig.1 Model configuration

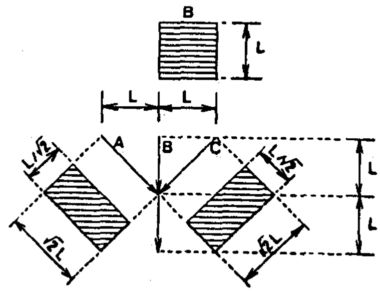

Fig.2 Plane size assignment

MODEL COMPONENTS

This DISCAS model comprises with six submodels or components and each pair of components or grids is connected by vertical or horizontal flow directions. All components of the model are described hereunder.

- Interception component

The interception predictive model of the model calculates net precipitation reaching the ground surface through forest canopy. The part of precipitation that reaches ground surface by stem flow is considered to be small compare to that from canopy and not included in this component. The presented model is the modified one from the original model proposed by **Rutter et al.(1975)**. The rate of change of the water on canopy is,

$$\frac{dC}{dt} = P_n - D_c \qquad \dots\dots\dots\dots\dots\dots\dots(1)$$

$$P_n = (1-p)P - E_{op} \qquad \text{for} \quad C \geq S_{max}$$

or

$$P_n = (1-p)P - \frac{C}{S_{max}} E_{op} \qquad \text{for} \quad C < S_{max}$$

and

$$D_c = k * e^{b(C-S_{max})}$$

Where C is water on canopy, k, b are model parameters, S_{max} is canopy storage capacity, P_n is net precipitation, D_c is drainage from canopy, p is the ratio of free throughfall, P is total precipitation and E_{op} is potential evaporation of free water surface.

Throughfall, T_f, to ground surface of each square grid can be obtained by,

$$T_f = p_d(D_c + p*P) + (1-p_d)P \qquad \dots\dots\dots\dots\dots(2)$$

Where p_d is the ratio of ground surface area covered by trees to the area of each square grid.

- Infiltration component

A part or perhaps all of throughfall which reaches the ground surface will infiltrate into the soil, this process is described by this component. **Mein and Larson**(1971) modified the original Green-Ampt equation to describe the infiltration phenomenon under steady rainfall intensity condition and the infiltration capacity is expressed as :

$$f_p = K_s\left(1 + \frac{IMD * S_{av}}{F}\right) \qquad \dots\dots\dots\dots\dots\dots\dots(3)$$

Where f_p is infiltration capacity rate, K_s is saturated hydraulic conductivity, IMD is initial soil moisture deficit, S_{av} is average suction at wetting front and F is accumulative infiltrated volume.

This component of the model modifies their model to simulate infiltration under unsteady rainfall or throughfall intensities which occur often during the period of hydrological simulation. Under this condition, the model will consider the ponding and non-ponding states of the ground surface at every time step. To reduce some complexities, the model considers the soil to be uniform one-layer profile.

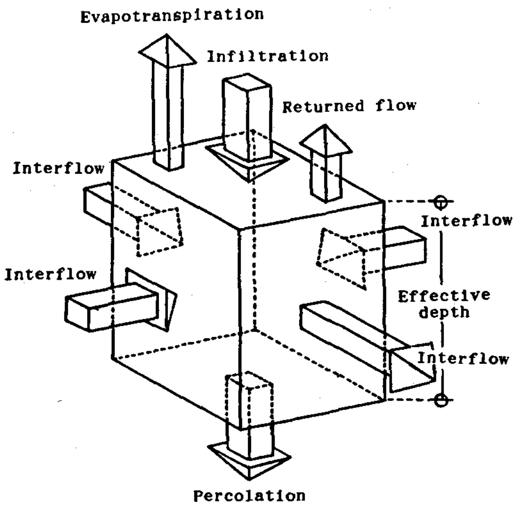

Fig.3 Root zone component

- Root zone component

This component receives infiltrated throughfall from infiltration component and interflows from the root zone components of its adjacent cells. The interconnecting directions between the considering cell and its neighbors are assumed same as the directions of surface flows. The root zone component of the model is shown in Fig.3 and some relationships of this component are,

$$T_{in}(t) = T_{if}(t) + \sum_{n=1}^{p(<8)} I_{tf}(n,t) \quad \ldots\ldots\ldots\ldots\ldots (4)$$

Where $T_{in}(t)$ is total inflow into considering cell at current time step, $T_{if}(t)$ is infiltrated throughfall at current time step and $I_{tf}(n,t)$ is interflow from n^{th} adjacent cell at current time step.

The total inflow is added to its storage and forms intermediate storage height which has moisture content Θ as:

$$RSDI = RSD(t-1) + T_{in}(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where RSDI is intermediate storage height and RSD(t-1) is the storage height at previous time step. Actual evapotranspiration is subtracted first from that intermediate height. The evapotranspiration model of this component is proposed as the following equations,

$$E_a = 0 \quad \text{for} \quad \Theta \le \Theta_{wp}$$

$$E_a = E_p\left[\frac{1}{2} + \frac{\sin}{2}\left\{\pi\left(\frac{\Theta - \Theta_{wp}}{\Theta_{fc} - \Theta_{wp}} - \frac{1}{2}\right)\right\}\right]^{C_e \cdot E_p} \quad \text{for} \quad \Theta_{wp} < \Theta < \Theta_{fc} \quad \ldots\ldots\ldots (6)$$

$$E_a = E_p \quad \text{for} \quad \Theta \ge \Theta_{fc}$$

Where E_a and E_p are actual and potential evapotranspirations, Θ is soil moisture content at current time step, Θ_{wp} and Θ_{fc} are soil moisture contents at wilting point and field capacity respectively and C_e is model parameter. Returned flow, $R_{tf}(t)$, is defined as the amount of water forced to ground surface when the root zone is saturated and can be expressed by,

$$R_{tf}(t) = RSDI - E_a(t) - \Theta_s * RD_e \quad \ldots\ldots\ldots\ldots\ldots (7)$$

otherwise $R_{tf}(t) = 0$ if eq.7 ≤ 0

Where Θ_s is saturated moisture content and RD_e is effective root zone depth.

Interflow and percolation occur when the soil moisture content is greater than its field capacity and their rates depend on nonlinear storage functions and are shown by the following equations.

$$I_{tf}(t) = k_i\left(\frac{\Theta - \Theta_{fc}}{\Theta_s - \Theta_{fc}}\right)^{\beta_i}(RSDI - E_a(t) - R_{tf}(t) - \Theta_{fc} * RD_e) \ldots\ldots\ldots (8)$$

and for percolation term,

$$P_{co}(t) = k_p\left(\frac{\Theta - \Theta_{fc}}{\Theta_s - \Theta_{fc}}\right)^{\beta_p}(RSDI - E_a(t) - R_{tf}(t) - \Theta_{fc} * RD_e) \ldots\ldots\ldots (9)$$

or

$$P_{co}(t) = K_s\left(\frac{\Theta - \Theta_{fc}}{\Theta_s - \Theta_{fc}}\right)^{\alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

$P_{co}(t)$ is set to the lower one between eq.9 and eq.10.

Where k_i, β_i, k_p, β_p, are model parameters and α is an empirical parameter which has values equal to 3.3(after **Averjanov**, 1950) or 3(after **Huggins et al.**, 1966).

- **Overland flow component**

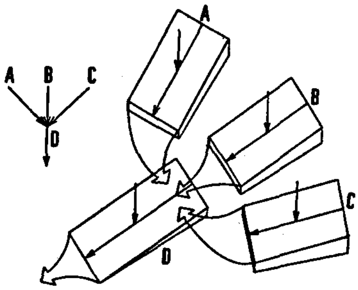

Fig.4 Overland flow component

Excess throughfall and returned flow are the input of this component and will be routed through cascade plane by kinematic wave theory until reach channels. The upstream conditions of considering plane are defined by the downstream conditions of its upstream planes by summing all downstream discharges that feed into this plane and is shown in Fig.4 and will form upstream discharge of this plane. The upstream discharge and its physical characteristics such as length, width(see Fig.2), roughness, elevation are used to calculate upstream depth and the downstream conditions can be found by applying kinematic wave routing. For sheet flow, the continuity equation is

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = T_{ec} + R_{tf} \quad \ldots\ldots\ldots\ldots\ldots\ldots(11)$$

and the momentum equation is reduced to Manning' s equation as

$$q = \frac{1}{n} h^{5/3} s^{1/2} \quad \ldots\ldots\ldots\ldots\ldots(12)$$

Where q is discharge per unit width, h is flow depth, n is Manning 's coefficient, s is the slope of plane, T_{ec} is excess throughfall and R_{tf} is returned flow. Equations 11 and 12 are used to calculate the flow conditions at the downstream of considering plane in advance time step by the following three schemes.

Scheme 1

The model applies the explicit finite difference scheme proposed by **Leclerc and Schaake**(1973) to solve eqs.11 and 12, the problems of stability and convergence are avoided by splitting the solution into two equations depending on Courant number.

Scheme 2

Another explicit finite difference scheme that was introduced to solve continuity and momentum equations is nonlinear scheme proposed by **Li et al.**(1975), this scheme was proved that is unconditional stable and convergence.

Scheme 3

Method of characteristic can also be applied to solve the flow conditions of cascade planes, the method traces the characteristic lines from upstream to downstream by selecting time step to be independent variable and obtains corresponding space step.

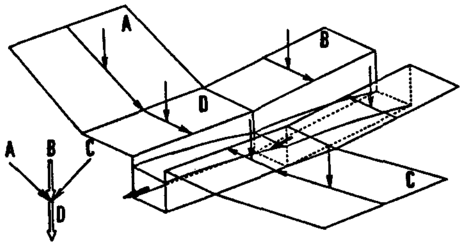

Fig.5 Channel flow component

- **Channel flow component**

Channel pixels receive flows from excess throughfall or returned flow which is generated by their own water-receiving areas, overland discharge and from interflows, these will be summed and called the lateral flow of the component, this lateral flow will be routed to the downstream end by using the same kinematic wave with overland flow component. The upstream flow conditions of considering segment is defined by combining the downstream discharge of all upstream segments that are connected to it, the schematic of this component is shown in Fig.5.

- Groundwater component

Only this component of the model is considered as lumped model, the model adopts the results obtained by **Ishihara** and **Takagi**(1965). The model considers baseflow to be two parts due to recharge and recessed baseflow as shown in Fig.6.

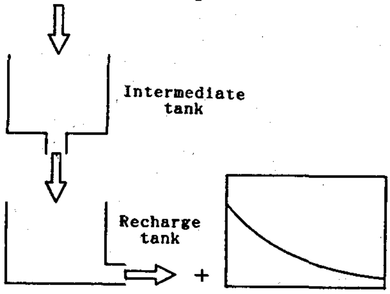

Fig.6 Groundwater flow component

CONCLUSION

Quasi - physically - based runoff model was developed, the model divides catchment into various small square grids, physical characteristics of each cell are assigned by using GIS data. The flow processes of all components are conducted at every point and combined through routing processes to form the runoff of the basin.

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