

## **A flash flood forecast model for the Three Gorges basin using GIS and remote sensing data**

**YANGBO CHEN**

*Department of Water Resources and Environment, Sun Yat-Sen University, Guangzhou 510275, China*  
[eescyb@zsu.edu.cn](mailto:eescyb@zsu.edu.cn)

**JIAXI HU**

*Department of Management, Three Gorges University, Yichang, Hubei 443002, China*

**JIE YU**

*Cascade Dispatching Centre, CTGPC, Yichang, Hubei 443002, China*

**Abstract** This paper presents a physically-based, distributed hydrological model for flash flood forecasting of the Three Gorges basin, which uses GIS techniques and remote sensing data. This model is divided into several sub-models, which include a Basin Digitization Model (BDM) to divide the whole basin into a number of square grid cells, Precipitation Feeding Model (PFM) to give grid-cell based precipitation, an Evapotranspiration Model (EM) to calculate cell-based evapotranspiration, a Runoff Production Model (RPM) to determine the runoff produced at cell scale, and a Runoff Routing Model (RRM) to route runoff to a basin outlet. This model mainly relies on remotely sensed data to physically derive model parameters, which is useful for ungauged or poorly gauged basins.

**Key words** digital elevation model; distributed model; flash flood forecast; GIS; remote sensing; weather radar

### **INTRODUCTION**

The Three Gorges basin, with a drainage area of 58 000 km<sup>2</sup>, is at the middle of the Yangtze River, China's largest river. The Three Gorges Dam, the largest dam in the world, is built at the end of the Three Gorges basin. The development of a better flood forecasting system is needed for the effective operation of the Three Gorges Dam. This paper presents a physically-based, distributed hydrological model for flash flood forecasting for the Three Gorges basin, which uses GIS techniques and remote sensing data. This model relies mainly on remotely sensed data to physically derive model parameters, which is a strong point for applications to ungauged or poorly gauged basins.

### **MODEL STRUCTURE**

The presented model uses GIS techniques and remote sensing data, including digital weather radar estimated precipitation, satellite sensed DEMs and vegetation information. The model is divided into several sub-models, which include a Basin Digitization Model (BDM), a Precipitation Feeding Model (PFM), an Evapotranspiration Model (EM), a Runoff Production Model (RPM) and a Runoff Routing Model (RRM).

In the BDM, a square-grid network DEM is employed to divide a study basin into a number of square grid cells, and every cell is considered as a sub-basin (called unit-basin), which consists of three layers: a canopy layer (CL), a soil layer (SL) and an underground layer (UL). For every grid cell, unique vegetation type and leaf area index are assigned. The flow direction, flow accumulation, slope, and flow length for every grid cell are calculated by ArcView based on the DEM.

The PFM treats precipitation information measured by digital weather radar and gauged precipitation. The digital weather radar rainfall reflectivity is first transferred into rainfall intensity and assigned to each grid cell. The precipitation measured by raingauges is given to each grid cell using the Thiessen Polygon method. The whole Three Gorges basin is not covered by the digital weather radar, therefore the spatial distributions of precipitation are created from weather radar and the raingauge information.

The EM calculates the grid-cell based evapotranspiration, which uses vegetation types and leaf area index as key parameters. The RPM determines runoff production that is formed by the Xinanjiang model at the grid-cell scale. Runoff is produced after the soil is saturated, and then divided into surface and subsurface runoff according to the steady infiltration rate.

The RRM routes the runoff to the basin outlet. The runoff routing is divided into hillslope routing that routes the surface runoff at each grid cell and river routing that routes the surface runoff through the river channel network. Hillslope routing is controlled by the flow velocity derived from the Manning equation, and river routing is governed by the flow velocity derived from the Darcy-Weisbach equation.

## **BASIN DIGITIZATION MODEL (BDM)**

### **Whole basin division**

The whole basin is divided into a number of unit-basins by using a Digital Elevation Model (DEM; EROS Data Center, 2001). The DEM used in this model is a square-grid network model, which divides the whole basin into a number of square grids. The grid is called a unit-basin that is treated as a uniform basin in which elevation, vegetation type, soil characteristics, and thus model parameters are considered to take the same values.

The unit-basin is then divided into three layers: the canopy layer, the soil layer and the underground layer. The canopy layer is from the terrain surface to the top of the vegetation. The evapotranspiration takes place in this layer, and the Evapotranspiration Model is used to determine the evapotranspiration at the unit-basin scale. In the soil layer, soil water is filled by the precipitation and depleted via evapotranspiration. The underground layer is beneath the soil layer, where water stored in the layer is assumed to move as steady flow.

### **Deriving parameters**

After the basin division, flow direction, flow accumulation, slope and flow length are derived from the DEM, which are important parameters for the Runoff Routing Model.

**Flow direction and runoff routing network** Runoff produced at each unit-basin

is assumed to flow to only one of its eight neighbouring unit-basins (Moore *et al.*, 1991). According to the flow direction of each unit-basin, a flow network is extracted. The network is referred to as a runoff routing network, which describes the runoff flow routes of every unit-basin from its centre to the basin outlet.

**Slope** The slope in each unit-basin is determined as:

$$\tan(\theta_i) = \frac{H_i - H_j}{D} \quad (1)$$

where  $\theta_i$  is the slope of unit-basin;  $H_i$  is the elevation of the  $i$ th unit-basin;  $H_j$  is the elevation of the destination unit-basin of the  $i$ th unit-basin, and  $D$  is the projected length of the unit-basin.

**Flow length** The flow length  $L_i$  in each unit-basin is calculated as follows:

$$L_i = \frac{D}{\cos(\theta_i)} \quad (2)$$

## PRECIPITATION FEEDING MODEL (PFM)

The Precipitation Feeding Model (PFM) is used to convert the precipitation measured by radar or raingauges to grid-cell based precipitation. The resolution of radar measured precipitation is usually  $1 \text{ km} \times 1 \text{ km}$ . The precipitation of each unit-basin simply takes the precipitation of the nearest radar grid. To give gauged precipitation to each unit-basin, the Thiessen polygons method is adopted. The Thiessen polygon consists of several polygons, and each polygon has one raingauge inside it. In this case, one polygon covers several unit-basins, and the precipitation of unit-basins inside the polygon is assumed to the same as that of the raingauge in it.

## EVAPOTRANSPIRATION MODEL (EM)

The land cover of the whole basin is classified into three types: water surface, soil surface (with no vegetation) and vegetated surface. According to the land cover classification, different evapotranspiration schemes are applied.

The water surface evaporation is calculated as the follows:

$$E_{i,t} = EC_i \quad (3)$$

where  $E_{i,t}$  is the evaporation of the  $i$ th unit-basin at time  $t$ , and  $EC_i$  is potential evaporation of water surface. The soil evaporation is calculated as follows:

$$E_{i,t} = ES_i \quad \text{if} \quad P_{i,t} > ES_i$$

$$E_{i,t} = P_{i,t} + (ES_i - P_{i,t}) \left( \frac{W_{i,t}}{WM_i} \right)^2 \quad \text{if} \quad P_{i,t} < ES_i \quad (4)$$

where  $E_{i,t}$  is the evaporation of the  $i$ th unit-basin at time  $t$ ,  $ES_i$  is potential evaporation of soil surface,  $P_{i,t}$  is the precipitation of the  $i$ th unit-basin at time  $t$ ,  $W_{i,t}$  is the storage

of the  $i$ th unit-basin at time  $t$ , and  $WM_i$  is the storage capacity of the  $i$ th unit-basin.

The vegetated surface evapotranspiration includes two parts: the canopy evaporation and transpiration. Canopy evaporation takes place during wet stages. In the period the canopy intercepts precipitation that is depleted via evaporation. The canopy evaporation is calculated as follows:

$$E_{i,t} = \min \left[ U_{i,t}, EP_i \left( \frac{U_{i,t}}{UM_i} \right)^2 \right] \quad (5)$$

where  $EP_i$  is potential evaporation over the canopy,  $U_{i,t}$  is the intercepted water at time  $t$ , and  $UM_i$  is the interception capacity, which is calculated as:

$$UM_i = k \cdot LAI_i \quad (6)$$

where  $LAI_i$  is the leaf area index of the  $i$ th unit-basin, and  $k$  is a coefficient that is taken as 0.2 mm (Xu *et al.*, 1994). The transpiration takes place when intercepted water is depleted, which is calculated as:

$$E_{i,t} = EC_i \left( \frac{W_{i,t}}{WM_i} \right)^2 \quad (7)$$

where  $EC_i$  is potential transpiration.

### **RUNOFF PRODUCTION MODEL (RPM)**

The Runoff Production Model calculates the runoff produced in each unit-basin. The runoff is classified into three types corresponding to the land cover types: runoff produced on water surface, runoff produced on soil surface and runoff produced on vegetated surface.

Runoff produced on water surface is calculated as:

$$R_{i,t} = \max(0, P_{i,t} - E_{i,t}) \quad (8)$$

where  $R_{i,t}$  is the runoff produced in the  $i$ th unit-basin due to the precipitation of  $P_{i,t}$ . Runoff production on a soil surface unit-basin is controlled by the saturation module. Net precipitation first fills out the soil layer, and only after the soil layer is saturated, runoff is produced. The runoff produced on a soil surface unit-basin is calculated as:

$$R_{i,t} = \max(0, P_{i,t} - E_{i,t} + W_{i,t} - WM_i) \quad (9)$$

The water balance equation of the soil layer is expressed as:

$$W_{i,t+1} = W_{i,t} + P_{i,t} - E_{i,t} - R_{i,t} \quad (10)$$

The method for calculating the runoff produced on a vegetated land surface is the same as a soil surface. First net precipitation  $P'_{i,t}$  is calculated as:

$$P'_{i,t} = \max(0, P_{i,t} + U_{i,t} - E_{i,t} + UM_i) \quad (11)$$

The precipitation first fills the soil layer, and only after the soil layer is saturated, the

runoff is produced, which is calculated as:

$$R_{i,t} = \text{MAX}(0, P'_{i,t} + W_{i,t} - WM_i) \quad (12)$$

The runoff produced on the water surface is considered as surface runoff. The runoff produced on the soil and vegetated unit-basins is divided into surface runoff and subsurface runoff. Subsurface runoff  $RG_{i,t}$  is controlled by the infiltration, which is calculated as:

$$RG_{i,t} = I_i \quad (13)$$

where  $I_i$  is steady infiltration rate. The difference between the total runoff and subsurface runoff is surface runoff  $RS_{i,t}$ :

$$RS_{i,t} = R_{i,t} - RG_{i,t} \quad (14)$$

### RUNOFF ROUTING MODEL (RRM)

The runoff routing includes surface runoff and subsurface runoff routing. The surface runoff routing is divided into river routing and hillslope routing. The river routing is the runoff routing along the river channel, while the hillslope routing is the runoff routing along the land surface, mostly along a slope. The division between hillslope routing and river routing is made through the flow accumulation threshold value. If the flow accumulation value is larger than the threshold value, then the surface routing within the unit-basin is river routing, otherwise it is hillslope routing. In this study, the threshold value is set to 200.

The most important parameter for surface runoff routing is the velocity of the runoff along the routing network. If the routing velocity on a unit-basin is known, then the routing time along the unit-basin is determined as:

$$\Gamma_i = \frac{L_i}{v_i} \quad (15)$$

where  $\Gamma_i$  is the surface runoff routing time along the  $i$ th unit-basin,  $v_i$  is the surface runoff routing velocity along the  $i$ th unit-basin. Summing up  $\Gamma_i$ , the total routing time of the  $i$ th unit-basin is determined.

If the river routing is considered as the one-dimensional open channel steady flow, the cross-section of the river channel is assumed as rectangular, and river bed slope is constant within a unit-basin, the river channel routing velocity can be derived as:

$$v = \sqrt{\frac{2gs}{fB}} \quad (16)$$

according to the Darcy-Weisbach equation, where  $g$  is gravity velocity,  $s$  is the river bed slope,  $B$  is the width of river channel, and  $f$  is Darcy-Weisbach constant.

The hillslope routing is described by the Manning equation and the continuity equation. Assuming the flow is distributed uniformly on the hillslope, the average hillslope flow velocity is derived as:

$$v = 2.3031 \frac{s^{0.2994} R^{0.4012}}{n^{0.5988} (DL)^{0.4012}} \quad (17)$$

where  $s$  is the slope,  $R$  is the runoff, and  $n$  is the Manning coefficient.

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## REFERENCES

- EROS Data Center (2001) HYDRO1K Documentation, downloaded from USGS website at: <http://www.edcdaac.usgs.gov/gtopo30/hydro/readme.html>
- Moore, I. D., Grayson, R. B. & Ladson, A. R. (1991) Digital terrain modeling: a review of hydrological, geomorphologic and biological applications. *Hydrol. Processes* January–March, 3–30.
- Xu, L., Lettenmaier, D. P., Wood, E. F. & Burges, S. J. (1994) A simple hydrologically based model of land surface water and energy fluxes for GSMs. *J. Geophys. Res.* **99**(D7), 14, 415–428.