II.3-XIN-SMA XINANJIANG SOIL MOISTURE ACCOUNTING

Introduction

The Xinanjiang model is mainly used in humid and semi-humid regions.

The Xinanjiang model was developed by the Flood Forecast Research Room of the River and Ocean University China (East China Technical University of Water Resources before 1985) [R. J. Zhao, et. al. (1978) and R. J. Zhao (1984)] and was initially applied for inflow forecasting of the Xinanjiang Reservoir. It is a conceptual model the structure of which is strong in physical meaning and the parameters can be defined by basin characteristics.

In most cases, the Xinanjiang model should be used as a distributed model by dividing the basin into sub-basins. Computation of soil moisture runoff yield and concentration are done for each sub-basin and summed up to give the hydrograph at the basin outlet.

The Xinanjiang Operation contains only the soil moisture accounting portion of the Xinanjiang model. Output time series for the Operation are channel inflows. The flow chart of the Operation for one sub-basin is shown in Figure 1. Letters written inside the blocks are inputs, output and state variables; those outside the blocks are parameters.

The Xinanjiang Operation was developed by Qingping Zhu of the Yellow River Conservancy Commission in China.

Formation of the Runoff

In humid areas, it is found that the intensity of a storm is not an important item to determine the quantity of the runoff. The volume of the runoff mainly depends on the initial soil moisture and rainfall amount. In the Xinanjiang model, the formation of runoff is simplified as occurring only when soil moisture storage is full. That is, in the course of rainfall, no runoff would occur before the soil moisture in the unsaturated zone reaches the field capacity. After reaching the field capacity, all rainfall becomes runoff, i.e., the volume of runoff equals to precipitation (except for evapotranspiration).

The water balance equation for a soil block is as follows:

Before reaching capacity: $$P - E = WC2 - WC1 \qquad (1)$$

After reaching capacity: $$P - E - R = WM - WC1 \qquad (2)$$

where P is the precipitation
E is the evapotranspiration
R is the runoff
WM is the field capacity
WC1 is the soil moisture contents at the start of the time

interval

WC2 is the soil moisture contents at the end of the time interval

Field capacity is defined as the moisture content of soil after gravity drainage is complete. The field capacity contains a small level of moisture that is generally unavailable for plant use or evapotranspiration. It represents a lower limit of moisture and is not included in computations. In the Xinanjiang model, the portion of the unsaturated zone field capacity that can be removed by evapotranspiration is defined as the tension water capacity. It represents the maximum deficit of soil moisture for evapotranspiration. Therefore, WM, WC1, and WC2 can be regarded as the tension water capacity and tension water contents.

Volume of the Runoff

Both equations 1 and 2 are just point water balance equations. In modeling a catchment area, the distribution of tension water capacity should be considered since we know that it is non-uniform. In the Xinanjiang model, a tension water capacity curve is used as shown in Figure 2(a). In Figure 2(a), the coordinate is point tension water capacity Wm', F is the area of the basin, f is the area in which tension water capacity is equal to or less than Wm', and IMP is impervious areas.

For a catchment area, runoff would only occur in areas where the soil moisture contents reach the tension water capacity. The water balance equation can be written as:

$$P - E - R = WC2 - WC1 \qquad (3)$$

where WC1 is the mean areal tension water content at the start of a time interval

WC2 is the mean areal tension water content at the end of a time interval

This procedure can be illustrated by using the tension water capacity curve as shown in Figure 2(a). The tension water capacity curve can be expressed as a parabola of Bth order:

$$f/F = (1 - IMP) * \left[1 - \left(1 - \frac{Wm'}{WMM} \right)^{B} \right] + IMP \qquad (4)$$

If IMP = 0 it is simply:

$$f/F = 1 - \left(1 - \frac{Wm'}{WMM} \right)^{B} \qquad (5)$$

where WMM is the maximum point tension water capacity in the basin

According to this, the mean areal tension water capacity is equal to:

$$WM = \int_0^1 Wm' d(f/F) = WMM * (1 - IMP)/(1+B) \tag{6}$$

The Y coordinate relative to initial soil moisture WC1 is:

$$A = WM * [1 - (1 - WC1/WM)^{1/(1+B)}] \tag{7}$$

If precipitation is less than evapotranspiration, i.e. P-E ≤ 0, no runoff would occur (i.e., R = 0). Otherwise, if P -E + A ≤ WMM, then:

$$R = P - E - WM + WM * [1 - (P - E + A)/WMM]^{1+B} \tag{8}$$

or if P - E + A > WMM, then:

$$R = P - E - WM + WC1 \tag{9}$$

Based on the above equations, a rainfall-runoff relation can be derived as shown in Figure 2(b).

An important characteristic of the Xinanjiang model is that:

$$\frac{dR}{d(P-E)} = 1 - (1 - Wm'/WMM)^B = f/F \tag{10}$$

Thus it is easy to understand that runoff from the runoff producing area (f/F) is equal to P - E and no runoff occurs in the rest of the area.

The parameters of the Xinanjiang model involved in this phase are:

WM - mean areal tension water capacity. This is a measure of how arid the basin is. It varies from 80 MM in humid areas to 180 MM and even more in semi-humid areas.

B - The exponent of the tension water curve. It represents the degree of non-uniform distribution of tension water capacity. Generally, it is a function of basin area, 0.1 for basins smaller than 10 KM2 and 0.4 for basins of thousands of KM2.

IMP - impervious areas in the basin, such as streams, lake surfaces, etc. For natural basins, IMP usually is more than 0.02.

<u>Surface, Interflow and Groundwater Runoffs</u>

Runoff occurs at the points where the soil moisture reaches the tension water capacity. Referring to the concepts of hillslope hydrology, runoff is divided into three types: surface, interflow (subsurface) and groundwater runoff. Surface runoff would occur after soil moisture fills the free water storage. Free water is defined as the additional water in excess of field capacity.

Runoff from impervious areas is always surface runoff and is computed as:

$$RB = IMP * (P - E) \tag{11}$$

where RB is the impervious runoff (P - E > 0)

For non-impervious areas, the computation of surface runoff involves the distribution of free water capacity. Similar to tension water, a free water capacity distribution curve is used and is expressed as:

$$f/F = 1 - \left(1 - \frac{SM}{SMM}\right)^{EX} \tag{12}$$

According to Equation 12 the volume of surface runoff is calculated as:

$$SMM = (1 + EX) * SM \tag{13}$$

$$AU = SMM\left[1 - \left(1 - \frac{SC}{SM}\right)^{\frac{1}{1+EX}}\right] \tag{14}$$

If P-E + AU < SSM, then:

$$RS = \{P - E - SM + SC + SM * [\ 1-(PE + AU)/SMM]^{1+EX}\} * FRC \tag{15}$$

or if P-E + AU $\geq$ SSM, then:

$$RS = (P - E + SC - SM) * FRC \tag{16}$$

where RS is the surface runoff
SC is the free water contentFRC =runoff producing area, free water exists only in this area
SM is the mean areal free water capacity
SMM is the maximum point free water capacity
EX is the exponent of the distribution curve of free water capacity
AU is the coordinate relative to initial free water content, SC

In the Xinanjiang Model, the relative contribution of free water to interflow and groundwater is specified by the coefficients KSS and KG. The contributions are computed as:

$$RSS = SC * FRC * KSS \quad (17)$$

$$RG = SC * FRC * KG \quad (18)$$

where RSS is the interflow runoff
RG is the groundwater runoff
KSS is the interflow runoff coefficient
KG is the groundwater runoff coefficient

The parameters involved in this phase are:

SM - mean areal free water capacity. This parameter controls the magnitude of the surface runoff. The value of SM depends on the depth of the high permeability surface layer. It is normally from 10-25 MM, but in a basin with heavy vegetation, SM can exceed 50 MM.

EX - exponent of the free water capacity distribution curve. The value of EX is normally 1.0 - 1.5.

KSS - daily interflow coefficient

KG - daily groundwater coefficient

KSS/KG represents the ratio of interflow runoff to groundwater runoff. KSS+KG represents the drainage rate of free water. For a basin near 1000 KM2, KG+KSS is usually equal to 0.7.

Channel Inflow

This phase represents the movement of water from the soil blocks to the network of streams. In the Xinanjiang model, as in most models, surface and impervious runoff flows directly to the stream channels. The interflow runoff and groundwater runoff are adjusted by a linear reservoir. The interflow channel inflow, QIC, is computed as:

$$QIC_t = QIC_{t-i} * CI + RSS * (1 - CI) \quad (19)$$

The groundwater channel inflow, QGC, is computed as:

$$QGC_t = QGC_{t-i} * CG + RG * (1 - CG) \quad (20)$$

where CI is the recession coefficients of interflow for the time interval used
CG is the recession coefficients of ground water runoff for the time interval used.
t is the time

RS, RB, QIC and QGC are summed up to get the total channel inflow, CIN:

$$CIN = RS + RB + QIC + QGC \quad (21)$$

The parameters involved in this phase are:

CI - daily interflow recession coefficient

CG - daily groundwater recession coefficient

Both CI and CG can be determined from the observed streamflow hydrograph. Daily values of CG are typically in the range 0.985 - 0.998. CI can vary from 0.0 - 0.9.

Evapotranspiration

As the soil block dries from evapotranspiration, moisture is withdrawn from tension water storage. The unsaturated zone is divided into an upper, lower and deep zone. Mean areal tension water capacities of these zones are WUM, WLM and WDM, respectively. Both storage and withdrawal of moisture occur in the order of upper to lower to deep zones. In other words, withdrawal of lower zone tension water would happen after upper zone has been dried up.

The potential evapotranspiration (EM) can be estimated from observed pan evaporation, or computed using meteorological data. A coefficient K is used to adjust the value of potential evapotranspiration. If values of pan evaporation are used, K represents the ratio of potential evapotranspiration to pan evaporation. A seasonal curve can be used to adjust potential evapotranspiration values as a function of the time of the year.

In the upper zone, evapotranspiration is equal to potential evapotranspiration. Thus if WUC>EM then:

$$EU = EM \qquad (22)$$

where WUC is the upper zone tension water content
EM is the potential evapotranspiration
EU is the upper zone actual evapotranspiration

In the lower zone, evapotranspiration is equal to potential evapotranspiration times the ratio of lower zone tension water content to capacity. Thus if WUC=0 then

$$EL = EM * WLC/WLM \qquad (23)$$

where EL is the lower zone actual evapotranspiration
WLC is the lower zone tension water content

In the deep zone, evapotranspiration is a fraction of the potential evapotranspiration. Thus if WUC=0 and WLC=0 then:

$$ED = C * EM \qquad (24)$$

where ED is the deep zone actual evapotranspiration
C is the coefficient of deep evapotranspiration

If computed lower zone evapotranspiration is less than C * EM (i.e., WLC/WLM<C) the lower zone evapotranspiration is adjusted to be equal

to C * EM. Thus if WLC/WLM<C then:

$$EL = C * EM \quad (25)$$

Total evaporation (E) is computed as the sum of the evapotranspiration from each zone, that is:

$$E = EU + EL + ED \quad (26)$$

The parameters involved in this phase are:

- K - adjustment coefficient for potential evapotranspiration. Because it can change the amount of evaporation significantly, this parameter is important for long-term bias adjustments.

- WUM - upper zone tension water capacity (mean areal). The value of WUM is between 5 MM (deforested areas) to 25 MM (forest areas).

- WLM - lower zone tension water capacity (mean areal). The value of WLM is typically in the range of 60-90 MM.

- WDM - deep zone tension water capacity (mean areal). Since we think that the total tension water capacity represents the maximum soil moisture available for evapotranspiration, WDM should be set large enough to keep a small value during very dry seasons.

- C - the coefficient of deep evapotranspiration. It varies from 0.2 in humid areas to 0.08 in semi-humid areas. It is inactive during wet periods and is very important during dry periods.

<u>References</u>

Ren Jiun Zhao, et al, 1978, 'The Flood Forecast Methods Applied in Humid Areas of China', East China Technical University of Water Resources, Nanjing, China.

R. J. Zhao, 1984, 'Xinanjiang Model Applied in China', East China Technical University of Water Resources, Nanjing, China.

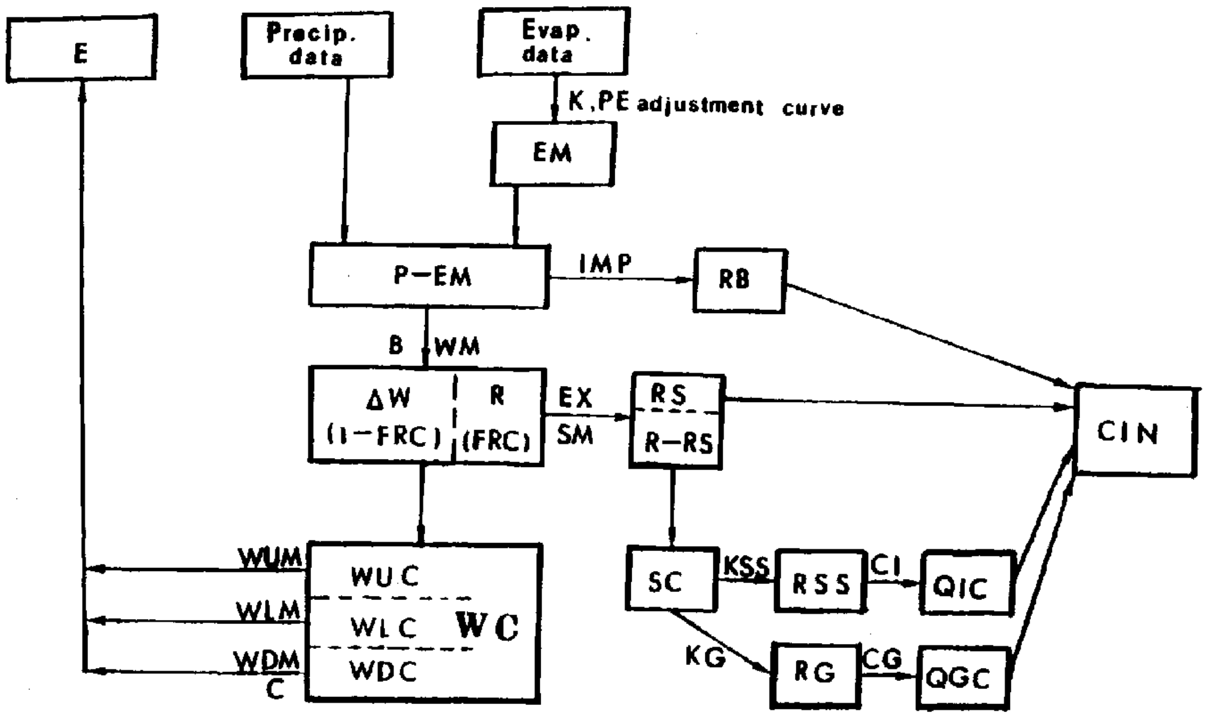

Figure 1. Flowchart of the Xinanjiang Soil Moisture Accounting Model.

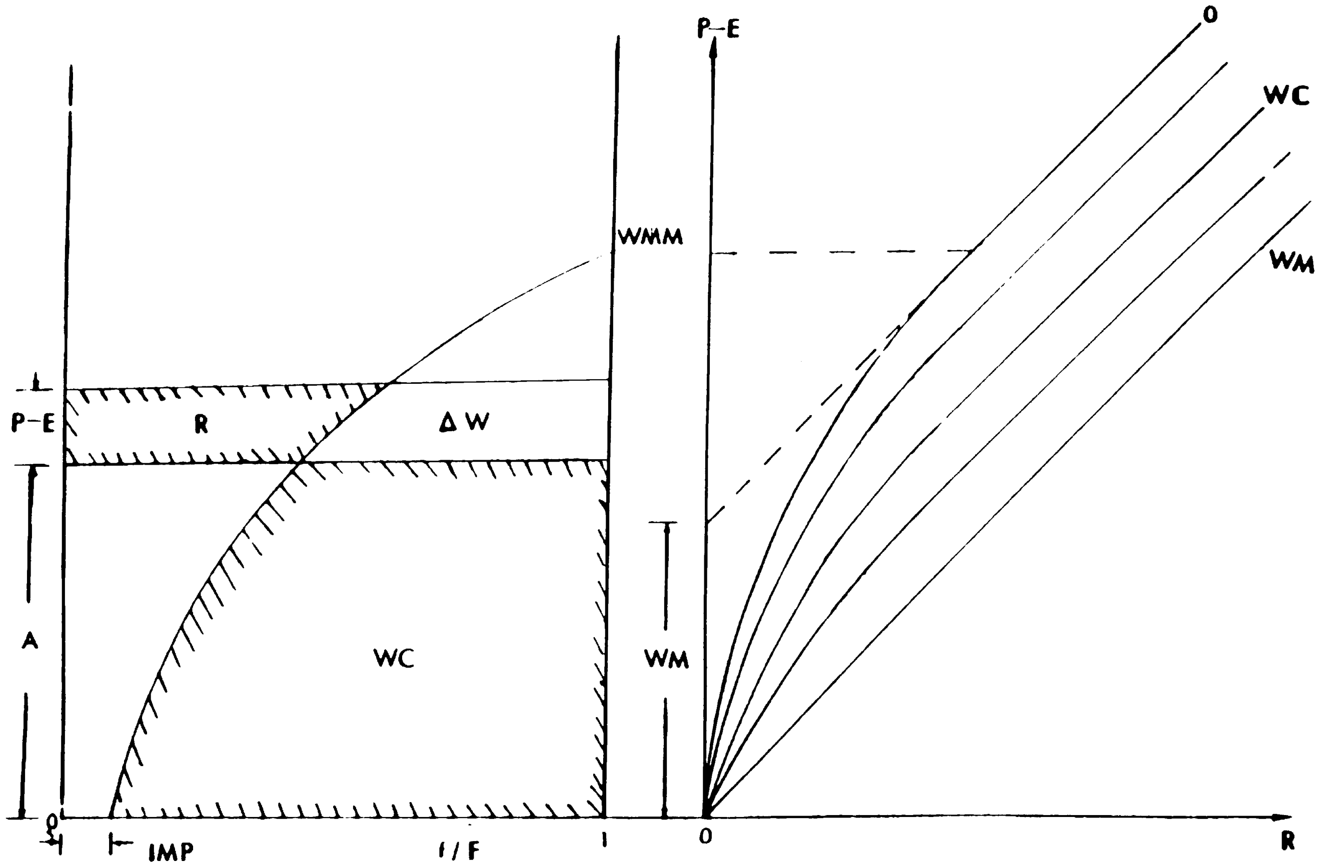

Figure 2(a). Tension water capacity curve.

Figure 2(b). Rainfall-runoff relationship derived from the Xinanjiang Model equations.