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Estimation of River Discharge using Xinanjiang Model

by

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This paper presents the performance of Xinanjiang rainfall-runoff model for a basin (524.9 Km^2), of Yodo River catchment in Japan. The model has been modified to use the evapotranspiration values computed using the Energy Balance Method instead of the conventional pan evaporation method. This has been achieved by using the hourly precipitation and discharge observations in addition to the hourly evapotranspiration values. To compute the hourly evapotranspiration the Energy Balance method has been used which originally provides the daily values, therefore time distribution procedure for short wave radiation has been incorporated and AMeDAS data was used for the computations. The performance of Xinanjiang model was checked using hourly and daily data.
Key Words : *Rainfall-runoff model, Evapotranspiration, Xinanjiang model, Energy Balance method*

1. Introduction

Water plays a fundamental role in the redistribution of solar energy, through the energy associated with evapotranspiration, the transport of atmospheric water vapor and precipitation. To predict future time and space distribution of water resources, it is very important to develop a closed water cycle model linked with a meteorological model. To do this, as a part of a total water cycle system, we must model the hydrologic cycle considering the water and energy interaction between atmosphere and land surface. To develop this kind of hydrologic model two approaches can be considered, one is a geographically fully distributed model like SHE model (M. B. Abbott et al.[1]) and the other is a parameter distributed model. The geographically fully distributed model would be really able to represent the basin in details but to deal with it will be cumbersome and difficult for a large area, because these models require a large number and amount of data. On the other hand the parameter distributed model is easier to work on and is able to represent the basin farely well. The Xinanjiang model[2] is one of the parameter distributed model. The performance of Xinanjiang model was checked by Wood et al.[3] using GCM output and also Lu et al.[4] worked on this model and explained its performance using Priestley-Taylor method for evapotranspiration values.

In this present study, we have checked the performance of this model with daily and hourly data from year 1988 to 1991. Energy Balance method was used to compute the evapotranspiration and data needed for this purpose was AMeDAS routine observation data.

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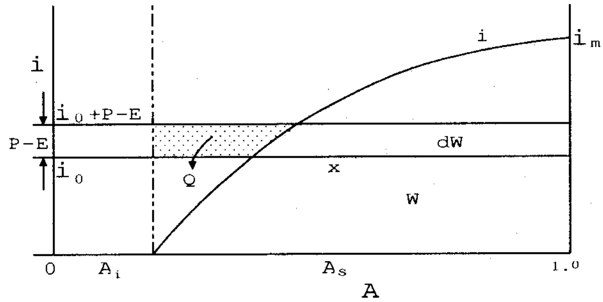

Fig. 1 The distribution of tension water capacity in the sub-basin.

2. Methodology

2.1 Xinanjiang Model

This is a rainfall-runoff, parameter distributed basin model for use in humid and semi-humid regions. Runoff production occurs on repletion of storage to capacity values which are assumed to be distributed throughout the basin. The outflow hydrograph is first simulated and then routed down the main outlet. The inputs to the model are P, the measured areal mean rainfall depth on the sub-basin and E, the computed evapotranspiration (originally the measured pan evaporation) in the same unit. The output is the discharge, Q. As shown in **fig.1** the storage capacity i over an area is represented by a function,

$$i = \begin{cases} 0 & \text{if } 0 \leq A < A_i \\ i_m \left[1 - \left(1 - \frac{A - A_i}{1 - A_i}\right)^{1/B}\right] & \text{if } A_i < A \leq 1.0 \end{cases} \quad (1)$$

where B is a shape parameter. A is a ratio parameter and A_s is the proportion of pervious area whose tension water capacity is less than or equal to i, and i_m is the maximum storage capacity within the basin. A_i is the impervious proportion of the basin which will generate direct runoff immediately. The discharge from the pervious area Q is given by

$$Q = \begin{cases} (P - E)(1 - A_i) - W_c + W & \text{if } i_m \leq i_0 + P - E \\ (P - E)(1 - A_i) - W_c + W + W_c\left(1 - \frac{i_0 + P - E}{i_m}\right)^{1+B} & \text{if } i_m \geq i_0 + P - E \end{cases} \quad (2)$$

W is the present tension water storage, i_0 is the present storage capacity, dW the increase and W_c is the maximum tension water storage over the basin (in depth unit) given by

$$W_c = \int_{A_i}^{1.0} i dA = (1 - A_i)\frac{i_m}{(1 + B)} \quad (3)$$

Q is divided into three components viz. surface, interflow and ground water discharge.

2.2 Energy Balance Method

The pan evaporation data is not always available, therefore Energy Balance approach was adopted to compute evapotranspiration (Kondo [5] and Brutsaert[6]).

The net radiation R_n is given by

$$R_n = S\downarrow - S\uparrow + L\downarrow - L\uparrow \quad (4)$$

where $S\downarrow$, $S\uparrow$, $L\downarrow$ and $L\uparrow$ are incoming and outgoing short wave and long wave radiation respectively. It is expressed as,

$$R_n = R\downarrow - \varepsilon\sigma Ts^4 \tag{5}$$

$R\downarrow$ consists of two components, $R\downarrow = (1-\alpha)S\downarrow + L\downarrow$ where α is the surface albedo To compute hourly short wave radiation, first, daily short wave radiation is computed as follows

$$S_d = \begin{cases} S_{0d}\cdot c & \text{if} \quad \frac{N}{N_0} = 0 \\ S_{0d}(a + b\frac{N}{N_0}) & \text{if } 0 < \frac{N}{N_0} < 1 \end{cases}$$

where N and $N_0(= 2H/0.2618)$ represent actual number of hours of bright sunshine, the number of daylight hours, and a,b and c are constant values which depend on the kind of sunshine recorder. Here $a = 0.511$, $b = 0.244$, $c = 0.118$. S_{0d} is computed as follows,

$$S_{0d} = \frac{I_0}{\pi}\left[\frac{d_0}{d}\right]^2 (H\sin\phi\sin\delta + \cos\phi\cos\delta\sin H) \tag{6}$$

$$H = \cos^{-1}(-\tan\phi\tan\delta)$$

$$\left[\frac{d_0}{d}\right]^2 = 1.00011 + 0.034221\cos\eta + 0.00128\sin\eta + 0.000719\cos 2\eta + 0.000077\sin 2\eta$$

$$\delta = \sin^{-1}(0.398\sin a_2)$$

$$a_2 = 4.871 + \eta + 0.033\sin\eta$$

$$\eta = 2\pi.a_i/365$$

$$a_i = 30.36(month - 1) + iday$$

where iday is day of the month, I_0 (solar constant) = 1365 $\mathrm{Wm^{-2}}$, and ϕ is the latitude. To subdivide the daily short wave downward radiation to hourly short wave downward radiation,

$$S\downarrow = \begin{cases} 0 & \text{if} \quad 0 \le t \le 12 - \frac{N_0}{2} \\ \frac{S_{max}}{N_0/2}\{t - 12 + \frac{N_0}{2}\} & \text{if} \quad 12 - \frac{N_0}{2} \le t \le 12 \\ -\frac{S_{max}}{N_0/2}\{t - 12 - \frac{N_0}{2}\} & \text{if} \quad 12 \le t \le 12 + \frac{N_0}{2} \\ 0 & \text{if} \quad 12 + \frac{N_0}{2} \le t \le 24 \end{cases} \tag{7}$$

where S_{max} represents short wave downward radiation at noon, $S_{max} = 48\cdot\frac{S_d}{N_0}$. The long wave downward radiation is computed from ,

$$L\downarrow = \sigma T^4\left[1 - (1 - \frac{L_{df}}{\sigma T^4})\cdot C\right] \tag{8}$$

$$C = \begin{cases} 0.2235 & \text{if} \quad \frac{N}{N_0} = 0 \\ 0.826(\frac{N}{N_0})^3 - 1.234(\frac{N}{N_0})^2 + 1.135(\frac{N}{N_0}) + 0.298 & \text{if } 0 < \frac{N}{N_0} < 1 \end{cases}$$

where, C is cloudiness factor and L_{df} represents daily mean long wave downward radiation in clear sky condition. We have used the Ångström-Limke [7] equation for L_{df} viz. $\frac{L_{df}}{\sigma T^4} = 0.806 - 0.236 \times 10^{-0.052e}$, here e is vapor pressure and T is the air temperature.

At the surface, R_n is divided into sensible heat H, latent heat λE(E: water vapor flux, λ: the latent heat of evaporation = 2500), and heat storage G.

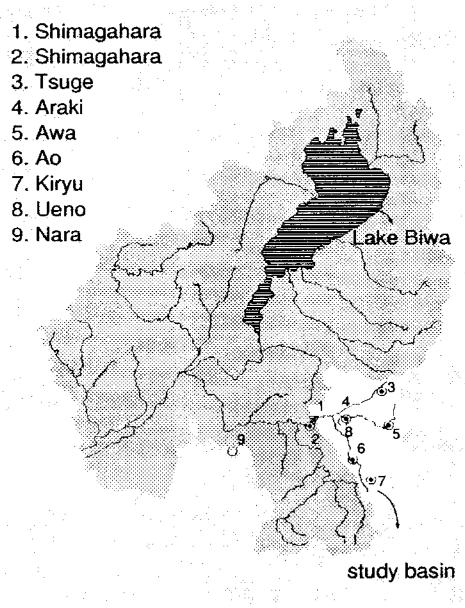

Fig. 2 Yodo River Basin

$$Rn = H + \lambda E + G \tag{9}$$

Sensible heat H is expressed as

$$H = C_p \cdot \rho \cdot C_H \cdot u \cdot (T_s - T) \tag{10}$$

where C_p = 1005 (J Kg^{-1} K^{-1}), the specific heat of the air, $\rho = 1.293$ ($\simeq$ 1.2 Kg m^{-3}), the density of the air, C_H the Bulk constant, and T_s is surface temperature. Here we set C_H as 0.005. Latent heat λE is expressed as

$$\lambda E = \lambda \cdot \rho \cdot \beta \cdot C_H \cdot u \cdot (q_{sat}(T_s) - q) \tag{11}$$

where $q_{sat}(T_s)$ is the saturation specific humidity at temperature T_s (^0C), u the mean wind speed (m/s), q the mean specific humidity and β the surface moisture availability, taken here as 0.3 which is good for paddy field. We set the heat storage G as 0, because the study area has more than 70% of forest area .

From equation (5), (10), (11) and (12), we get the equation

$$0 = \varepsilon \cdot \sigma \cdot Ts^4 + C_p \cdot \rho \cdot C_H \cdot u \cdot (T_s - T) + \frac{C_p}{\gamma} \cdot \rho \cdot \beta \cdot C_H \cdot u \cdot (e_{sat}(T_s) - e) - R \downarrow \tag{12}$$

This equation is a function of T_s which is solved by Newton-Raphson method, and E is obtained from equation (12).

3. Study Area And Data Used

A sub-basin (524.9 Km^2) of Yodo River basin was studied for this work. As shown in **Fig.2**, this sub-basin, shown as white area, is located in the south-east of Yodo River basin and is dominated by mountaineous region and paddy field. Dark shaded area is lake Biwa. At the outlet point, Shimagahara discharge observation station is there. Within the sub-basin there are 6 precipitation measurement sites, viz. Shimagahara, Ao, Araki, Awa, Tsuge and Kiryu. Discharge and precipitation data are acquired from Ministry of Construction

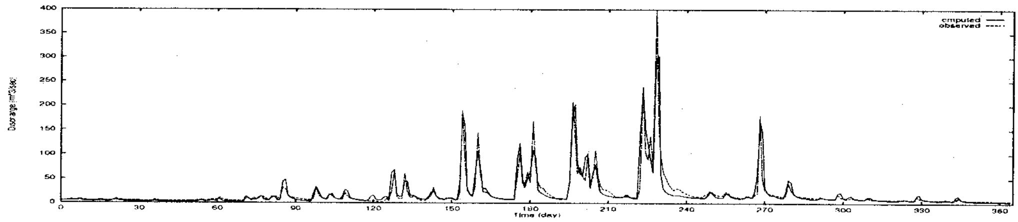

Fig. 3 Daily hydrograph for the year 1988

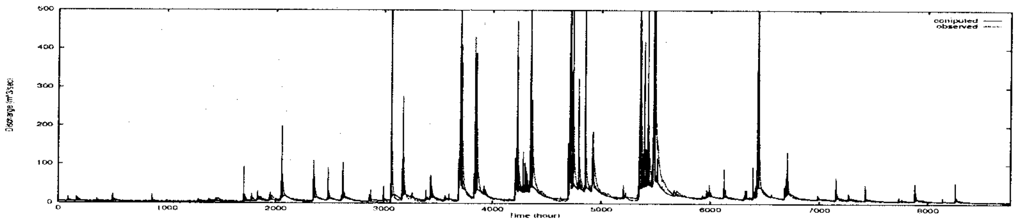

Fig. 4 Hourly hydrograph for the year 1988

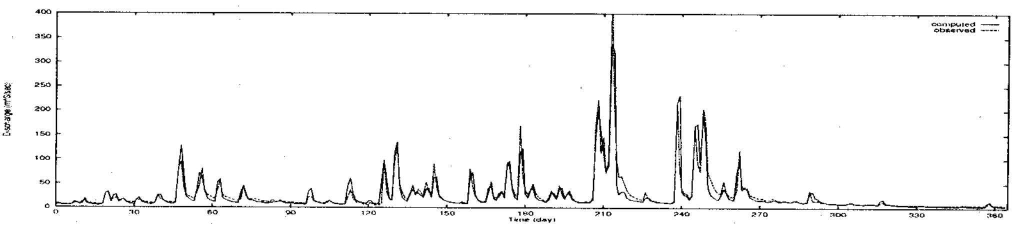

Fig. 5 Daily hydrograph for the year 1989

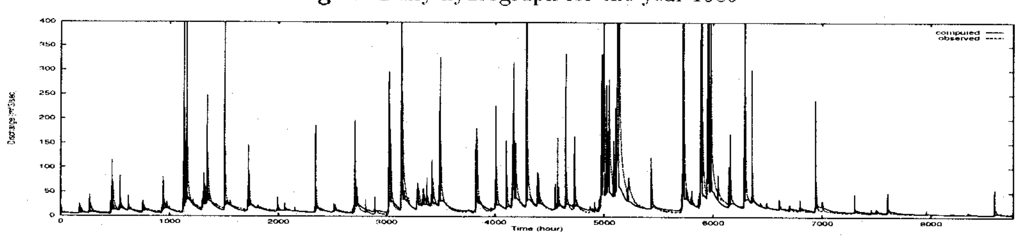

Fig. 6 Hourly hydrograph for the year 1989

and AMeDAS data for the sunshine hours, temperature and wind velocity at Ueno and the vapor pressure observed at Nara were used. There are four sets of hourly values having one complete year (1988 to 1991) in each set. Similarly four sets of daily values were taken up.

4. Results And Conclusion

The performance of the model is good for daily discharge estimation (**Figs.3,5,7,9**) but does not give good results for the hourly data values as shown in (**Figs.4,6,8,10**). The nature of the model is such that if the flood does not stay for more than a day it does not work well which is why it has to be further worked on to improve its response for Japanese river flows, which are topographically steep. Also, this model dose not include human activities, e.g. agricultural water use, flood control etc.

5. Future Works

For modeling large river basin hydrologic cycle, we must develop a methodology to estimate hydrologic parameters using remote sensing data. Also we must model the effect of human influence like agricultural water

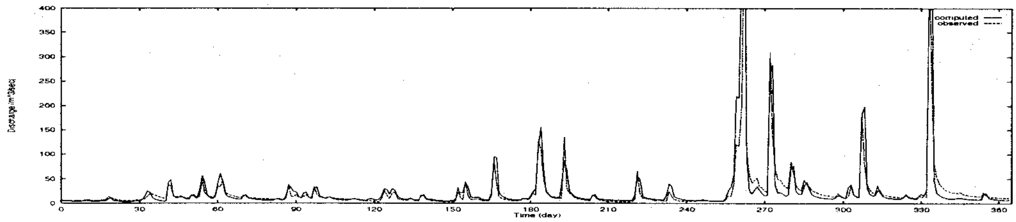

Fig. 7 Daily hydrograph for the year 1990

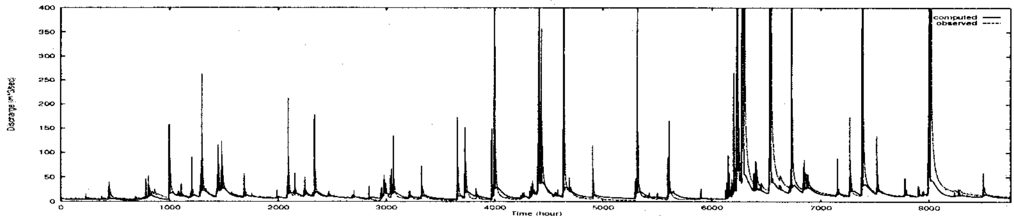

Fig. 8 Hourly hydrograph for the year 1990

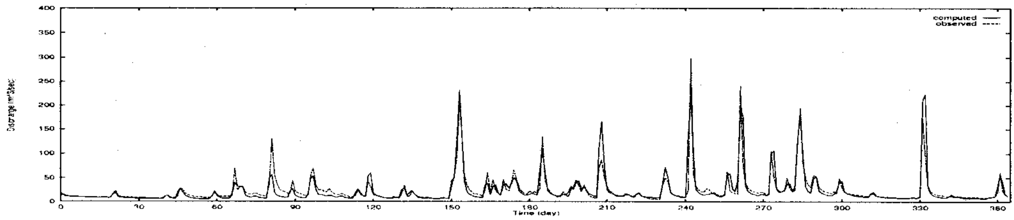

Fig. 9 Daily hydrograph for the year 1991

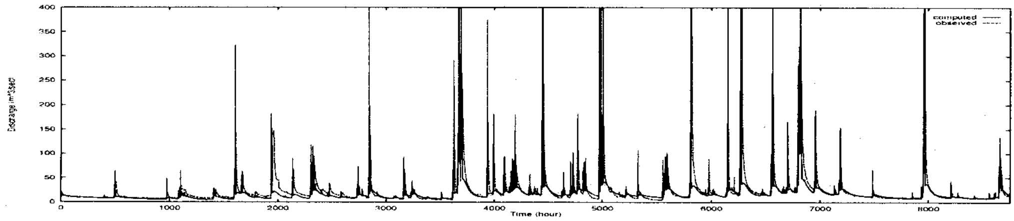

Fig. 10 Hourly hydrograph for the year 1991

use, flood control etc. and incorporate these features into the model, for example the Xinanjiang model could be modified.

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