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Daily river discharge prediction using GCM generated atmospheric data

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Abstract An attempt to simulate daily river discharges in Mekong and Chao Phraya river basins from macroscale atmospheric data is presented. Atmospheric data for the studies were taken from International Satellite Land Surface Climatology Project (ISLSCP) CD-ROMs and field observations. Land surface hydrology was modelled using the variable infiltration capacity (VIC) model. A modified soil moisture infiltration capacity variation curve was used in the study.

Key words GCM generated atmospheric forcings; VIC model; modified Xinanjiang model; Mekong River; Chao Phraya River, Thailand

INTRODUCTION

The use of general circulation model (GCM) generated atmospheric forcings for river discharge prediction in macroscale river basins has gained increasing attention in recent years. In this context, the water and energy balances are calculated out by a land surface model (LSM), which is linked to a grid based runoff routing model. Land surface models over the years have varied greatly in structure and complexity. They range from the simple bucket model to the more sophisticated soil–vegetation–atmosphere transfer (SVAT) model which gives vegetation a more direct role in determining the surface energy and water balance. In recent LSMs, consideration of the sub-grid variability of hydrological processes has also been an important factor, in addition to the consideration of the vertical complexity. The former is important because of the vast differences in GCM and basin scales. The variable infiltration capacity (VIC) model is one of the LSMs that accounts for spatial variation of hydrological processes. In this study, the VIC model and its variations are used as the LSM and a high-resolution runoff routing model consisting of a surface component and a groundwater component are used to produce the river discharges.

In the original VIC model (Wood *et al.*, 1992), which follows the Xinanjiang model (Zhao *et al.*, 1980; Zhao, 1992), a single parabolic curve is used to represent the spatial variation of soil moisture infiltration capacity. The use of the single curve may not be sufficient to describe complex patterns, particularly when one pattern, either that over the dry areas and in the dry seasons, or that over the wet areas and in the wet seasons, does not control the catchment. In this paper, the single parabolic curve is replaced by a double parabolic curve (Jayawardena & Zhou, 2000), which has the potential to model wet, dry and transition conditions. This is believed to be more appropriate in view of the large size of a typical GCM cell (≈ 10 000km^2).

The proposed modified VIC model together with the high-resolution runoff routing model is then applied to produce river discharges in two macroscale basins in Asia, namely, the Mekong and the Chao Phraya. The nested approach was adapted in linking the LSM to the runoff routing model. The VIC model was run on a 1° × 1° (latitude/longitude) grid using atmospheric forcings published in ISLSCP CD-ROMs (Sellers *et al.*, 1995). Surface and groundwater components generated by the LSM, were then routed through a grid based runoff routing model on a 5′ × 5′ (latitude/longitude) grid. River discharge simulations were compared with observations at both daily and monthly time scales.

THE VIC MODEL

The VIC model (Wood *et al.*, 1992) assumes that infiltration capacities (defined as the maximum depth of water that can be stored in the soil column), and therefore runoff generation, vary within an area due to variations in topography and soil properties (Fig. 1(a)). Quantitatively, it is defined as:

$$i = i_m[1 - (1 - A)^{1/B}] \tag{1}$$

where A represents the fraction of the GCM cell area for which the infiltration capacity is less than i (thus $0 \leq A \leq 1$), B is a shape parameter and i_m is the maximum infiltration capacity within the area.

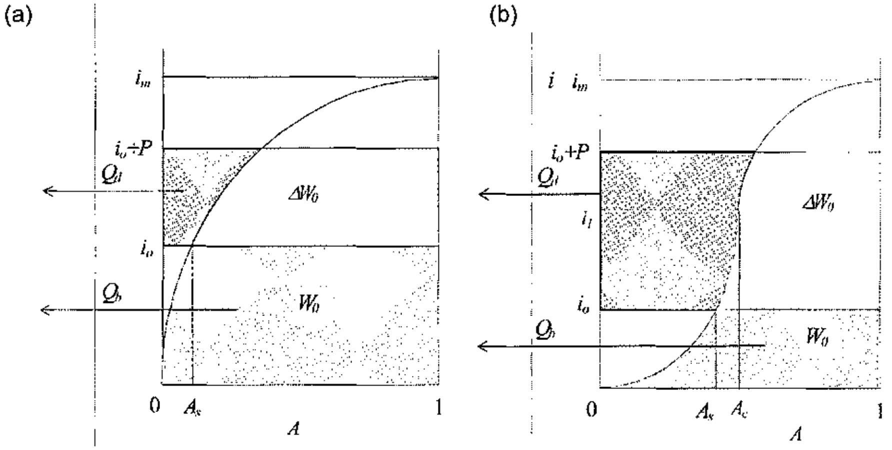

Fig. 1 (a) VIC model; and (b) modified VIC model. (A represents the fraction of the GCM area that is less than i (thus $0 \leq A \leq 1$), i is infiltration capacity, i_m is maximum infiltration capacity, P is precipitation, Q_d is surface runoff, Q_b is baseflow, and W_o is soil moisture storage.)

MODIFIED VIC MODEL

Following the concept of the modified Xinanjiang model (Jayawardena & Zhou, 2000), the infiltration capacity i over an area (GCM cell in this study) with the modified VIC model (Fig. 1(b)) can be represented as follows:

$$i = i_m \left[A^{\frac{1}{B}} A_c^{\frac{B-1}{B}} \right] \qquad \text{when } 0 < A \le A_c \tag{2a}$$

$$i = i_m \left[1 - (1 - A)^{\frac{1}{B}} (1 - A_c)^{\frac{B-1}{B}} \right] \qquad \text{when } A_c < A \le 1 \tag{2b}$$

In equation (2), and Fig. 1(b), A_c refers to the fraction of the total area corresponding to the point of inflexion of the curve. The maximum infiltration capacity (i_m) within the area can be expressed as a function of the maximum soil moisture storage capacity W_c (also expressed as a depth) which is the total area under the modified curve).

RUNOFF ROUTING MODEL (RRM)

The routing model follows that suggested by Liston *et al.* (1994), which has been applied to the Mississippi basin on a 2.0° × 2.5° (latitude/longitude) grid. A better accuracy is expected in this study in which the features of the catchment are represented in a much finer grid using high-resolution ($5' \times 5'$ latitude/longitude) topographical data. The surface and groundwater runoff components computed by the VIC model as depths are converted into discharges using the cell area, and then used as inputs to the RRM. The RRM assumes two linear reservoirs having different time constants that reflect the differences in the runoff mechanisms. It is also assumed that the groundwater reservoir replenishes the corresponding surface store, and that the surface stores are connected via the river network. They can be represented by the following equations, applicable to a RRM cell:

$$\frac{\mathrm{d}S_s}{\mathrm{d}t} = Q_{si} + Q_{sr} + Q_g - Q_s \tag{3a}$$

$$\frac{\mathrm{d}S_g}{\mathrm{d}t} = Q_{gr} - Q_g \tag{3b}$$

where S_s is the surface storage, S_g is the groundwater storage, Q_s is the surface outflow, Q_{sr} is the RRM cell surface runoff (from the GCM gridded surface runoff), Q_g is the groundwater outflow, Q_{gr} is the RRM cell groundwater runoff (from the GCM gridded groundwater runoff), Q_{si} is the surface inflow from the adjacent cells, and t is time. Since the VIC model outputs are computed as depths, they are multiplied by the corresponding RRM cell area and divided by the VIC model time step to convert into equivalent discharge values. They will then be used in equations (3a) and (3b), as Q_{sr} and Q_{gr}. Using the linear reservoir assumption, equations (3a) and (3b) can be written as:

$$k_s \frac{\mathrm{d}Q_s}{\mathrm{d}t} = Q_{si} + Q_{sr} + Q_g - Q_s \tag{4a}$$

$$k_g \frac{\mathrm{d}Q_g}{\mathrm{d}t} = Q_{gr} - Q_g \tag{4b}$$

in which k_s and k_g represent the surface and groundwater reservoir constants, which have dimensions of time. They are functions of travel distance (which is a function of the grid size) stream bed slope, roughness, stream length, stream width, and stream depth. An empirical equation published in Liston *et al.* (1994) was used to compute RRM cell specific k_s values. The value of k_g was found by trial and error to be 10.

DATA SOURCES

Several types of data were used in this study. The digital elevation data of the study area were taken from the global $5' \times 5'$ topography data compiled by the National Geophysical Data Centre of National Oceanography and Atmospheric Administration (NOAA). International Satellite Land Surface Climatology Project (ISLSCP) CD-ROMs of NASA Goddard DAAC Science Data Series (Meeson *et al.*, 1995; Sellers *et al.*,1995, 1996) provided global gridded $1^\circ \times 1^\circ$ resolution soil moisture storage at the beginning of the month, monthly mean temperatures at 0, 6, 12 and 18 h UTC, vegetation classification, soil texture, monthly mean Leaf Area Index (*LAI*), surface roughness, albedo, daily values of dew point (at 2 m), temperature, surface pressures, wind magnitude (at 10 m), radiation hybrids (short and long wave) and precipitation at 0, 6, 12 and 18 h UTC. Daily runoff data at seven stations (Table 1) across the Mekong used for comparison purposes were obtained from the Global Runoff Data Centre (GRDC, Koblenz, Germany). All the hydrological data used in the study were for the years 1987 and 1988. In the Chao Phraya basin, the daily discharge data at Nakhon Sawan (15°40′12″N, 100°7′12″E; catchment area: 110 569 km^2) were obtained from the GRDC (Table 2). Measured daily rainfall, and minimum and maximum temperature time series at eight stations in the basin were obtained from the International Center for Disaster Mitigation Engineering, Institute of Industrial Science, University of Tokyo, Japan, for the period 1980–1989.

Table 1 Daily river discharge gauging stations in the Mekong River basin.

Station name	Station	Latitude (°N)	Longitude (°E)	Country	Catchment area (km^2)
G1	Luang Prabang	19°52′48″	102°7′48″	Laos	268 000
G2	Vientiane	17°55′12″	102°37′12″	Laos	299 000
G3	Pakse	15°7′12″	105°48′00″	Laos	545 000
G4	Chiang Saen	20°16′12″	100°6′00″	Thailand	189 000
G5	Sop Kok	20°13′48″	100°7′48″	Thailand	201 000
G6	Nong Khai	17°52′12″	102°43′12″	Thailand	302 000
G7	Mukdahan	16°31′48″	104°43′48″	Thailand	391 000

APPLICATION

Mekong River

The Mekong River basin is geographically bounded between the latitudes 10°–35°N and the longitudes 90°–109°E. It is approximately 4200 km long and is the tenth longest river in the world. The basin area of the Mekong River is about 795 000 km^2. Originating from the snow-covered Tang-Ku La Mountains on the Tibetan plateau at an altitude of about 5000 m, this international river flows through Tsinghai and

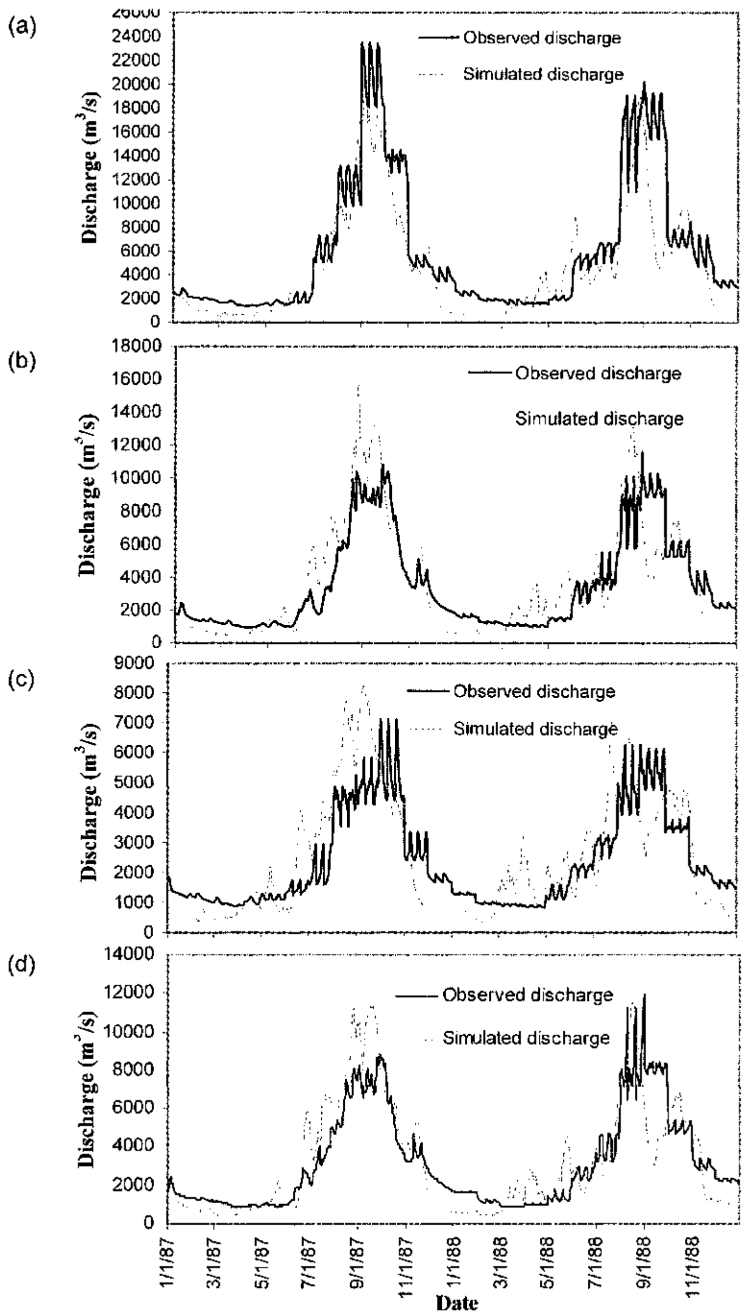

Fig. 2 Daily river discharges at (a) Mukdahan, Thailand, (b) Vientiane, Laos, (c) Chiang Saen, Thailand, and (d) Luang Prabang, Laos (1987–1988).

Yunnan provinces of China, Myanmar, Laos, Thailand, Cambodia, and Vietnam before discharging into the South China Sea.

Table 2 Daily river discharge gauging stations in the Chao Phraya River basin.

GRDC ID no.	Station	Latitude (°N)	Longitude (°E)	Country	Catchment area (km^2)
2964100	Nakhon Sawan	15°40′12″	100°7′12″	Thailand	110 569
2964130	Ban Re Rai	15°9′57″	100°11′32″	Thailand	120 693

Table 3 Comparison of model performance.

Model	Basin	Coefficient of determination	%RMSE	MAPE
VIC	Mekong	0.504	28.06	35.22
Modified VIC	Mekong	0.625	24.78	32.41
VIC-2L	Chao Phraya	0.563	49.37	29.26
Modified VIC-2L	Chao Phraya	0.821	27.48	18.72

RMSE: root mean square error; MAPE: mean absolute percentage error.

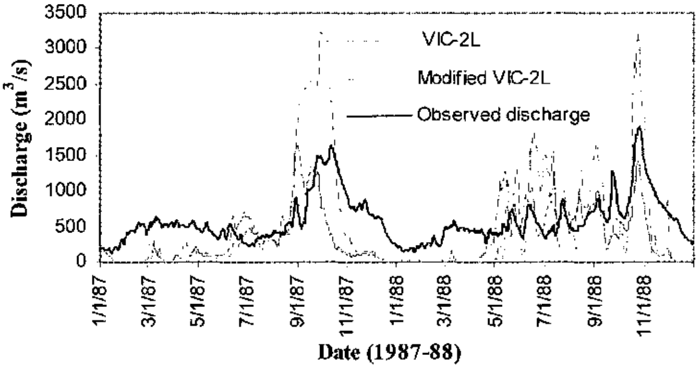

Fig. 3 Discharge simulations with VIC-2L, 1987–1988.

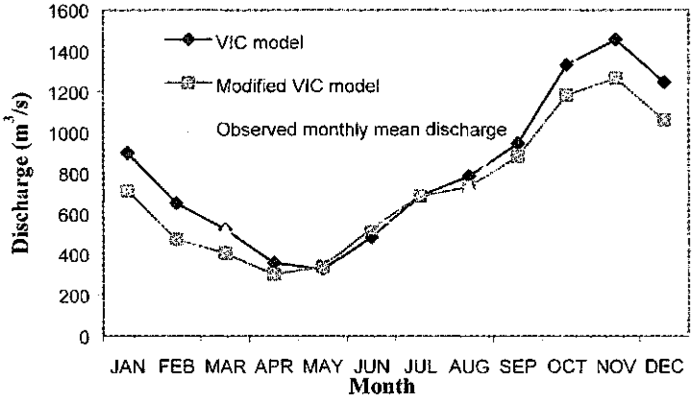

Fig. 4 Monthly mean discharges for 1980–1989.

In this study, the Mekong River basin is represented by 69 GCM cells. Surface and groundwater runoffs are computed separately by applying the water balance for each GCM cell. The computed runoffs are then routed through the RRM. The runoff routing model for the Mekong catchment consists of 9410 cells of $5' \times 5'$ resolution. Due to data limitations, only the original VIC model was applied to this basin. The river network is formulated through the term Q_{si}, which is considered to have contributions from eight (compass) directions. Part of the data series was used for calibrating the parameters of the model while the rest was used for comparison. Figure 2 illustrates some of the results of daily discharge simulations.

Chao Phraya River

The Chao Phraya basin lies within longitude 95°–105°E and latitude 12.5°–22.5°N. The river, which begins in northern Thailand, has two main tributaries, the Ping River and the Nan River. The river discharges used in this study are measured at Nakhon Sawan, just downstream of the confluence of the two main tributaries.

In this study, land surface was modelled using the original VIC model, the fully coupled VIC-2L model (Liang *et al.*, 1994), and their modified forms by using the double parabolic curve. Table 3 shows some performance indicators of discharge simulation with different versions of the VIC model using data for the period 1980–1989. Figure 3 shows comparison of daily discharges by the different models with the observed ones while Fig. 4 shows the monthly mean discharges.

At the scale concerned, river discharge predictions using atmospheric forcings generated by GCMs can be considered as satisfactory. Comparison between simple LSM (original and modified VIC models) simulation *vs* fully coupled LSM (original and modified VIC-2L models) simulation show that the latter models produced a better land surface simulation. The modification to the infiltration capacity curve also show an improvement in the VIC-2L simulation.

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