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Hydrological simulation by SiB2-Paddy in the Chao Phraya River basin, Thailand

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Abstract As a part of the GEWEX Asian Monsoon Experiment in the tropics (GAME-T), water and energy balances were estimated by simulations of the modified version of the Simple Biosphere Model (SiB2) using the International Satellite Land Surface Climatology Project (ISLSCP) forcing data for the Chao Phraya River basin, Thailand. Four simulations with/without applying realistic vegetation type and with/without incorporated paddy scheme were carried out, and the results were compared with the observed discharge data at Nakhon Sawan gauging station where the basin size is 110 569 km^2. Using the revised SiB2, simulated annual runoff compared well with the observations, when the flow controls by major two dams are considered, and the annual water balance is also well reproduced by the SiB2 simulation. In terms of energy balance, differences of each simulation result are not conspicuous. The ratio of latent heat flux to net radiation in the dry season is no lower than that of the wet season, which is concordant with the observational results. From the analysis of model calculations, this is due to the increase in transpiration from vegetation using soil moisture.

Key words GAME-Tropics; Simple Biosphere model (SiB2); runoff; energy balance; water balance; paddy

INTRODUCTION

Realistic simulation of the soil–vegetation–atmosphere transfer system is significant for prediction and understanding of the energy and water cycles and balances on the land surface. In recent decades, various soil–vegetation–atmosphere transfer schemes (SVATS) have been explored, and calibration and/or validation studies were carried out with the aim of simulating at higher performance in terms of hydrological, biogeochemical and vegetation dynamic processes (e.g. Giambelluca *et al.*, 1996; Colello *et al.*, 1998; Kucharik *et al.*, 2000). However, rice paddy is not well considered in these types of models, although rice paddy covers large areas of East Asia: much of the area is filled with water for parts of the year so that water and energy balances could be quite different at these times (Kim *et al.*, 2001).

From a hydrological point of view, much effort has been spent in developing macroscale hydrological models (e.g. Kalma & Sivapalan, 1995). One of the motivations to develop macroscale hydrological models (MSHMs) is, of course, simulation of hydrological cycles, particularly runoff, in continental-scale river basins. On the other hand, hydrological cycles at land surfaces are also focused on the Earth, as an important component of the climatological system, and attempts have been made to couple land surface models with atmospheric models. Therefore, coupling a MSHM with a general circulation model (GCM) of the global atmosphere is one of the typical motivations for developing MSHMs. For this purpose, it is not practical to optimize all the parameters used in the numerical model and they should be given from widely available observable quantities, such as land cover and topography. MSHMs enable the prediction of the regime shift of hydrological cycles in river basins, for example, associated with the anticipated land-use change. Since averaging in a wide region decreases temporal variation, simulations by MSHMs are sometimes evaluated at daily or longer time scales. Considering the coupling with GCMs, the coincidence of the peak discharge at an hourly time scale with that simulated by a MSHM and observation is not particularly relevant, but the mean water and energy balance at monthly or annual time scale should be reproduced accurately enough.

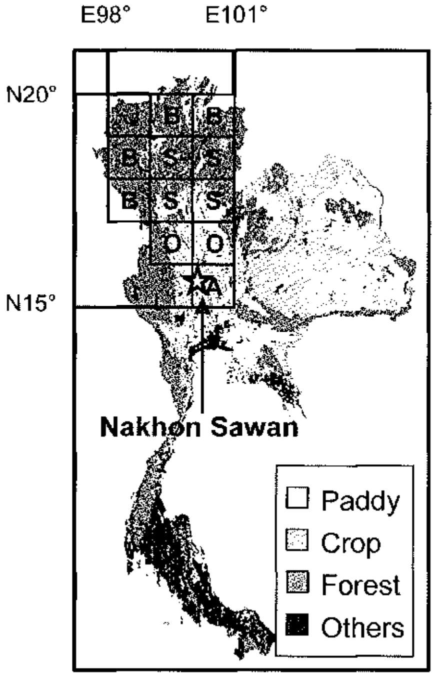
There seem to be two approaches for developing MSHMs. One is improving the energy balance processes within an existing hydrological model and enabling it to couple with an atmospheric model (e.g. Xu *et al.*, 1994). Another approach is the improvement of the hydrological processes in land surface models (LSMs) developed for atmospheric models for giving the land surface boundary conditions. The latter approach was adopted in this study to simulate the daily water and energy balance in a large river basin, namely the Chao Phraya River basin in Thailand. The basin is largely covered by rice paddy, which is one of the important land uses in the region and common throughout Asia. However, there are few numerical studies by SVATS to reveal the climatic role of rice paddy, probably because of the lack of suitable SVATS that can consider rice paddy properly. Thus the aims of this study are to simulate water and energy balances in the target region and to clarify the effect of rice paddy on those balances from simulations of SiB2 (Sellers *et al.* 1996a) and SiB2-Paddy (Kim *et al.* 2001).

EXPERIMENTAL SITE

The experimental site is Nakhonsawan watershed on the Chao Phraya River in the northwest part of Thailand (Fig. 1). Its extent is 15–20°N and 98–101°E, and the drainage area is 110 569 km^2. The climate of this area shows clear Asian monsoon characteristics; there are evident dry and wet seasons. The former is from November to March, with very little precipitation, while most rainfall occurs in the latter season. Annual rainfall is about 1200 mm and annual average temperature is about 24°C. Tropical broadleaf forest is found in the upper reaches of this watershed, while grassland, crop field and rice paddy are prevailing in the middle and lower reaches.

SIMULATION DESIGN

The study area is divided into 11 grid boxes of 1×1 degree size (Fig. 1). For the control run (S1, Table 1), the actual vegetation classification for each grid is given according to the International Satellite Land Surface Climatology Project (ISLSCP) Initiative I data set (Sellers *et al.*, 1996b); i.e. broadleaf–evergreen trees (B, 4 grids),



A: agriculture/C3 grassland B: broadleaf-evergreen trees
O: different from simulation (S or A) S: short vegetation/C4 grassland

Fig. 1 Vegetation type of simulation grids and Nakhon Sawan gauging station in Chao Phraya River basin.

short vegetation/C4 grassland (S, 4 grids and O, 2 grids) and agriculture/C3 grassland (A, 1 grid).

Three comparison runs, S2, S3 and S4, were carried out with different settings. In S3 and S4 the vegetation distribution was changed from the original ISLSCP. A newly developed paddy scheme named SiB2-Paddy (Kim *et al.*, 2001; Arai *et al.*, 2000) was used in S2 and S4 (Table 1). The only differences in parameters between the SiB2-Paddy model and the original SiB2 were the increase in water storage capacity (from 0.2 mm to 300 mm) over the surface soil layer and the decrease in hydraulic conductivity (from 2.5×10^{-6} m s^{-1} to 5.0×10^{-8} m s^{-1}) of soil layers at saturation. Of course, energy and water balance schemes for rice paddy were also incorporated in SiB2.

The time interval of simulation is 1 h for all runs and the period was 1987 for the spin-up run and 1988 for the experimental runs. All radiative and atmospheric forcing values were derived from the ISLSCP Initiative I data set. As the time interval of this

Table 1 Simulation design according to used scheme and numbers of grid due to vegetation type.

Simulation	Using the paddy scheme	Number of grid due to vegetation type (B : S : A)
S1	no	4 : 6 : 1
S2	yes	4 : 6 : 1
S3	no	4 : 4 : 3
S4	yes	4 : 4 : 3

data set is 6 h, we interpolated all forcing values using this data set as follows: interpolation of downward short-wave radiation was carried out according to solar angle at each hour, precipitation and downward long-wave radiation were supposed to keep the same value for 6 h, and a linear interpolation technique was used for other values.

As the initial state for spin-up, soil wetness for all soil layers was given at 75% of the soil saturation value. Then the simulation was carried out 10 times with 1987 forcing data. After this spin-up run, the soil moisture reached the seasonally-repeating equilibrium state for all grids, with less than 5% or 5 mm difference of soil moisture between 31 December of successive years (Dirmeyer & Zeng, 1999). The final state of this spin-up run was used in turn as the initial state of all runs S1–S4. The runs S1–S4 were driven by the forcing data in 1988.

RUNOFF DATA

The observed runoff at Nakhon Sawan gauging station (15°40′N, 100°6′E) in the Chao Phraya River basin was used to evaluate the simulation (Fig. 1). Bhumibol and Sirikit dams are located upstream of the gauging station in this target area, and they modify the flow regime artificially. The observed runoff at the gauging station consists of natural runoff and artificial runoff, and the influence by the dams is estimated as artificial runoff according to the record of the change in water storage of the dam site:

$$R_a = -\frac{\partial(S_B + S_S)}{\partial t} \tag{1}$$

where R_a is artificial runoff by dams (mm day^{-1}) and S is storage of dam (mm) calculated by inflow and release. The subscripts a, B and S refer to the artificial, Bhumibol Dam and Sirikit Dam, respectively. Consequently, the natural runoff is defined as:

$$R_n = R_o + R_a \tag{2}$$

where the subscripts n and o refer to natural and observed.

RESULTS AND DISCUSSION

The runoff data of catchments are effective for the evaluation of hydrological or land surface model simulation (e.g. Oki *et al.*, 1999). Before the comparison between observation and simulation, R_n is estimated as illustrated in Fig. 2. The R_n is well estimated as adjusted runoff is nearly 0 for the dry season (Day 1 to Day 120) because the river flow in this season is only that released from dams. The comparisons of observed and simulated runoffs are shown in Fig. 3 and Table 2. The simulations are similar to each other in terms of their temporal variation and the quantity; however, they do not agree well with observations during the dry season and early wet season. If we disregard the coincidence of the value in daily time scale between the simulations and observations, the mean water and energy balance at the annual time scale are reproduced sufficiently well. This is due to the water flow control by dams and irrigation systems in this river basin for those periods. Therefore it is necessary to

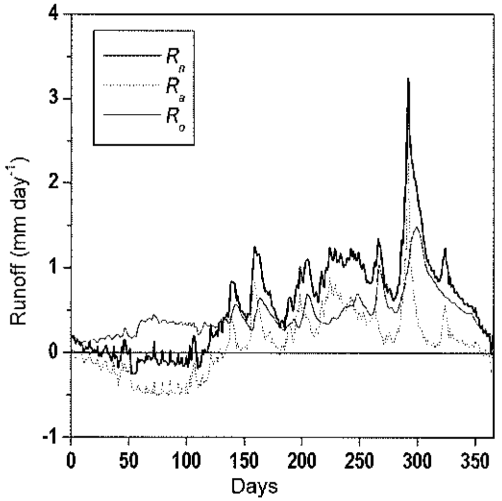


Fig. 2 Natural, artificial and observed runoff (R_n, R_a and R_o) in the Chao Phraya River basin (equation (2)). (R_a: observed artificial runoff between Bhumibol and Sirikit dams; R_o: observed runoff at Nakhon Sawan catchment gauging station.)

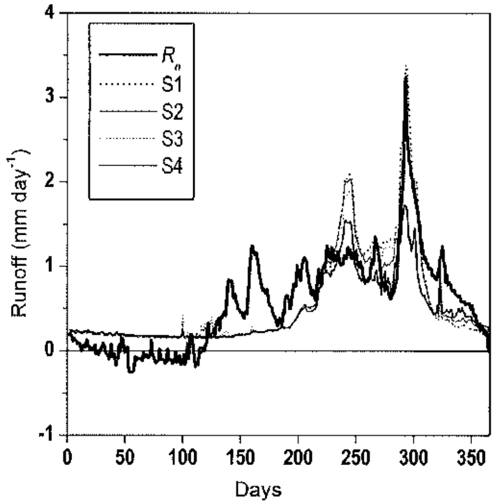


Fig. 3 Comparison of runoff between simulations and observation in Chao Phraya River basin. (R_n: natural runoff; S: simulation.)

adjust the parameters and to incorporate a river channel scheme in this kind of model for more realistic temporal variation of runoff. On the other hand, simulated annual discharge by S4 compared well with observations when the flow controls by two major dams are considered (Table 2).

Kim *et al.* (2001) reported that rice paddy covers large areas in East Asia, and also mentioned that, as rice paddy is seasonally filled with paddy water, the water and energy balance in such areas will become different from other agricultural vegetation, especially when leaf area index (*LAI*) is less than 2.0. Therefore, the new surface water

Table 2 Water balance of Chao Phraya River basin between observed and simulated runoff (mm year^{-1}).

		P	R_a	R_o	R_n	T	I	E
Observed		1314	10	166	176			
	S1				222	575	375	148
Simulated	S2				199	574	374	153
	S3				201	580	375	152
	S4				170	598	374	155

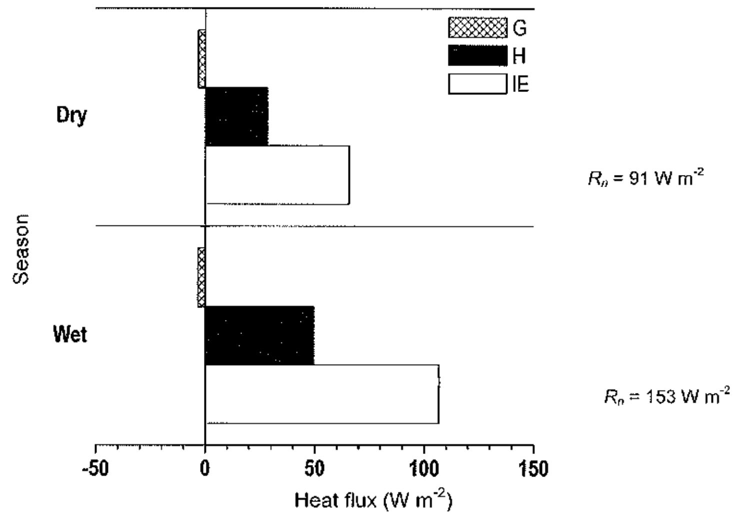
P : precipitation, T: transpiration, I: canopy interception, E: evaporation.

and energy balance calculation scheme of SiB2—named SiB2-Paddy (Kim *et al.*, 2001)—was developed to explain the water and energy balance of rice paddy. The SiB2-Paddy scheme was applied to the grid with vegetation type A (Fig. 1 and Table 1).

Comparing the results of S2 and S1 indicates that the implementation of the SiB2-Paddy scheme to an ISLSCP vegetation field (S2 run) seems to make a slight change both in water balances (Table 2) and in the runoff hydrograph (Fig. 3) compared to the control run (S1). However, the annual total runoff is still much more than the observed value (Table 2). In the S2 run, the SiB2-Paddy scheme was applied only to one grid with vegetation type A (Fig. 1). Although the ISLSCP initiative dataset tells us that the vegetation type of these two cells (symbol O in Fig. 1) is short vegetation/C4 grassland, from the land-use map of LANDSAT image (Fig. 1), these grids can also be the vegetation type "agriculture".

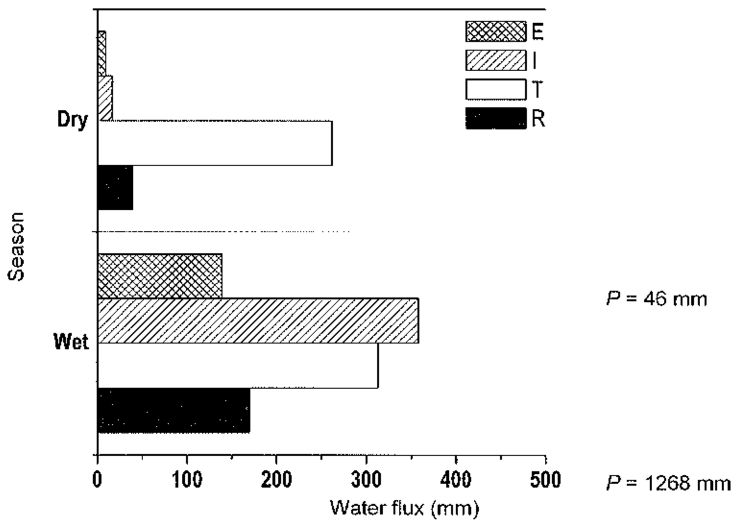
Then we carried out the S3 run, in which these two grids were designated as agricultural area but the SiB2-Paddy scheme was not used. The result did not show enough improvement from the S2 run. The S4 run is an experiment with the same land use as S3, and the SiB2-Paddy scheme was applied to a total of three agriculture grids in this run. The result of the S4 run showed improved water balance compared to all other runs (Table 2); the simulated annual natural runoff of S4 showed the best match to the observational value among the four runs. Therefore, it can be concluded that the SiB2-Paddy scheme can simulate water and energy balances, not only for point observation results (Kim *et al.*, 2001), but also for a large river basin under the condition that correct or realistic land-use properties for all calculation grids are given. Simulations of S2 and S4 with the paddy scheme led to slightly underestimation of runoff compared to S1 and S3, respectively. This is because the SiB2-Paddy has a buffer of water storage so that the time for possible evapotranspiration is longer, which means that a large amount of evapotranspiration can occur compared with the original SiB2 scheme.

The energy balance is necessary for understanding the water cycle and is studied with water balance for successful analysis. In the same study area through the dry season, Samakkee & Aoki (1998) and Suzuki *et al.* (1998) observed high latent heat flux in rice paddy and high transpiration in forest, respectively. All simulated latent heat flux is about 65% of net radiation for annual mean, and a difference between the dry and wet seasons was not shown (Fig. 4). The large ratio of latent heat flux to net radiation is caused by the high *LAI* and high soil moisture content in the lower soil layer. This results in transpiration that is absorbing/releasing the water from under the surface soil layer to the atmosphere by means of plants in the early dry season.



G: soil heat flux *H*: sensible heat flux
lE: latent heat flux R_n: net radiation

Fig. 4 Comparison of heat flux between dry and wet seasons in Chao Phraya River basin. (R_n: average net radiation for each season.)



E: evaporation *I*: canopy interception loss
R: runoff *P*: precipitation
T: transpiration

Fig. 5 Comparison of water flux between dry and wet seasons in Chao Phraya River basin. (*P*: total precipitation for each season.)

In particular, transpiration is 5.7 times greater than precipitation in the dry season (Fig. 5). Therefore the ratio of latent heat flux to net radiation does not become smaller than that of wet season.

SUMMARY

The two-dimensional offline simulations by SVATS (SiB2 and SiB2-Paddy) were carried out in Chao Phraya River basin and compared with the observed river discharge data at Nakhon Sawan gauging station. The results revealed:

The offline SVATS could simulate river discharge well without any optimization of model parameters as the artificial flow control by two major dams is taken into account. Therefore, this type of model can be used as an annual water balance predicting model even for a broad area.

The SiB2-Paddy scheme could simulate water and energy balance not only for point scales but also for a large river basin, if correct or realistic land-use properties for all calculation grids are given.

The ratio of latent heat flux to net radiation in a dry season is not lower than that of a wet season, which is concordant with the observation results. From the analysis of model calculations, this is due to the increase in transpiration from vegetation using soil moisture of the rhizosphere.

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