Effects of land use changes on hydrological responses of the Mekong River

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Abstract In hydrological modelling, one of the challenges is how to reflect the effects of physical basin features on hydrological responses. This paper focuses on investigating the effects of land use/land cover changes on hydrological responses for the Mekong River. In simulation, the strategy of gridded parameterization is explored for the physically based distributed hydrological model: block-wise use of the TOPMODEL with the Muskingum-Cunge routing method (BTOPMC); the basin is subdivided into 737 natural sub-basins; land use of the upper Mekong basin is changed into impervious area; rainfall and discharge data sets from 1980–1982 were used for optimization by the SCE-UA algorithm; data sets of 1985 were used for validation. The results indicate that land use changes will effect hydrograph and flow components.

Key words BTOPMC model; hydrological responses; land use changes; Mekong River

INTRODUCTION

Since the 20th century, the urbanization process in many countries has become quicker, especially in developing countries; concrete land cover is continually increasing and vegetation area is comparatively decreasing. Such human-made land-use changes will result in influences to the hydrological responses of a watershed, especially to the flood-runoff process. Quantitative studies on the effects of physical basin features on hydrological responses have significant value in protecting life, property and the natural environment in cities and downstream areas. Existing research indicates that parameters of physically-based distributed hydrological models can represent different physical basin features separately, such as vegetation, soil type, land use, etc. This kind of rainfall–runoff model has great potential for simulating hydrological responses resulting from natural and man-made land-use changes.

In this study, the Mekong River 3-year (1980–1982) hydrometeorological data sets are used for parameter estimation through calibration/optimization, in which the physically-based distributed hydrological model, block-wise use of the TOPMODEL with the Muskingum-Cunge routing method (BTOPMC), is used. Obtained parameters are used to simulate 1985 daily runoff of the five study sites in the lower Mekong mainstream. In simulation, land use/land cover of upper Mekong is assumed as concrete to investigate the effects on hydrological responses.

BTOPMC MODEL STRUCTURE AND PARAMETERS

BTOPMC is a physically-based distributed hydrological model which consists of several sub-models. It has the advantages of both lumped and distributed models (Ao *et al.*, 1999; Takeuchi *et al.*, 1999). There are only five parameters that need to be specified and they are briefly introduced as follows:

Topographic sub-model and its parameters

Automatic topographic analysis tools are used in BTOPMC to get all topographic variables. The watershed is described by drainage networks extracted from digital elevation maps (DEMs), in which all pits are filled with calculated small elevation increments (Ao *et al.*, 2001, 2003a). The topographic index, λ_i, of any grid cell, *i* (Beven & Kirkby, 1979; Quinn *et al.* 1995) is calculated by the following equation:

$$\lambda_i = \ln(a_i / \tan \beta_i) \tag{1}$$

where a_i is the drainage area per contour length, $\tan\beta_i$ denotes the slope of grid cell, i.

The basin is then divided into sub-basins, whose average topographic indices $\lambda(k)$ are calculated as:

$$\lambda(k) = \frac{1}{N_p(k)} \sum_{i=1}^{N_p(k)} \lambda_i \tag{2}$$

where k is sub-basin code and $N_p(k)$ is the total number of grid cells belonging to sub-basin, k. Equations (1) and (2) demonstrate the topographic parameters in BTOPMC. These are specified by DEM and subdivision level (Ao *et al.*, 2002, 2003b).

Runoff generation sub-model and its parameters

The assumptions and concepts of TOPMODEL are used for runoff generation for each grid cell by applying to each sub-basin. The effective precipitation $R_e(i,t)$ stored in the root zone at time step t is represented as:

$$R_e(i,t) = R_o(i,t) - S_{rmax}(i) - E_p(i,t) \tag{3}$$

where $E_p(i,t)$ denotes evapotranspiration; $R_o(i,t)$ is total precipitation approximated by the Thiessen method; S_{rmax} is maximum storage capacity of the root zone and is a parameter reflecting the effects of vegetation interception and soil moisture. The storage in the unsaturated zone is calculated as:

$$S_{uz}(i,t) = S_{uz}(i,t-1) + R_e(i,t) - q_v(i,t) \tag{4}$$

where $q_v(i,t)$ is the recharge to groundwater calculated by:

$$q_v(i,t) = T_0(k)\exp[-S(i,t)/m(k)] \tag{5}$$

where T_0 is the saturated soil transmissivity in m^2/h and m is the decay factor (in metres) of T_0. $S(i,t)$ is the local saturation deficit in metres that can be thought of as the distance from groundwater level to ground surface. It is determined by:

$$S(i,t) = S_{bar}(k,t) + m(k)[\lambda(k) - \lambda_i] \tag{6}$$

where $S_{bar}(k,t)$ is the average saturation deficit in meters of sub-basin k and calculated as:

$$S_{bar}(k,t) = S_{bar}(k,t-1) + \frac{1}{N_p(k)} \sum_{i=1}^{N_p(k)} (q_b(i,t) - \frac{1}{N_p(k)} \sum_{i=1}^{N_p(k)} q_v(i,t) \tag{7}$$

where $q_b(i,t)$ is the baseflow flowing into streams as calculated by:

$$q_b(i,t) = T_0(k)\exp[-S(i,t)/m(k)]\tan\beta_i \tag{8}$$

For $t = 1$, the initial value of the average saturation deficit, $S_{bar0}(k)$, which is a parameter to be calibrated, indicates $S_{bar}(k,0)$. As shown in equations (3), (5) and (7), in the runoff generation sub-model there are four parameters in total to be calibrated: $S_{rmax}(i)$, $T_0(K)$, $m(k)$ and $S_{bar0}(k)$.

Flow routing sub-model and its parameters

The Muskingum-Cunge (M-C) method (Cunge, 1969) is adopted for the flow routing sub-model. The equivalent Manning roughness coefficient for each grid cell is estimated/calibrated according to its land cover and soil type.

Evaluation criteria and objective function

Model performance is evaluated by the Nash-Sutcliffe Efficiency (E) measure and the Volume Ratio (V_r) of simulated to observed discharges. The objective function for optimization is designed as below:

$$F = 1 - E \; ; \; E = \sum_{i=1}^{N} w_i E_i \tag{9}$$

where N denotes the total number of calibration sites in study basin, w is the weighting factor and the sum of w_i equals 1.0. Here, each w_i equals 0.2 (Ao, 2004, 2005).

BASIN DESCRIPTION AND CALCULATION CONDITIONS

Basin description

The Mekong Basin, which is one of the largest international river basins in the world, is located in southeast Asia. Its headwater originates from the Tibetan highlands (elevation 4968 m) of China, and then flows through six countries: China, Myanmar, Laos, Thailand, Kampuchea and Vietnam, continuing in a southeasterly direction to the South China Sea. The basin has a drainage area of about 795 500 km^2. The length of the river is about 4620 km (excluding tributaries), and the basin is shaped like a violin; the upper basin being narrow and the lower part being wide. The basin's mean annual rainfall is about 1672 mm, and the average annual discharge is about 14 000 m^3 s^{-1}, measured at a site located approx. 545 km from the outlet (Hori, 1996). The five sites for simulating simultaneously along the lower portion of the mainstream are Chiang Saen, Luang Prabang, Vientiane, Mukdahan and Pakse, of which the total drainage area is 189 000–545 000 km^2, as shown in Fig. 1.

Topographic analysis

The DEM of the Mekong Basin was downloaded from the GTOPO30 database. For the purpose of shortening computational time, the grid cell size was enlarged from 1 × 1 km to 5.3 × 5.54 km by

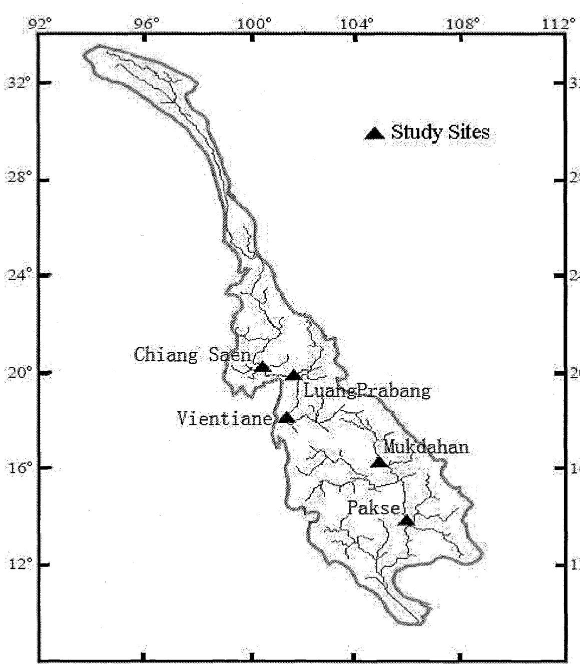

Fig. 1 Digital stream network of the Mekong River and the five study sites.

using the minimum elevation method. The digital drainage network of this basin is extracted from the pre-processed DEM. The whole basin was divided into 737 sub-basins with natural boundaries.

Data used

The 4-year (1980–1982 and 1985) hydro-climatic data sets are used, which include daily distributed basin precipitation of 43 raingauges obtained from the NOAA CD-ROM and the Yearbook of the Lower Mekong Basin, and daily observed stream discharges for the study sites attained from the Yearbook of the Lower Mekong Basin published in Thailand. The land cover map of IGBP Version 2 (USGS) and FAO soil map are used to get distributed data of land cover and soil types for each grid cell. Land cover is classified into four kinds. Three soil types which are clay, sand and silt have 108 combinations. The annual potential evapotranspiration was assumed to be 1700 mm.

Optimization description

The optimization is conducted by the SCE-UA algorithm (Duan *et al.*, 1994). Based on physical meaning of BTOPMC model parameters and modelling experience, all the five parameters of BTOPMC are optimized for each type of soil, land cover and topography. The three-year low flow rate during 1980–1982 was used to get parameter values, as shown in Table 1.

Table 1 Optimized model parameter values.

Parameter and unit	Physical interpretation	Physical properties	Final value
T_0 (m^2/s)	Saturated soil transmissivity	Clay	99.625
		Sand	298.098
		Silt	198.244
m (m)	The decay factor of T_0	Clay	0.004
		Sand	0.229
		Silt	0.027
$S_{r\max}$ (m)	Maximum storage capacity of the root zone	Deep rooted	0.017
		Shallow rooted	0.025
		Shallow rooted and irrigated	0.020
		Impervious area	0.003
S_{bar0} (m)	Initial value of averaged soil saturation deficit	$0 \leq \lambda \leq 10$	0.545
		$11 \leq \lambda \leq 20$	0.261
		$21 \leq \lambda \leq 30$	0.698
		$31 \leq \lambda \leq 40$	0.484
n_0	Equivalent Manning roughness coefficient	River mesh	0.015
		Built up area	0.002
		clay	0.043
		sand	0.043
		silt	0.044

Calculation strategy

To investigate the effects of land-use changes on hydrological responses, two cases are detailed here, and the same parameter values for each kind of physical basin features are shown in Table 1. Case 1 is to use original land cover and vegetation conditions for simulation of daily discharge of 1985. In case 2, land use/land cover of all the upper Mekong Basin, in which latitude ranges from 23 to 34, is assumed as impervious area. The hydrographs of the two cases are compared to investigate the hydrological effects of land-use changes.

Table 2 Comparison of hydrological responses of the two cases for the five study sites (validation).

Indices		Study sites	Chiang Saen	Luang Prabang	Vientiane	Mukdahan	Pakse
Average daily discharge ($m^3 s^{-1}$)	Surface	Case1	294	1071	1141	3123	4751
		Case2	896	1749	1836	3929	5784
	Subsurface	Case1	1606	2695	2834	3941	4525
		Case2	402	1441	1570	2632	3160
	Total	Case1	1900	3766	3975	7067	9276
		Case2	1298	3190	3406	6561	8944
Peak discharge ($m^3 s^{-1}$)	Surface	Case1	1764	5988	6109	19234	23543
		Case2	3520	7680	7896	19103	23657
	Subsurface	Case1	2725	5138	5482	8778	9811
		Case2	772	3683	3988	7185	8124
	Total	Case1	3615	10850	11430	25141	30457
		Case2	4248	11178	11830	23824	29315

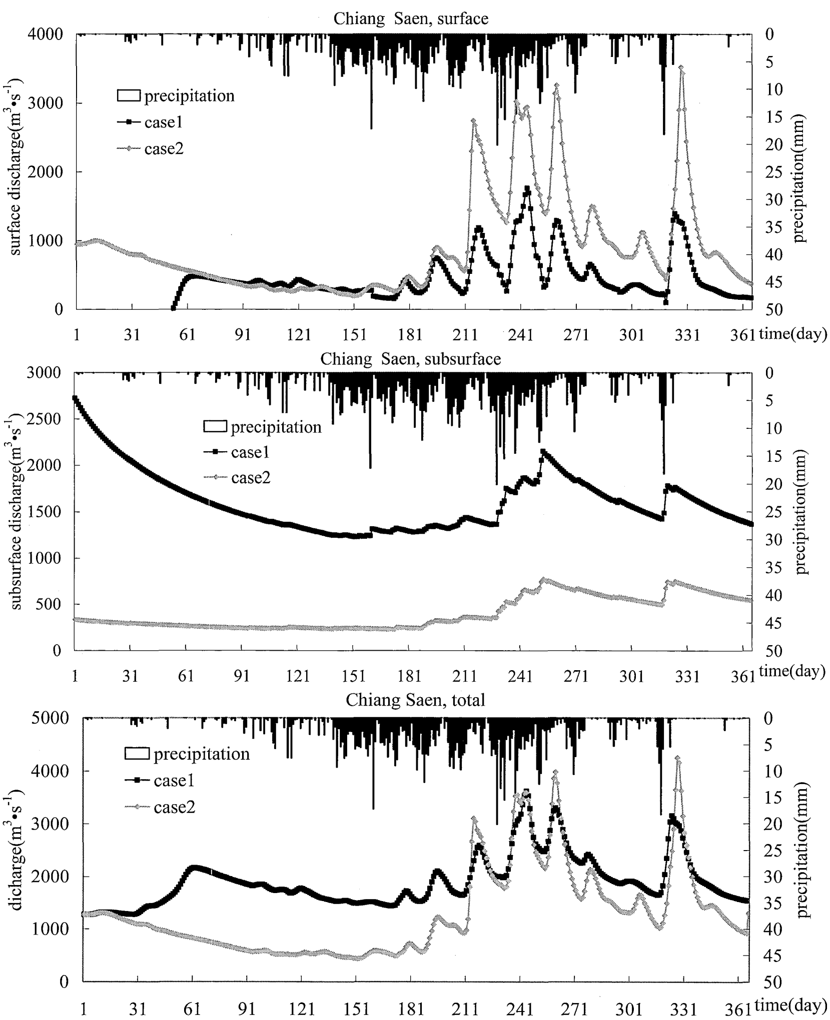

Fig. 2 Comparison of simulated hydrographs of Chiang Saen in the two cases, 1985 (validation).

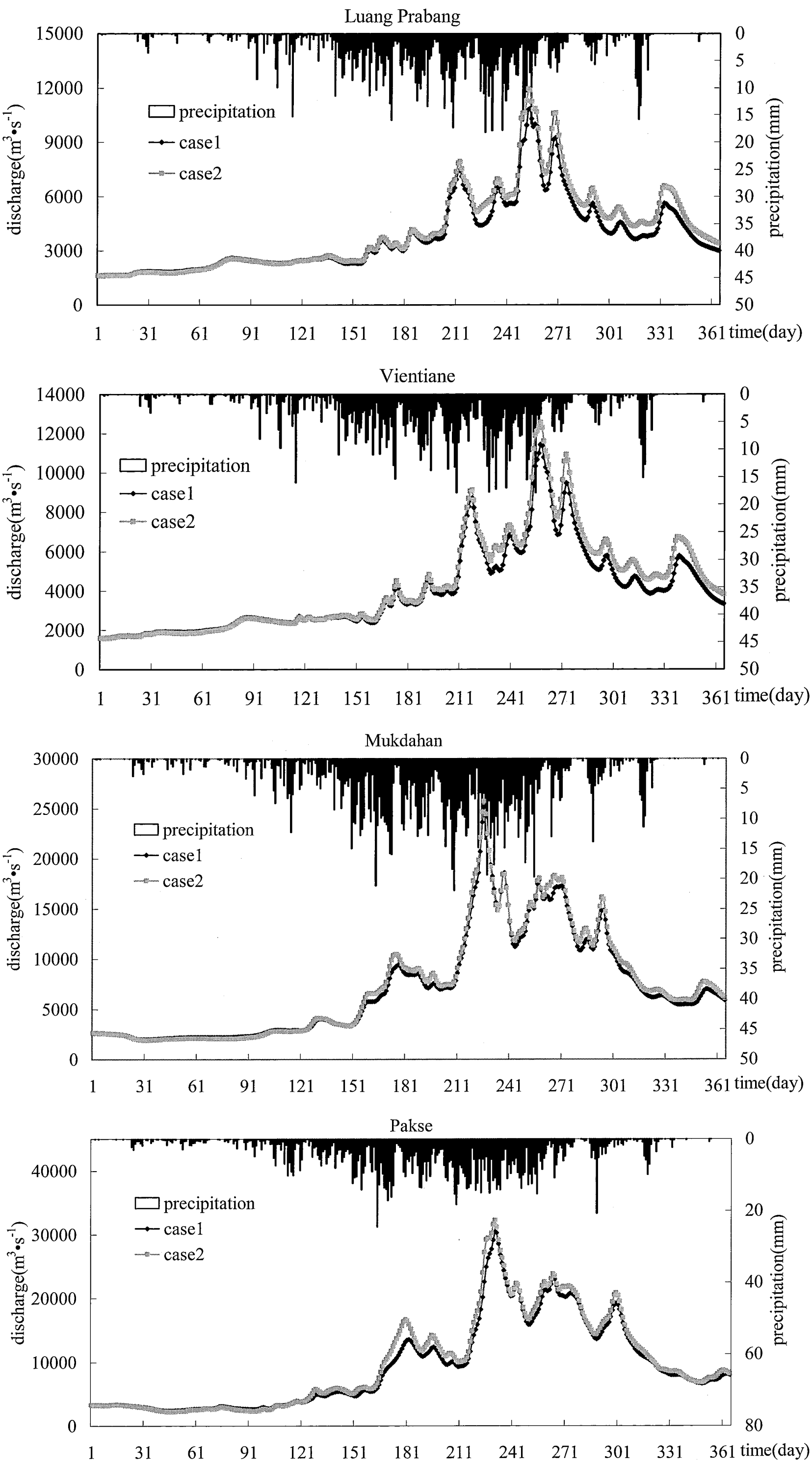

Fig. 3 Comparison of simulated hydrographs of the other four study sites in the two cases, 1985 (validation).

RESULTS AND ANALYSIS

Using the calculation strategy described above, two sets of BTOPMC validation performances corresponding to the two cases are summarized in Table 2. As validation results, the hydrograph of the first study site, Chiang Saen, of which all drainage area is changed into impervious area, is shown in Fig. 2, and the hydrograph of the other four study sites are shown in Fig. 3. From Table 2 and Figs 2 and 3, it can be seen that:

- In Table 1, optimized model parameters can be thought of as physically reasonable, these parameter values approximately reflected their corresponding physical basin features. Furthermore, from Table 2 and Figs 2 and 3, it can been seen that different land use leads to different hydrological responses, implying that BTOPMC and its parameters have the potential to reflect the effects of basin changes on its hydrological responses.
- Table 2 indicates that, for all the five study sites, land use changes result in changes of flow component. In detail, as the concrete area increases the ration of surface flow is increased while subsurface flow is decreased. This is reasonable because in the former case less water is available for infiltration.
- Table 2, Figs 2 and 3 also indicate that land use changes will influence peak flow. Peak flow increases with the increase of concrete area in the upper drainage area. This can be explained as concrete area generates more runoff and makes water flow fast.
- From Figs 2 and 3, it can be seen that for different study sites the degree of the effect is different. In this study, the upper study sites get more influence of hydrological responses than lower study sites. This can be considered as the effects of multiple factors, such as the distribution of rainfall, branches, reservoirs, etc.
- Table 2 indicates that land-use changes will influence the total amount of annual runoff. In this study, the bigger the ratio of concrete drainage area, the smaller the total runoff. This could be partly considered as the effects of evaporation, namely, more water is evaporated in the case of having a larger concrete drainage area.

CONCLUSIONS

In this study, physically-based distributed hydrological model BTOPMC was applied to the Mekong River to explore the effects of land use/land cover changes on hydrological responses. The preliminary main findings are summarized as follows:

- Model parameters obtained from gridded optimization can approximately reflect corresponding physical basin features such as land use/land cover, vegetation and soil types.
- Assuming land use of the upper Mekong as impervious concrete area, hydrographs and flow components at the lower Mekong River are different. This implies that BTOPMC and its parameters have the potential to simulate the effects of physical basin feature changes on the basin's hydrological responses.

However, due to the limitation of data set, scale problem, etc., further study is needed in the future to get more reasonable and accurate simulation results.

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