Toward the application of the physically based distributed hydrological model BTOPMC to ungauged basins

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Abstract For hydrological prediction and estimation in ungauged or data-poor basins, it is required that model parameters can be identified by using basin characteristics rather than calibrations. As the first step of exploring such a physically based identification method for the physically-based distributed hydrological model, BTOPMC (block-wise use of TOPMODEL with the Muskingum-Cunge method), preliminary studies on two aspects were carried out in this paper. First, through floods and annual runoff simulations for the Fuji-kawa and the Nakagawa basin of Japan, the effects of sub-basin scale on runoff simulation were investigated. It was found that smaller average sub-basin size produces higher peak discharge, larger baseflow and larger total runoff for floods, while similar effects on annual runoffs do not show any determined tendency and are not obvious; this is considered to be the effect of averaging scale of the topographic index. Furthermore, when average sub-basin area is smaller than about 1/150 of the entire basin, simulation results seem stabilized, indicating that a proper sub-basin scale for BTOPMC may exist, at which uncertainty due to subdivision level can be reduced to quite a low level. This subdivision level can be used as a reference value in establishing the relationship between model parameters and basin features. Second, for four USA basins, comparisons were conducted between the two-year hydrographs obtained separately from *a priori* estimation and automatic calibration; trials attempting to relate parameter values to basin features were carried out. The preliminary results of limited study cases suggest that it appears possible to establish the quantitative relations between parameter values and basin features for the BTOPMC model.

Key words BTOPMC model; Fujikawa River basin; MOPEX; Nakagawa River basin; parameterization; sub-basin scale; uncertainty

INTRODUCTION

How to predict and estimate hydrological phenomena in ungauged basins is a worldwide research challenge being faced by hydrology. To solve this problem, one of the fundamental or important requirements is to identify parameter values based directly on watershed physical features rather than the classical trial-and-error calibration, because there is not enough observed hydro-meteorological data such as precipitation and stream discharges to do calibration for ungauged basins. For many physically-based distributed hydrological models, it seems possible to explore such physically-based identification methods because of the physical basis/meaning in model equations and parameters, although various assumptions are usually contained.

However, some obstacles should be overcome in relating model parameters to basin features. For example, sub-basin and/or grid cell size selection will generally lead to predictive uncertainty in distributed hydrological modelling (e.g. Blöschl & Sivapalan, 1995; Sivapalan & Kalma, 1995). Although such a serious scale problem is still far from being solved, many valuable ideas have been proposed to attempt to solve it and hence improve model reliability. For instance: the simple scaling and multiscaling frame (e.g. Gupta *et al.*, 1994); the REA (Representing Element Area) concept (e.g. Wood *et al.*, 1988); the GLUE (Generalized Likelihood Uncertainty Estimation) framework (e.g. Beven & Binley, 1992); the HRU (Hydrological Response Units) concept of Flügel, 1995; as well as the basin-scale model equations (e.g. Kavvas *et al.*, 1998), etc. In addition, a lot of effort has been focused on the effects of grid size on model parameters/performances (e.g. Quinn & Beven, 1991; Franchini *et al.*, 1996; Saulnier *et al.*, 1997; Horritt & Bates, 2001; Snada *et al.* 2001).

At the current stage, the quantitative relationship between parameter values and watershed features are not yet available for many distributed hydrological models, since lots of parameters are immeasurable and also due to the effects of the scale problem. Moreover, as the numbers, physical interpretations, and value extents of parameters are actually model-dependent, no matter whether the specified parameters are effective values or measurable, different models will probably have different quantitative relationships between parameter values and watershed features, if they exist.

In the case of the physically-based distributed hydrological model, BTOPMC (Block-wise use of TOPMODEL with Muskingum-Cunge method), topographic/-spatial scale including both sub-basin and grid cell size is closely related to runoff to be generated, and the quantitative relationships between model parameters and basin features are not yet available. In this study, at first the effects of subdivision level (sub-basin scale) on runoff simulation were investigated, then a preliminary trial was conducted to investigate the strategy and possibility of relating parameters to basin features.

OUTLINE OF THE BTOPMC MODEL

The BTOPMC model is developed for hydrological simulation for large river basins (Ao *et al.*, 1999; Takeuchi *et al.*, 1999). In this model, runoff generation is based on TOPMODEL (Beven & Kirkby, 1979; Quinn *et al.*, 1995); flow routing is carried out by the Muskingum-Cunge method (Ao *et al.*, 2000); drainage networks are generated using the automated pit-removal method of Ao *et al.* (2001); study basins are automatically subdivided into either rectangular blocks or natural sub-basins over which groundwater balance was taken (the latter by the Pfafstetter numbering system, see Verdin & Verdin, 1999); calibration can be achieved either manually or automatically. Automatic optimization is accomplished by the SCE-UA algorithm (Shuffled Complex Evolution Method for Global Optimization–the University of Arizona, see Duan *et al.*, 1992).

BTOPMC has five parameters with physical meaning and four of them need calibration at the current stage, including the saturated soil transmissivity T_0 (m^2 h^{-1}), the decay factor m (m) of T_0, the maximum storage capacity S_{ramx} (m) of root zone due to vegetation, etc., the initial value of averaged saturation deficit S_{baro} (m), and the Manning roughness coefficient, n_0. The other parameter—the average topography index λ is directly identified by drainage networks. Among those S_{baro}, n_0 and λ should be given for each block/sub-basin, while T_0, m and S_{ramx} can be given either for each grid cell or for each block/sub-basin.

ON THE CHOICE OF SUB-BASIN SCALE

BTOPMC is a grid- and topography-based model in which the quantitative effects of topography on runoff generation is indirectly represented by the following equation:

$$S(k, i) = \{S_{av}(k) + m(k)[\lambda_{av}(k) - \lambda(k, i)]\}^{+} \tag{1}$$

where k is sub-basin number; i is grid number; $\{\cdot\}^{+}$ indicates that the value of $\{\cdot\}$ is non-negative and zero if negative; $S(k, i)$ is the saturation deficit of grid i; $S_{av}(k)$ is the average saturation deficit of sub-basin k; m is the decay factor of saturated soil transmissivity; $\lambda_{av}(k)$ is the average topographic index of sub-basin k, which is defined as an arithmetic mean of the local topographic index $\lambda(k, i)$ given by:

$$\lambda(k, i) = \ln[a(k, i)/\tan \beta_i] \tag{2}$$

where a is the area of the hillslope per unit contour length that drains through point i; $\tan \beta_i$ is the local topographic slope.

In this model, because the local saturation deficit $S(k, i)$ in equation (1) is directly used for overland flow and baseflow calculations, the difference between average and local topographic index, $\lambda_{av}(k) - \lambda(k, i)$, will probably have a significant impact on runoff generation. Here, we define:

$$\Delta\lambda(i) = \lambda_{av}(k) - \lambda(k, i) \tag{3}$$

as *effective topographic index*. In this equation, as local value $\lambda(k, i)$ is a constant for a given grid size, so the spatial distribution of effective topographic index Δλ and hence runoffs to be generated will directly be effected by the mean value $\lambda_{av}(k)$, i.e. by the shapes and sizes of sub-basins. Therefore, it can be said that in BTOPMC (and also in TOPMODEL), in addition to grid size, subdivision method and subdivision level are also very important topographic scale problems; this should be emphasized and studied further.

Basic considerations and study cases for sub-basin scale problem

In order to focus on the effects of sub-basin scale, the following three aspects were taken into account. Firstly, as we have seen from equation (3), both sub-basin scales and grid sizes can effect the spatial distribution pattern of the effective topographic index $\Delta\lambda(i)$. Therefore, grid size needs to be fixed in exploring the effects of sub-basin scales. Considering the worldwide comprehensive availability of DEM (digital elevation model) and for reducing data requirements for large watersheds, 30″ × 30″ GTOPO30 DEMs were selected in the current study. Secondly, from the standpoint of water balance, it is better that sub-basin shape reflects the actual drainage boundary. For this reason the Pfafstetter method was used to subdivide study areas into natural sub-basins with different average scales. Thirdly, soil type and vegetation were assumed homogeneous, parameter optimizations for each study basin were carried out for the case of no subdivision only, and the model was run with all parameters kept constant for all subdivision levels. This implies the simulated hydrographs of other subdivision levels will probably have worse fitness to the observed one than that of no subdivision. Therefore, the emphasis was placed on the comparison of simulation results of different subdivision levels, rather than the comparison with the observed hydrographs.

Based on the above conditions and considerations, the BTOPMC model was applied to the 3500 km^2 Fuji-kawa basin and the 3270 km^2 Nakagawa basin of Japan. Figure 1(a),(b) show their drainage networks and the study sites. The upstream of Shimizubata and Noguchi are subdivided into 1–249 and 1–153 sub-basins/units, respectively. Figure 2 shows the density distribution curves of the effective

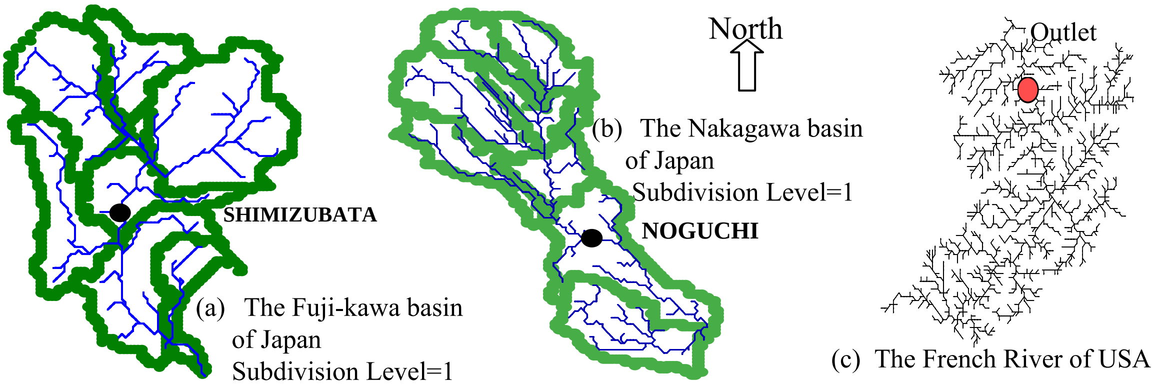

Fig. 1 Stream networks of the study basins and study sites.

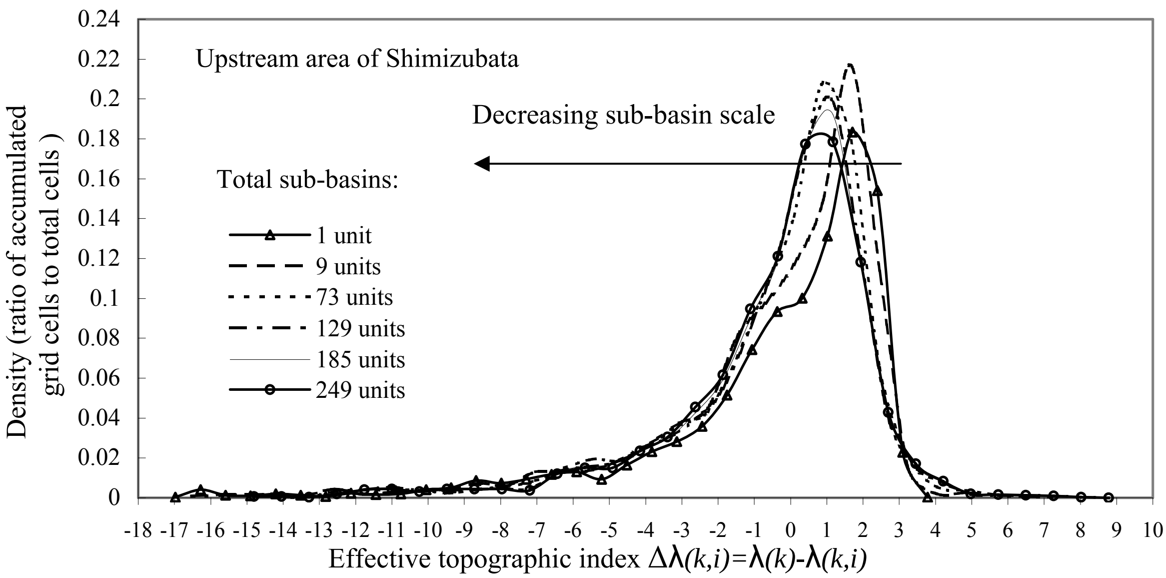

Fig. 2 Effects of subdivision level on the density distribution of the effective topographic index over the upstream area of Shimizubata.

topographic index $\Delta\lambda(i)$ corresponding to each subdivision level for Shimizubata. In Fig. 2, the case of one unit means no subdivision; and the larger the number of total sub-basins (units), the smaller the scale (average area) of sub-basins. From this figure it can be seen that subdivision level (sub-basin scale) does have effects on the spatial distribution of $\Delta\lambda(i)$ to be used in runoff calculations.

Corresponding to these subdivision levels separately, the flood of the Fuji-kawa basin in September 1993 and its annual runoff of 1990–1991, and the flood of the Nakagawa basin in 1989 were simulated by using hourly rainfall data sets, respectively.

RESULTS AND ANALYSIS

By analysing all hydrographs and model performance indices such as the volume ratio (the proportion of simulated total runoff to observed total amount) and the percentage of baseflow, etc. the effects of sub-basin scale on runoff simulation are summarized as follows:

Effects of sub-basin scale on peak time

The output data files of simulations indicated that even subdivision level increased from no subdivision to the highest level, the maximum difference of peak time was only one time-step earlier in the case of floods, while no difference of peak time appeared for the two-year runoff. Moreover, from the hydrographs shown in Figs 3 and 4(a), almost no obvious difference of peak time can be observed, in spite of the magnitude of all peaks. Therefore, it can be said that subdivision level has no significant effects on peak time.

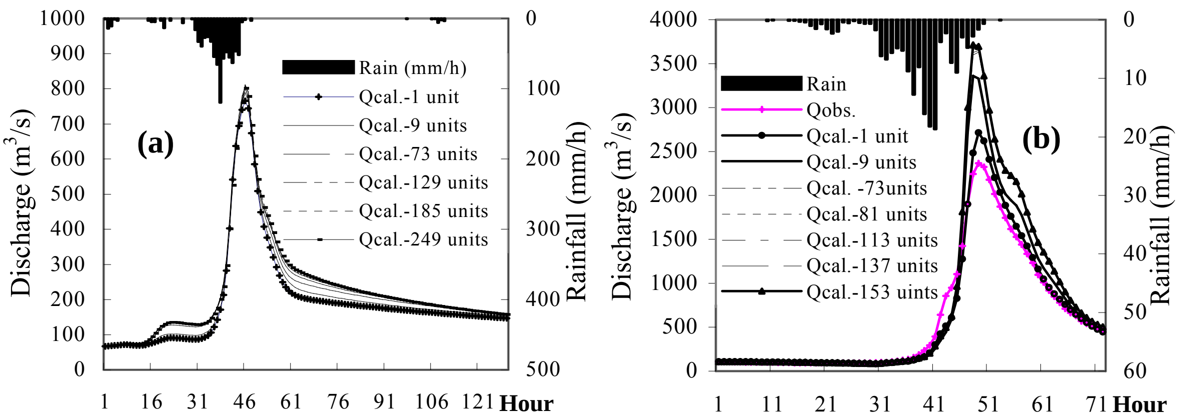

Fig. 3 Effects of subdivision level on hydrograph during flood/wet period. At Shimizubata of the Fuji-kawa basin, September 1991; (b) At Noguchi of the Nakagawa basin, August 1989.

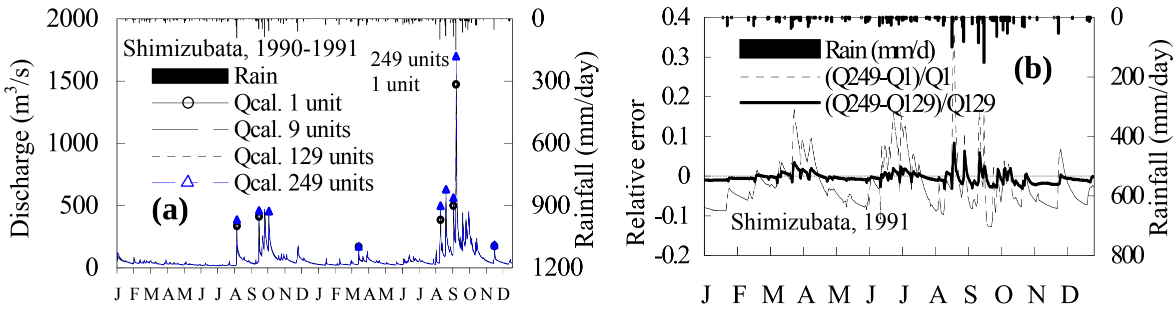

Fig. 4 Effects of subdivision level on annual runoff simulations for Shimizubata of the Fuji-kawa basin, 1990–1991: (a) hydrographs; (b) relative error.

Effects on total runoff and the temporal distribution of discharges

As shown in Figs 3 and 4, as the decrease of sub-basin scale, the discharges are generally increased during flood/wet periods while decreased during dry season. Consequently, due to such temporal distribution characteristics, higher subdivision levels produce larger total runoff for floods (Fig. 5(a),(b)), whereas in the case of annual runoff simulations, the differences between total runoffs are not obvious and are almost negligible (Fig. 5(c)).

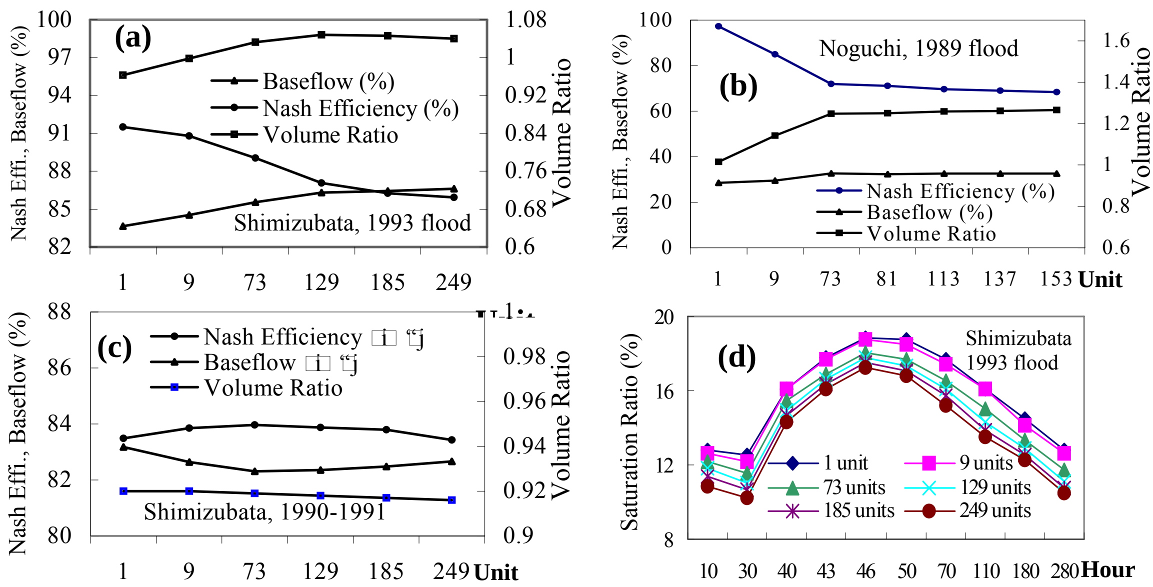

Fig. 5 Effects of sub-basin scale on model evaluation indices and on basin response processes. (a) Flood of Shimizubata in 1993; (b) Food of Noguchi in 1989; (c) Two-year runoff of Shimizubata during 1990–1991; (d) Saturation ratio.

Effects on flow components and response processes

Figure 5(a),(b) and (d) indicate that during flood/wet period, smaller sub-basin scales generate higher baseflow (e.g. 3–7% higher) and a lower saturation ratio. On the other hand, during the dry season as shown in Fig. 4(b), smaller sub-basin scales produce lower baseflow, since there is almost no overland runoff contained in discharges. Because of this tendency, the flow components of annual runoff are not sensitive to sub-basin scales as shown in Fig. 5(c).

Stabilized subdivision level

By further analysing Figs 3–5, it can be observed that although sub-basin scale does have various effects on runoff simulation results as stated above, the differences among hydrographs and the evaluation indices of model performances become smaller and smaller as subdivision levels increase; and as even further subdivisions were made, simulation results appear to be stabilized. This behaviour suggests that a sub-basin scale may exist, i.e. the so-called stabilized sub-basin scale, at which uncertainty in modelling due to subdivisions can be reduced to quite a low level. From the standpoints of both such stabilities and avoiding too many sub-basins, it seems that subdividing a study area into sub-basins with an average area of around 1/150 of the entire basin might be used as a referential subdivision level.

From the preliminary results mentioned above, it can be concluded that the main effects of sub-basin scale is on total runoffs of floods and the temporal distribution of annual runoff. This is because different subdivision levels will generate different spatial distribution patterns of the effective topographic index. While this distribution pattern tends to be almost the same when the mean area of sub-basins is smaller than about 1/150 of the entire basin, so that around this scale modelling results appear stabilized. Although the value 1/150 obtained from the limited simulation cases is not a strictly accurate one, it may be used as a referential scale for catchment subdivision both in modelling large river basins and in establishing the relationship between model parameter values and basin features.

ON THE POSSIBILITY OF RELATING PARAMETERS TO BASIN FEATURES

In this preliminary trial, the common strategy of the MOPEX (MOdel Parameter Experiment, http://www.nws.noaa.gov/oh/mopex/) was adopted. First, in order to quantitatively examine the parameter transferability for the BTOPMC model, blind tests were carried out. The parameter values of a data-rich and well-calibrated reference catchment were used as *a priori* estimation for all the study basins. This is because the quantitative relationship between parameters and basin features is not yet available for the current BTOPMC, and consequently *a priori* estimation cannot be done reasonably. Second, calibrations corresponding to blind tests were conducted. Because sub-basin scale has no significant effect on model performance for annual simulations as mentioned previously, no study basins were subdivided, implying that all five parameters are automatically optimized for each entire basin, respectively. Aiming at creating the quantitative relationship mentioned above, the optimized values of T_0 and S_{ramx} for three of the study basins were used for investigating their dependency on dominant soil types and land covers separately (strategy for inverse problem).

Study catchments and data sets

Four basins in the USA were selected (Table 1), with drainage areas ranging from 1024 to 4133 km^2. Using the areally-averaged data of daily precipitation, potential evaporation and daily stream discharge provided by MOPEX, their daily simulations of 1981–1982 were carried out. In a blind test, the parameter values of the 3500 km^2 Fuji-kawa basin of Japan were applied to these four catchments. Drainage networks (e.g. Fig. 1(c), the French River) were generated from 30″ × 30″ DEMs of GTOPO30. Soil type and land cover data are basin statistic fractions, respectively. Data of water use systems and snow melting are not available.

Table 1 Some basin features and model performance of estimated and calibrated.

Basin Name	Area (km^2)	Precipitation & Potential Eva. (mm 2 years)	Nash Efficiency (%) Estimated	Nash Efficiency (%) Calibrated	Volume Ratio $V_{cal}/V_{obs.}$ Estimated	Volume Ratio $V_{cal}/V_{obs.}$ Calibrated	Baseflow (%) Estimated	Baseflow (%) Calibrated
Monocacy River	2116	1823; 1795	17.9	56.4	1.42	1.03	69.5	68.6
Rappannock River	4133	1864; 1842	–18.4	53.4	1.63	1.11	56.9	70.8
Bluestone River	1024	1948; 1483	32.0	54.0	1.22	1.07	72.9	67.3
French River	2448	2429; 1639	49.9	76.7	1.27	1.01	77.3	80.14

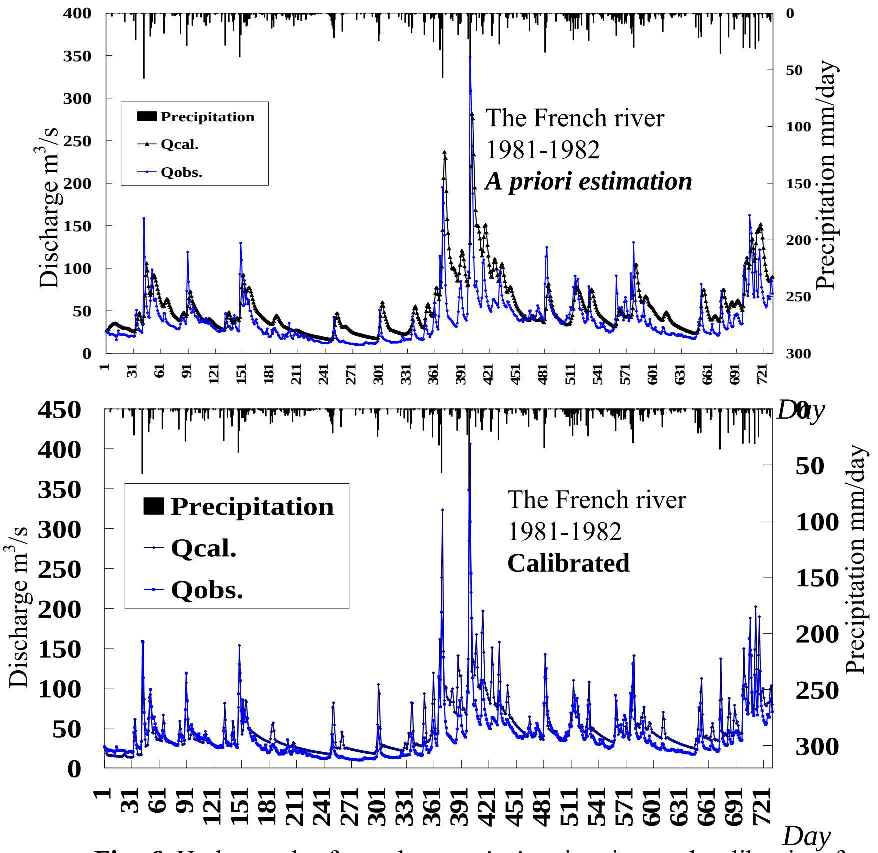

Fig. 6 Hydrographs from the *a priori* estimation and calibration for the French River basin, USA.

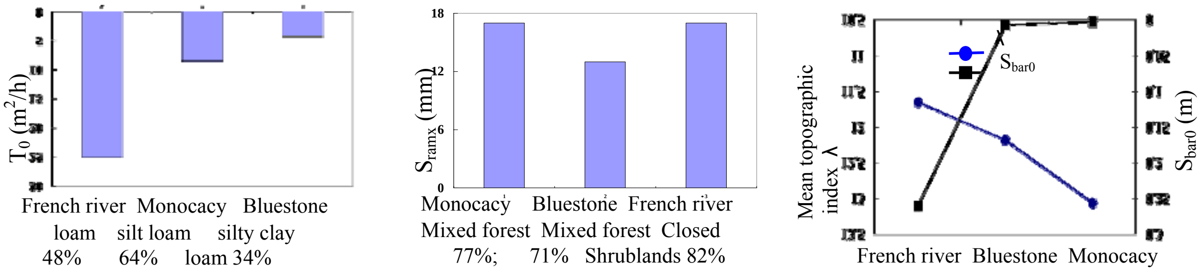

Fig. 7 Preliminary results: the dependency of some model parameters on main soil type, vegetation and topography.

RESULTS AND DISCUSSION

As summarized in Table 1, the French River has the best results (Fig. 6) among the four basins, with either estimated or calibrated parameters, while convergent optimization and better results were not obtained for the others. This might have resulted from the reliabilities of the effective precipitation and observed discharge data according to our visual inspection. Even so, as represented by Fig. 6, all estimated hydrographs have shown similar patterns to their observed ones. Our sensitivity analyses indicated that such hydrographs could be readily improved by appropriate parameter adjustments. In addition, because satisfied parameter values were not obtained due to data quality, it is not yet the time to create the quantitative relationships relating parameters to basin features. However, it can be seen from Fig. 7 that model parameters have a corresponding dependency on related physical features to some degree. These results suggest that it might be possible to set up the quantitative relationships for BTOPMC.

CONCLUDING REMARKS

The preliminary results obtained from the limited study cases indicate that it appears possible to establish a physically-based parameter identification method for BTOPMC on the base of a stabilized sub-basin scale, and it is hopeful for making hydrological prediction and estimation in ungauged watersheds using the BTOPMC. However, in general, although physically-based distributed hydrological models, including the BTOPMC, have the potential to be applied to ungauged or information-poor basins, a lot of problems still exist for further studies. For this purpose, the close cooperation of theoretical hydrology and observation hydrology etc. are extremely necessary.

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