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Effects of sub-basin scale on runoff simulation in distributed hydrological model: BTOPMC

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Abstract Scale problems result in uncertainty in hydrological modelling and is far from being solved. A distributed hydrological model BTOPMC (Block-wise use of TOPMODEL with Muskingum-Cunge method) analyses the effects of sub-basin scale on runoff in the Fuji-kawa and the Nakagawa basins in Japan. Study basins were subdivided into natural sub-basins using the Pfafstetter method. Results indicate that smaller average sub-basin size produces higher peak discharge, larger baseflow and total runoff for floods, while similar effects on annual runoff do not show any determined tendency and are not obvious. This shows the effect of averaging scale of the topographic index. Furthermore, threshold values of average sub-basin areas were found for study basins, around which simulation results seem stabilized, indicating that there may exist a proper sub-basin scale for BTOPMC, at which uncertainty due to subdivision level can be reduced to quite a low level.

Key words basin subdivision; Fuji-kawa Basin; Japan; Nakagawa Basin; Pfafstetter numbering; physically based distributed hydrological model BTOPMC; scale issue

INTRODUCTION

It has been widely recognized that spatial and temporal scales generally lead to predictive uncertainty in distributed hydrological modelling (e.g. Sivapalan & Kalma, 1995; Blöschl & Sivapalan, 1995). Model parameter dependence on sub-basin size and/or grid cell size is an example. Although such difficult and serious scale problems are yet far from any form of solution, many valuable ideas have been proposed to attempt to solve it and hence improve model reliability. For example, 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). In addition, many efforts have been focused on the effects of grid size on model parameters and performances (e.g. Quinn & Beven, 1991; Franchini *et al.*, 1996; Saulnier *et al.*, 1997; Sunada *et al.*, 2001; Horritt & Bates, 2001).

In the case of a physically based distributed hydrological model, BTOPMC (Block-wise use of TOPMODEL with Muskingum-Cunge method), topographic spatial scale of sub-basin and grid cell size is closely related to runoff to be generated.

In this study, the effects of subdivision level (sub-basin scale) on runoff simulation were investigated, attempting to find a proper sub-basin scale for applying BTOPMC to large watersheds, especially to ungauged/data-poor basins.

THE SIGNIFICANCE OF SUB-BASIN SCALE IN BTOPMC MODEL

The BTOPMC model is developed for hydrological simulation for large river basins (Takeuchi *et al.*, 1999; Ao *et al.*, 1999). In this model, runoff generation is based on TOPMODEL (Beven & Kirkby, 1979; Quinn *et al.*, 1995) and flow routing is carried out by the Muskingum-Cunge method (Ao *et al.*, 2000). Drainage networks are generated using the automated pit-removal method by Ao *et al.* (2001). Study basins are automatically subdivided into natural sub-basins by the Pfafstetter numbering system (Verdin & Verdin, 1999) or rectangular blocks, over which groundwater balance is taken. Model parameters are automatically calibrated using the SCE-UA optimization algorithm (Duan *et al.*, 1992).

BTOPMC is a grid- and topography-based model, in which 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 saturation deficit of grid i; $S_{av}(k)$ is average saturation deficit of sub-basin k; $m(k)$ is decay factor of saturated soil transmissivity of sub-basin k; and $\lambda_{av}(k)$ is 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 grid 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 significant impacts 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, thereby the spatial distribution of effective topographic index $\Delta\lambda$ and hence runoff generation could be significantly affected by the mean value $\lambda_{av}(k)$, i.e. by the shapes and sizes of sub-basins. Therefore, in BTOPMC (and also in TOPMODEL), in addition to grid size, subdivision method and subdivision size are also very important topographic scale problems to be studied.

STRATEGY INVESTIGATING SUB-BASIN SCALE PROBLEM AND CASE STUDY

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 equations (2) and (3), both sub-basin scales and grid sizes could have great impact on 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 river basins, GTOPO30 DEMs were selected here. Secondly, the Pfafstetter method was used to subdivide study areas into natural sub-basins to reflect the actual drainage boundary. Thirdly, assuming soil and vegetation types to be homogeneous, parameter optimizations for study basins were carried out only for the case of no subdivision, and all parameters were kept constant for runoff simulations of all subdivision levels. This implies the simulated hydrographs of other subdivision levels will likely have worse fitting 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 observed hydrographs.

Based on the above conditions and considerations, BTOPMC was applied to the Fuji-kawa Basin (3500 km^2) and the Nakagawa Basin (3270 km^2) in Japan. Figure 1 shows their drainage networks and the study sites. The upstream of Shimizubata and Noguchi were subdivided into 1 to 249 and 1 to 153 sub-basins (units), respectively. Figure 2 shows the density distribution curves of the effective 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) have significant impact on the spatial distribution of $\Delta\lambda(i)$ used in runoff calculations.

Corresponding to these subdivision levels, a flood simulation in September 1993 and an annual runoff simulation from 1990 to 1991 at the Fuji-kawa basin, and a flood simulation in 1989 at the Nakagawa Basin were conducted by using spatially distributed hourly rainfall datasets. In all simulations, rainfall input for a grid cell was always given the record of its nearest rain gauge and not affected by subdivision level. The only difference of computational conditions for each simulation is the subdivision level.

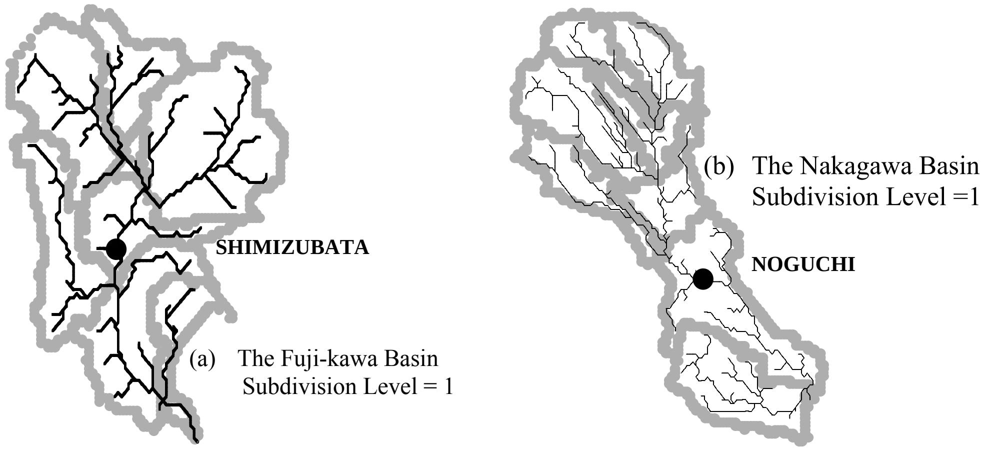

Fig. 1 Stream networks of the study basins and study sites.

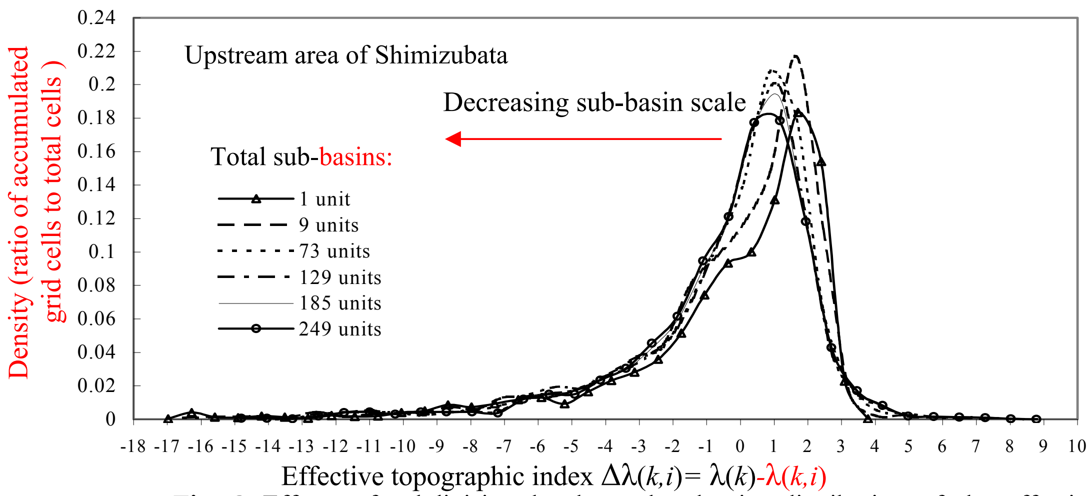

Fig. 2 Effects of subdivision level on the density distribution of the effective topographic index over the upstream area of Shimizubata.

RESULTS AND CONCLUSIONS

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

Effects of sub-basin scale on peak time. The simulation results 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 flood simulations, and no difference of peak time appeared for the two-year runoff simulation. Moreover, from the hydrographs shown in Figs. 3 and 4(a), almost no obvious difference of peak time is observed in spite of the magnitude of flood peaks.

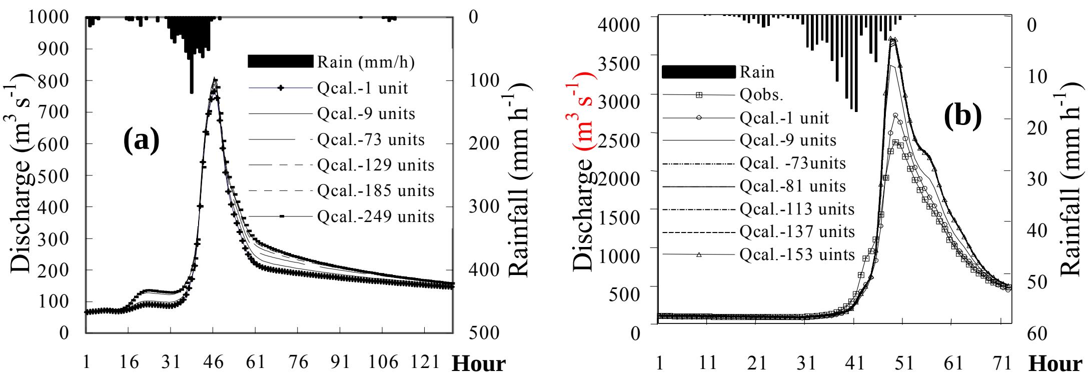

Fig. 3 Effects of subdivision level on hydrograph during flood/wet period. (a) Shimizubata of the Fuji-kawa Basin, September 1991; (b) Noguchi of the Nakagawa Basin, August 1989.

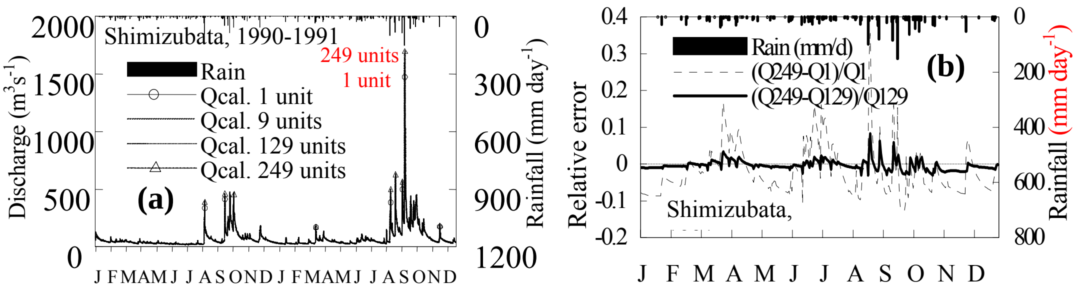

Fig. 4 Effects of subdivision level on annual runoff simulations for Shimizubata of the Fuji-kawa Basin, 1990-1991. (a) Simulated hydrographs; (b) Relative error among different sub-basin scale.

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

Effects of sub-basin scale on flow components and response processes. Figures 5(a), (b) and (d) indicate that during flood/wet period, the models with smaller sub-basin scales generate higher baseflow (e.g. 3-7% higher) and lower saturation ratio. On

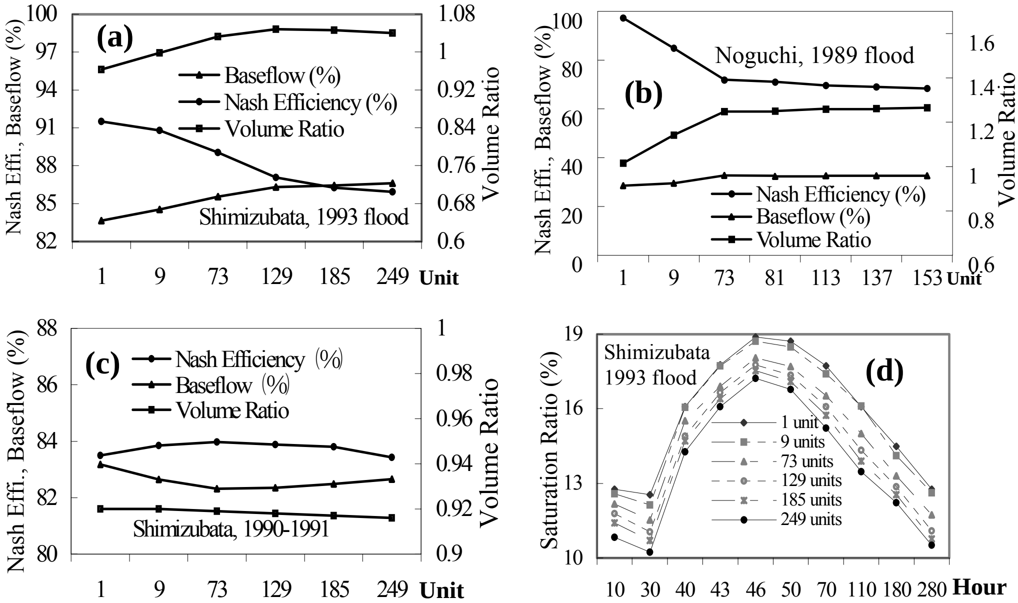

Fig. 5 Effects of sub-basin scale on model evaluation indices and basin response processes. (a) Flood simulation at Shimizubata in 1993; (b) Flood simulation at Noguchi in 1989; (c) Two-year runoff simulation at Shimizubata during 1990-1991; (d) Temporal change of saturation ratio in flood simulation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

the other hand, during dry season, as shown in Fig. 4(b), the models with smaller sub-basin scales produce lower baseflow since almost no overland runoff is contained in discharges. Because of such tendency, the flow components of annual runoff behave insensitive 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 that among corresponding evaluation indices of model performances become smaller and smaller as subdivision levels increase (average sub-basin size decreases); and even further subdivisions were made, simulation results appear stabilized. These behaviours suggest that there may exist an average sub-basin scale at which uncertainty in modelling due to subdivisions can be reduced to quite a low level. Here we define such average sub-basin size as the threshold of subdivision. As shown in Figs. 5(a) and 5(b), the subdivision threshold for Shimizubata may be estimated as about 1/130 of its drainage area and 1/75 for the Nakagawa Basin. Here the threshold appears to depend on the basin and the structure of stream networks. Therefore, more case studies are needed to explore a common threshold for different basins. As a conservative estimation for the current two study basins, their common threshold may be set as 1/130-1/150 of their drainage areas, by which simulation stabilities and avoiding too much sub-basins can be achieved.

From the preliminary results mentioned above, it is concluded that the main effects of sub-basin scale appear in flood simulations. This is because different subdivision level generates different spatial distribution pattern of the effective topographic index. The distribution pattern tends to be almost the same when the mean area of sub-basins is smaller than a threshold. This phenomenon suggests that there may exist a proper subdivision level for BTOPMC that may be used both in modelling large river basins and in establishing the relationship between model parameter values and basin features. However, further study is required to explore the basin dependence of the subdivision threshold.

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