京 都 大 学 防 災 研 究 所 年 報　第48号 C　平成17年4月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 48 C, 2005

Delineating Hydrological Response Units in Hydrological Modelling

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Synopsis

In this paper a new approach is proposed to delineate sub-basin in a watershed model using watershed topographical features and soil properties. Modified BTOPMC (Block-wise TOPMODEL with Muskingum-Cunge flow routing method) was applied to part of the Mekong River basin. The watershed is divided into several imaginary blocks in order to understand the effect of dividing into blocks on hydrological simulations. Number of blocks that gives the highest standard deviation of block average soil topographic index is suggested as the optimum number of blocks for BTOPMC simulations.

Keywords: BTOPMC model, watershed model, Mekong river basin, hydrological response unit

1. Introduction

Regional-scale catchments are important integrators of many physiographic and climatic forces. Water resources professionals should re-examine many aspects of the way that the decisions were made for planning and management of water resources systems to meet increasing demands for sustainable development. This needs sound hydrological models to gain knowledge on current and future hydrological conditions and processes.

Since the introduction of the first blueprint of distributed hydrological model (Freeze and Harlan, 1969) hydrological modelers' have been trying to model exact processes occurring in complex watershed terrains as accurately as possible. Availability of Geographical Information System (GIS) data sets of watershed physical properties such as land use, soil types, geology and advancements in obtaining distributed meteorological variables with the help of GIS have stimulated the development of physically based hydrological models. TOPMODEL (Beven and Kirkby, 1979) is a parsimonious physically-conceived semi-distributed catchment scale rainfall runoff model based on spatially distributed soil topographic index. It has been widely used to simulate hydrological processes in small scale watersheds and also to address different hydrological problems such as scaling theory, flood frequency problems, and water table depth. Beven et al. (1995) discussed the problems associated with use of coarse grid cells and the applicability in large scale basins.

BTOPMC (Block wise TOPMODEL with Muskingum-Cunge flow routing method) is a semi distributed hydrological model designed to extend the applicability of TOPMODEL from hundreds of square kilometers to several ten thousands of square kilometers (Takeuchi et. al, 1999). In original TOPMODEL local saturation deficit is estimated with respect to average saturation deficit of a basin. The BTOPMC uses the block average saturation deficit instead of basin average value to calculate local saturation deficit.

Over the past two decades a consensus has begun to form that the physics of catchment behavior can be captured in a meaningful way at an appropriate scale. Different approaches have been suggested for appropriate representative modelling unit. The question of when to stop the process of division of a basin into ever smaller units is vexed. As one possible answer to this question, the concept of a representative elementary area (REA) was introduced by Wood et al. (1988). A REA can be considered as an appropriate scale at which a simple rainfall runoff processes could be obtained. The REA is the hypothesized smallest area, on the order of 1 km for catchments studied by Wood and his co-workers, for which the pattern of local heterogeneity is relatively unimportant in the sense that heterogeneities can be treated statistically, without regard to the exact spatial pattern of the heterogeneity. The ultimate utility of the REA concept to the science of catchment hydrology remains to be determined. In this paper an effective approach for block delineation is discussed for extending TOPMODEL concept for large scale watersheds.

2. Modified BTOPMC hydrological model

Hydrological modelling consists of basin representation and response simulation. The manner that response is simulated depends on the type of model used and spatial and temporal scales as well as the parameterization. Hydrological models have best performance in basins where model assumptions are met. Owing to constrains in available data and difficulties in understanding the exact processes, assignment of hydrological model parameters to represent watershed physical properties is not an easy task.

Beven and Kirkby (1979) proposed the TOPMODEL (Fig. 1) based on contributing area concept in hill slope hydrology. Since then, there have been many developments to the model. TOPMODEL is based on original exponential transmissivity assumption that leads to the $ln(a/T_0 tan\ \beta)$, soil-topographic index, where a is the upstream catchment area draining across a unit length of contour line (m^2m^{-1}), T_0 is the lateral transmissivity under saturated conditions (m^2h^{-1}), and β is the local gradient of ground surface. It is a combination of lumped and distributed model concepts using soil-topographic characteristics. However, the applications were limited to relatively small basins up to several hundreds square kilometers (Beven and Kirkby, 1979). Due to lack of measurements of internal state variables and catchment characteristics, the applicability of the TOPMODEL with modeler's perceptions is high while introducing minimum number of parameters.

The BTOPMC is a physically based distributed hydrological model based on block wise use (Fig. 2) of TOPMODEL with Muskingum–Cunge flow routing

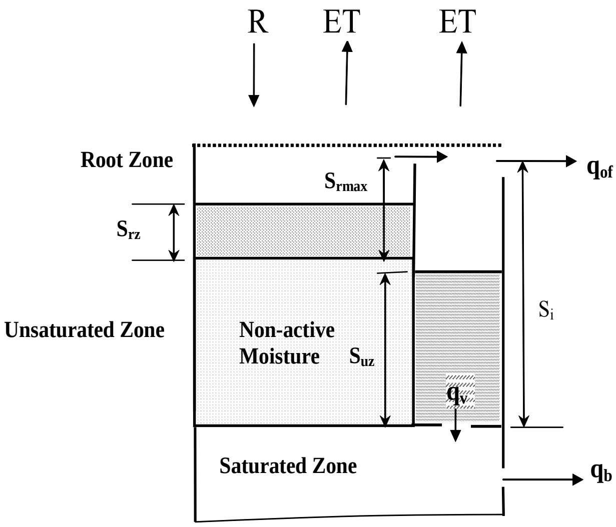

Fig. 1 Column model of the original TOPMODEL

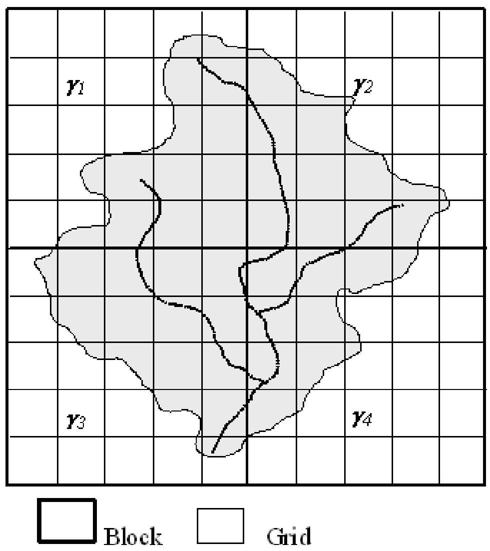

Fig. 2 Block wise concept

method (Takeuchi et al., 1999). Nawarathna et al. (2001) discussed the problems that arise in applying BTOPMC to large scale watersheds. The model was originally developed in the Takeuchi/Ishidaira laboratory, Yamanashi University, Japan.

In the block wise approach, the watershed is divided into several blocks and local saturation deficit which controls the depth to the saturation zone is calculated with respect to the block average saturation deficit. Model parameters T_0, m, maximum root zone storage (Sr_{max}), and flood plain Manning's coefficient, are assigned depending on land use database in the distributed BTOPMC model. Because of the difficulties in finding high resolution soil property databases for the study region, it is assumed that soil properties are largely related to land use in areas where human interference has not changed natural environment drastically.

Runoff contributed from any gird cell is composed of overland flow and base flow in BTOPMC formulations. Saturation deficit controls the discharge from local area. The local saturation deficit is determined from local soil-topographic index relative to its block average value (γ). Both overland flow and base flow depend on local saturation deficit. Local saturation deficit depend on block average saturation deficit and local soil- topographic index. Thus, the soil-topographic index is the critical controlling factor in runoff generation and is a function of topography and soil type.

Over a block, an average saturation deficit $S(t+1)$ is determined from equation (1).

$$S(t+1) = S(t) - Q_v(t) + Q_b(t) \qquad (1)$$

Where,

$S(t)$ - previous average saturation deficit,

$Q_v(t)$ - input to saturation zone storage from infiltration zone

$Q_b(t)$ - groundwater discharge to the stream over all grids in the block in m.

The local saturation deficit $S(i,t)$ at grid cell i is estimated with respect to the block average saturation deficit $S(t)$, and the magnitude of local soil topographical index relative to its block average value γ. In the TOPMODEL both γ and $S(t)$ are calculated for the whole basin.

$$S(i,t) = S(t) + (\gamma - m \ln(a/T_0 \tan\beta)) \qquad (2)$$

Where, m is a soil depth parameter (decay factor), dependant on the rate of change of conductivity with depth in the profile. The value γ for the distributed BTOPMC model can be given as follows:

$$\gamma = \frac{1}{A}\sum_i m_i \ln\frac{a_i}{T_{0,i}\tan\beta_i}$$

In the original TOPMODEL, it was assumed that the upslope contributing area has a homogeneous recharge rate in deriving Eq. (2). This assumption may not be valid for the large watersheds. When comes to block wise approach, it assumes a homogeneous recharge at each block.

The root zone (interception store) first receives rainfall on the i^{th} grid cell. The storage in root zone $S_{rz}(i,t)$ changes over time as follows

$$S_{rz}(i,t) = S_{rz}(i,t-1)+R(i,t)-E(i,t) \qquad (3)$$

Where R is precipitation and E is the potential evapotranspiration. If available water in the interception zone is not enough to meet evapotranspiration demand, model takes water from infiltration zone. The excess of root zone storage ($S_{rz}(i,t)$- $S_{rzmax}(i,t)$) overflows into the infiltration zone and its storage $S_{uz}(i,t)$ can be given as

$$S_{uz}(i,t) = S_{uz}(i,t-1)+ S_{rz}(i,t)- S_{rzmax}(i,t) \qquad (4)$$

Overland flow from grid cell i $q_{of}(i,t)$ can be given as follows

$$q_{of}(i,t) = S_{uz}(i,t) - S(i,t) \qquad (5)$$

The decline of local transmissivity with decreasing storage in the soil profile has been approximated by an exponential function (Beven and Kirkby, 1979).

$$T = T_0\, e^{-S(i,t)/m} \qquad (6)$$

Groundwater discharge is considered semi-steady depending on the saturation deficit. Hydraulic gradient is assumed parallel to the ground surface. Groundwater discharge from grid cell i is determined from Eq. (7).

$$q_b(i,t) = T_0\, e^{-S(i,t)/m} \tan\beta \qquad (7)$$

The discharge per unit width from grid cell i to the stream is the sum of $q_{of}(i,t)$ and $q_b(i,t)$. Total discharge contributed from the cell and surface run off to the cell is routed to the down stream along the river network using Muskingum-Cunge flow routing method.

3. The Mekong river basin

The Mekong River flows in a pan-shaped basin that drains into the South China Sea (Fig. 3). The Mekong flows through six countries: China, Myanmar, Lao PDR, Thailand, Cambodia, and Vietnam. It is the twelfth longest river, 8th largest river in terms of annual runoff (475 000 MCM) and the world's least exploited major water course in terms of dams and water diversions. It begins its 4,200 km journey through steep mountainous gorges in the highlands of eastern Tibet. It gathers runoff contributions from an area of 795,500 square kilometers before meeting the South China Sea. Fed by melting snow on the Tibetan Himalayas and monsoon rains, the river nourishes lives of over 60 millions of peoples in Southeast Asian region.

The climate of the Mekong basin is dominated by two distinct monsoons. The rainy southwest monsoon, which occurs from Mid May to early October, is the main source of precipitation to the region. Melting snow in Tibet and Yunnan from March to June and dry northeast monsoon from October to March only account for about 10 % of the total precipitation. The normal annual rainfall in the region varies from 1000 mm near Khon Kaen in North-eastern Thailand to 4000 mm in the mountainous fringes of the basins lying in Laos, Cambodia and Vietnam. About 88 % of the annual rainfall falls between May and October. The rainfall regime depends largely on topographical features. Because of its long path over the sea, the Southwest monsoon carries more moisture resulting heavy rainfall especially in hilly and mountainous parts. The Northeast monsoon on the other hand which flow mainly over land is relatively dry and brings practically no rains other than to the coastal slopes in Vietnam. Cyclone is one of the natural disasters which diversely disturb the life style. The region is subjected to cyclones often in the months of August and September causing serious flooding.

The Mekong river basin's land cover mainly composed of irrigated land and forest (Fig. 4). The forests in the basin have undergone periodic cleaning and re-growth due to many generations of widespread agriculture in the lower and middle regions. The basin forests comprise of two major groups, evergreen and deciduous. The prevailing farming systems are predominantly relying on rain fed paddy cultivations.

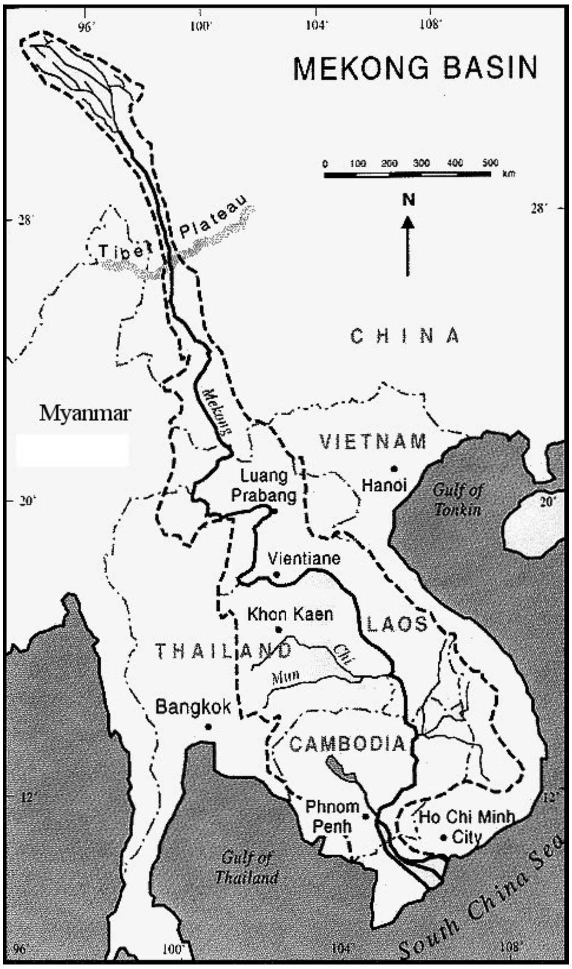

Fig. 3 Location map of the Mekong Basin

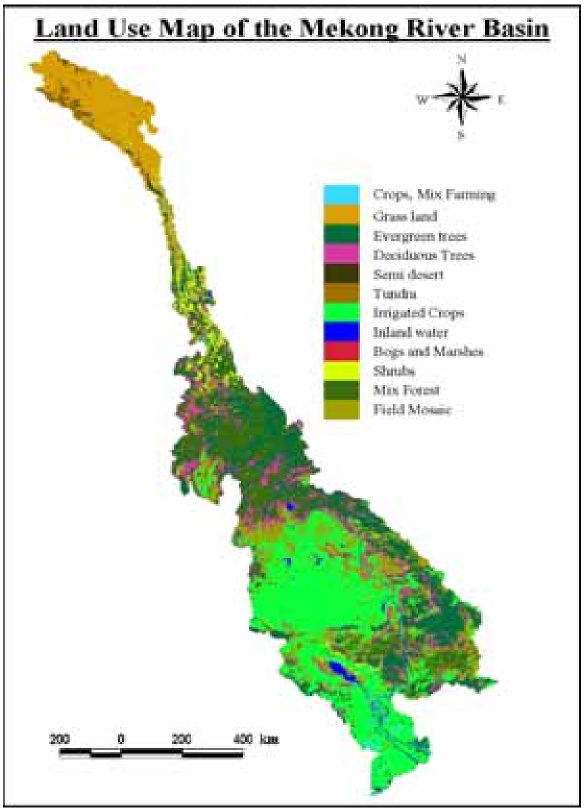

Fig. 4 Land use map of the Mekong River basin

4. Model application to the Mekong river basin

In this research, distributed BTOPMC model is used to model hydrological processes of the effective watershed from Luang Prabang to Pakse gauging station (Fig. 5). The model performs calculation on pixel-by-pixel basis. It is intended to assign parameters to each pixel by considering heterogeneity of soils, land use and geology. However, present parameters were obtained by only considering the land use. The Mekong River routes the upstream discharge at Luang Prabang to most down stream gauging station in Pakse. Travel time between the generation point and the downstream gauging station of a particular model out put mainly depends on the Manning's *n* value for large-scale watersheds. Assignment of different Manning's coefficients for the Mekong River, tributaries and flood plain as functions of land use and slope enhanced the simulations results. Thresholds for effective drainage area values were defined to differentiate the mainstream, tributaries and flood plains.

The Manning's coefficient along the main stream and tributaries are assigned as a function of slope and the best Manning's coefficient value at the most downstream location. Best Manning's *n* value of the Mekong River was selected considering the patterns of both simulated and observed hydrographs without rainfall. Average Manning's coefficient values found for both the main river and tributaries are 0.029 and 0.034, respectively. Flood plain Manning's coefficients were assigned depending on the simplified land use type of the pixel. Root zone maximum storage (S_{rmax}), T_0 and m values for all land use classes were assigned using the previous research work (Nawarathna *et al.*, 2001).

Functions were introduced to consider intentional water storages in irrigated fields and reservoirs. Hydrographs at different gauging station were simulated and compared with measured values. Simulated hydrograph with four number of blocks from Khong Chiam to Pakse (154,000 km^2) for year 1993 is shown in Fig. 6.

The evaluation of model performance with different number of blocks is based on Nash-Sutcliffe efficiency criteria. (Nash and Sutcliffe, 1970).

$$\text{Nash-Sutcliffe Coefficient} = 1 - \frac{\sum (Q_{obs} - Q_{cal})^2}{\sum (Q_{obs} - \overline{Q_{obs}})^2} \quad (8)$$

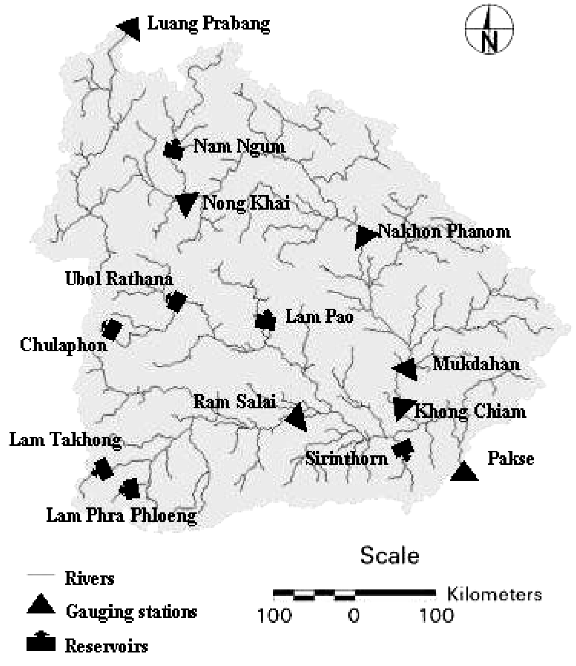

Fig. 5 Study Area

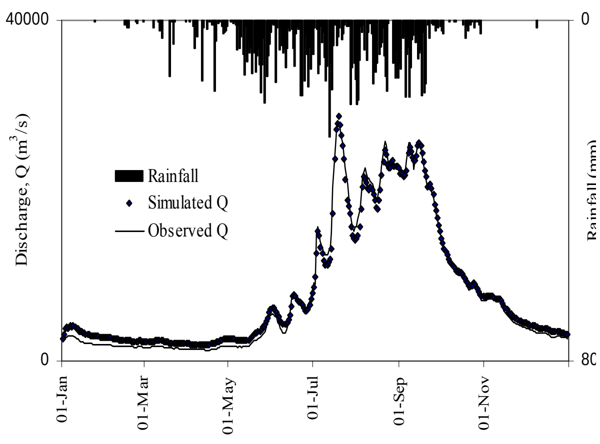

Fig. 6 Simulated hydrograph from Khong Chiam to Pakse (154,000 km^2 effective watershed)

Where, Q_{cal} is the simulated daily discharge, Q_{obs} is the observed daily discharge and $\overline{Q_{obs}}$ is the annual mean observed daily discharge.

5. Effect of delineation of blocks on hydrologic simulations

It is important to discuss the usefulness of bock wise estimation of saturation deficit in the BTOPMC when the model is used to simulate hydrological processes in large watersheds. TOPMODEL is a topographically based model and simulation results strongly depend on topographical features (elevation and slope) of the study area. Local saturation deficit depends on depth to the saturation zone from the soil surface and the soil properties. In the model average saturation deficit which depends on block size, and soil topographic properties control the local saturation deficit.

The accuracy of estimating local saturation deficit largely controls the efficiency of hydrological simulation. Average saturation deficit is the datum in estimating local saturation deficit which controls the depth to the ground water surface. Thus optimum block size may depend on soil topographic properties of the basin. For a flat watershed, a large block size may be suitable because of the less standard deviation in saturation deficit. On the other hand, a smaller block size is needed to accurately model a watershed with complex water table profiles. If the standard deviation of soil topographic index is very high in a block, it may results in abrupt changes in saturation deficit within that block. Finding the optimum number of blocks can be interpreted as the optimum number of datums of local saturation deficit in the watershed to simulate hydrological processes.

Simulations were carried out to understand the pattern of variation of Nash efficiency criteria with different number of blocks in BTOPMC. Result to determine the optimum number of blocks in the study region is shown in Table 1. The average observed discharge at Pakse is 8130 m^3/s for the year 1993. The graph of Nash efficiency coefficient against number of blocks is shown in Fig. 7.

Results suggested that the best model performance at Pakse is obtained with four blocks for number of blocks less than 32 with 1-km grid resolution. When the number of blocks increases to 306, Nash coefficient

Table 1 Results to evaluate optimum number of blocks (values at Pakse)

No of Blocks	Average Simulated discharge / (m^3/s)	Nash efficiency coefficient / (%)
1	8325	89.5
2	9000	93.9
4	8720	94.7
6	9100	93.3
8	9090	93.2
12	9140	93.0
16	9150	93.0
32	9160	92.8

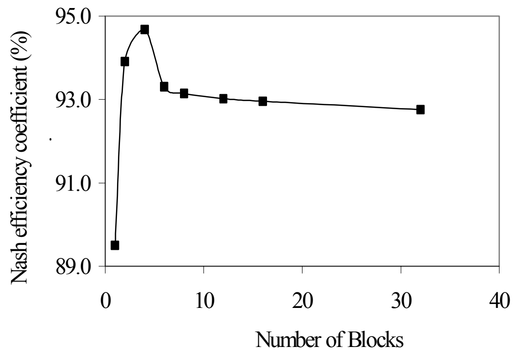

Fig. 7 The graph of Nash coefficient at Pakse against the number of blocks

increases to 94.5. But the suitability of large number of blocks in the BTOPMC has to be discussed.

The investigations to find out the reasons for four blocks to give the best results were carried out with respect to variations of soil topographic properties of the basin. Least variation of topographical features between blocks is necessary to have continuous ground

Table 2 Important statistical variables influencing optimum number of blocks

Number of Blocks	Standard Deviation					
	Ave. Ele.	Ave. Slope	Var. Slope	C.V. Slope	Ave. S.T.I.	C.V. S.T.I.
2	169.74	0.030	0.0047	0.599	0.046	0.051
4	135.79	0.025	0.0040	0.479	0.051	0.018
6	221.99	0.041	0.0054	0.652	0.050	0.044
8	263.89	0.045	0.0050	0.679	0.048	0.031
12	253.63	0.037	0.0044	0.535	0.048	0.056
16	239.77	0.040	0.0047	0.589	0.048	0.037
32	275.69	0.039	0.0046	0.498	0.049	0.066

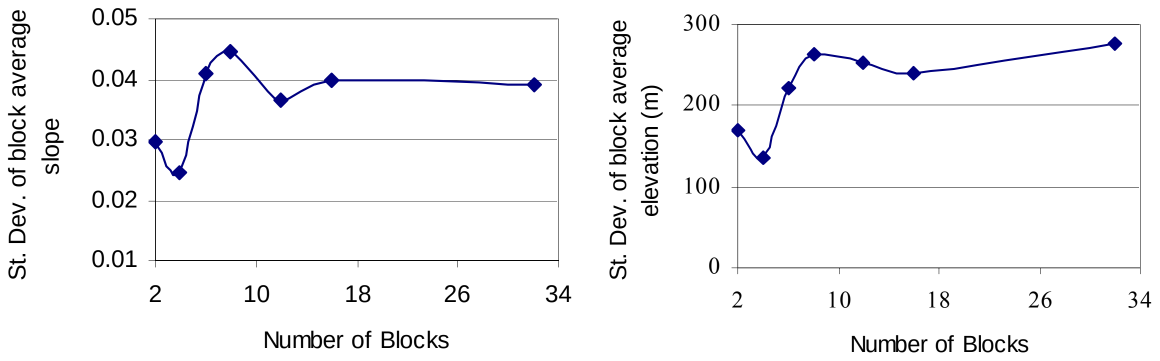

Fig. 8: Standard deviation of block average elevation / Slope versus number of blocks

water profile. This suggests that the statistical variance and coefficient of variation are the suitable variables to study the theory behind assigning optimum number of blocks. In Table 2 and Fig. 8 - Fig. 9 standard deviation is used to describe the parameter variations among blocks.

Soil topographic index is the controlling parameter governing hydrological processes in BTOPMC model. Local saturation deficit can be given with respect to block average value and soil topographic index (Eq. 2). In TOPMODEL all points having same soil topographic index value, hydrologically behaves in an identical manner. If the standard deviation of soil topographic index is very high over a block, it may results in abrupt changes in saturation deficit within that block. Thus number of blocks should be decided in order to have highest level of variation of soil topographic index (Fig. 9) among blocks to delineate hydrologic units of the basin effectively.

At the initial stage, before tuning m and T_0, optimum number of blocks has to be decided considering the variation of slope and elevations among blocks. The graph of standard deviation of block average elevation against number of blocks is depicted in Fig. 8. The graph shows the minimum value at four numbers of blocks. The graph is the inverse shape of the Nash coefficient values at Pakse which represent the efficiency of the hydrological simulations. The graph of standard deviation of block average slope versus number of blocks also shows similar variation (Fig. 8). Variation of standard deviation and coefficient of variation of block wise slope with number of blocks also give the minimum values at four numbers of blocks. The above mentioned figures show similar patterns and give the minimum or maximum values at

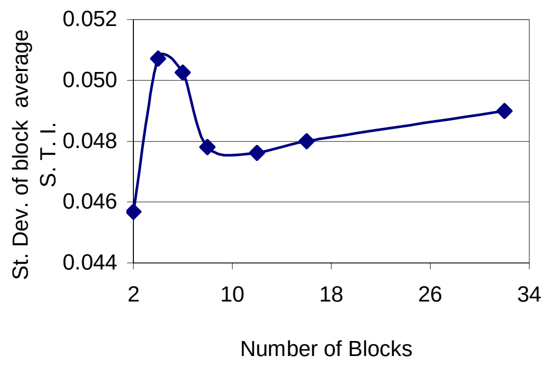

Fig. 9: Standard deviation of block average soil topographic index versus number of blocks

four numbers of blocks. Once soil topographic indices are computed, users of the model should check the variation of soil topographic index among blocks.

It can be conclude that the number of blocks which produce maximum standard deviation of block average soil topographic index or minimum standard deviation of block average elevation or minimum standard deviation of block average slope or minimum standard deviation of block wise coefficient of variation is suitable for hydrological simulations of BTOPMC model.

6. Conclusions

Even though the latest version of BTOPMC is distributed, it uses block concept to derive local saturation deficit. The equation to estimate local saturation deficit uses the block average of soil topographic index, block average saturation deficit and local soil topographic index. This model can be used to simulate hydrological processes of large scale watersheds. For hydrological modelers, it is useful to start calculation with optimum number of blocks. As optimum values of T_0 and m are not known at the start of hydrological simulation, the block number that gives the minimum standard deviation of block average elevation or slope is suggested as the optimum number of blocks for simulations. Once the optimum values for parameters T_0 and m are established it is necessary to verify that the number of blocks selected provides the highest standard deviation of block average soil topographic index. The delineation procedure is solely based on topography, which is only one of the many interacting environmental factors of soil formation. For the selected study region four blocks provided the best hydrological simulation result. And it complies with the conclusion drawn to choose optimum number of blocks. The finding can be applied to other watershed models in applying BTOPMC model concept to delineate sub basins / blocks. It will help to reduce the CPU time as well as data requirement. Thus it can conclude the method is transformable in watershed models in similar climatic regions.

Acknowledgements

This research was supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) 21st Century COE Program for DPRI, Kyoto University (No.14219301, Program Leader: Prof. Yoshiaki Kawata).

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水文モデルにおける単位応答要素の抽出について

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要旨

物理分布モデルの重要性が広く認識されて久しいが、どのスケールで現象を捉えモデル化するか、という問いに対して未だ明確な答は得られていない。水文モデリングの適切なサイズを決定することは、洪水予測モデルの構築やハザードマッピングを実現するための基本課題である。本研究は、地形と土壌特性に着目し、それらの流域特性と流出応答にもとづいた合理的な単位応答要素を決定する方法を提案する。

キーワード: BTOPMC の改良モデル，水文モデル，メコン河，水文学の応答単位

C-33

水文モデルにおける単位応答要素の抽出について
Delineating Hydrological Response Units in Hydrological Modelling

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従来、水文モデルは観測データをもとにパラメータを同定する概念モデルが主流であったが、最近の 20 年間、水文素過程をできるだけ物理法則にしたがってモデル化する物理分布モデルの重要性が広く認識されるようになった。この場合、どのスケールで現象を捉えモデル化するかが非常に重要である。水文モデリングの適切なサイズを決定することは、洪水予測モデルの構築ややハザードマッピングを実現するための基本課題である。

ポイントスケールから斜面スケールまで、連続時間の中で 3 次元的な広がりの中で発生する水文過程は、流域の物理的特性や気象要素に大きく影響を受ける。この水文過程をモデル化するために、ポイントスケールや斜面スケールで発生している現象を、ある単位の中でプロセスの heterogeneity を考慮しながら集中化する必要がある。その単位を決定する基本的な要素として、地形によって定まる流域界を考える必要がある。

ある流域で成功した水文モデルを他地域でも利用するためには、流域の物理特性と水文モデルの構成単位の大きさとの関連を事前に理解することが重要である。そのために、本研究では、水文モデルの基本要素としてのサブ流域の設定方法を新たに提案する。

ここで提案する BTOPMC (Block wise TOPMODEL with Muskingum-Cunge flow routing method)の改良モデルは、流域平均の土湿不足量を計算するために、ある矩形ブロック領域を単位とするのではなく、地形に従うサブ流域を単位とする。このモデルをメコン河のパクセ地点上流域(277,000 km^2)に適用した。4 つのパラメータ T_0(飽和時の透水量係数)、m (decay factor)、 S_{rmax} (根系層の最大貯留水深)、マニングの粗度係数は土地利用タイプごとに設定する。また、河道部のマニングの粗度係数は、勾配と粗度係数の関数とし、その関数は既知の勾配と粗度係数とから設定する。なお、ルアンプラバンにおける日観測流量を上流側の了解条件として用いる。

流域の分割数と水文シミュレーション結果との関連を明らかにするために、分割数を変えて流出シミュレーションを実行した。その結果を図 1 に示す。非常に興味深いことは、サブ流域ごとに計算される土壌地形指数の平均値の標準偏差が最大となるときに、Nash 指標が最も高い値をとり、流量の再現性が高くなっていることである。つまり、土壌地形指数の平均値の標準偏差が最大となるような流域分割数が BTOPMC において最もふさわしい分割数を与えることが明らかになった。これによれば、一旦 T_0 と m の最適値を定めた後で、土壌地形指数の平均値の標準偏差が最大となるように流域分割数を定めればよい。今回対象としたメコン河の部分流域では分割数を 4 つとすることがもっとも再現精度の高い流量シミュレーションとなった。これは、分割数を増やせば精度の高い水文シミュレーションを実現するとは限らないことを示している。

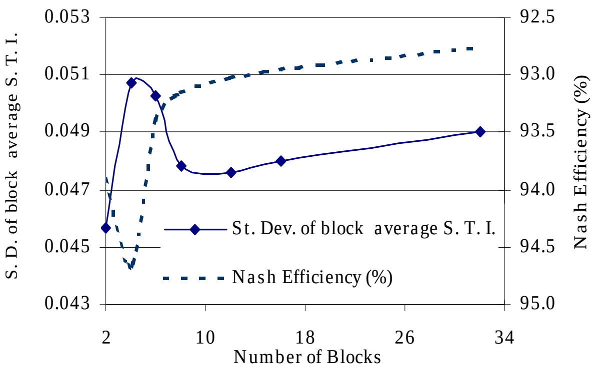

Fig. 1 流域分割数と Nash 指標、土壌地形指数の平均値の標準偏差との関係