METHOD TO DELINEATE BLOCKS IN BTOPMC MODEL FOR LARGE SCALE WATERSHEDS

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BTOPMC (Block wise TOPMODEL with Muskingum-Cunge flow routing method) is an extension of TOPMODEL. The BTOPMC uses the block average saturation deficit instead of basin average value that is proposed in the TOPMODEL to calculate local saturation deficit. In this paper a methodology has been proposed to determine the optimum number of blocks when applying to large scale basins. The model was applied to simulate hydrological processes in the Mekong River basin upstream of Pakse with catchment area of 277,000 square kilometers. Four parameters namely; lateral transmissivity under saturated conditions T_0, decay factor *m*, maximum root zone storage S_{rmax}, and Manning's coefficient *n*, were assigned depending to land use. The Manning's coefficient along the main stream and tributaries were assigned as a function of slope and the best Manning's coefficient value at the most downstream location. Daily observed discharges at Luang Prabang gauging station were used as an upstream boundary condition to the model. The watershed was divided into several blocks in order to understand the block size effect on hydrological simulations. It was found that the number of blocks which results the minimum standard deviation of block average slope or soil topographic index produces the best hydrological simulation.

Key Words: *BTOPMC model, Hydrologic model, Mekong river basin, Land use, Hydrologic 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 modellers' 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 (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. In this paper an effective approach for block delineation is discussed for extending TOPMODEL concept for large scale watersheds.

2. DISTRIBUTED BTOPMC 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 parameterisation. 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, 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 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,

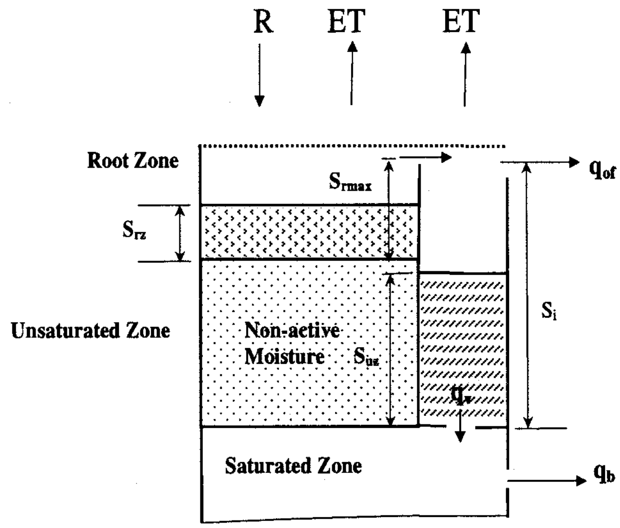

Fig. 1 Column model of the original TOPMODEL

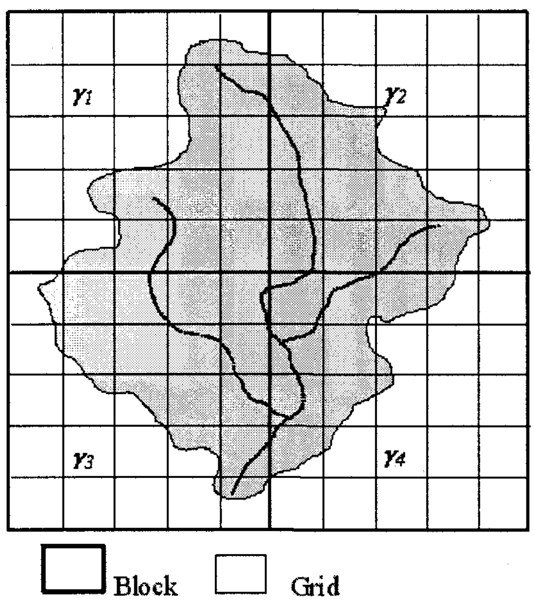

Fig. 2 Block wise concept

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 Kirby, 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 on to the cell is routed to the down stream along the river network using Muskingum-Cunge flow routing method.

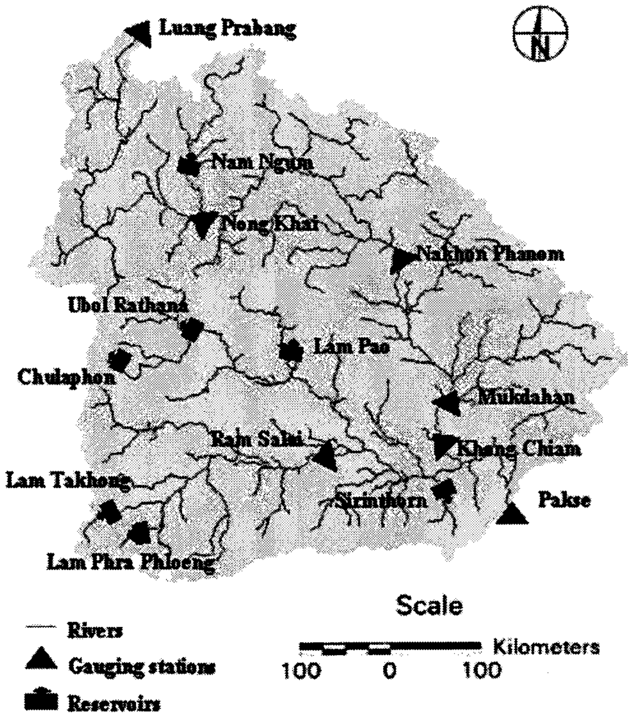

Fig. 3 Study basin

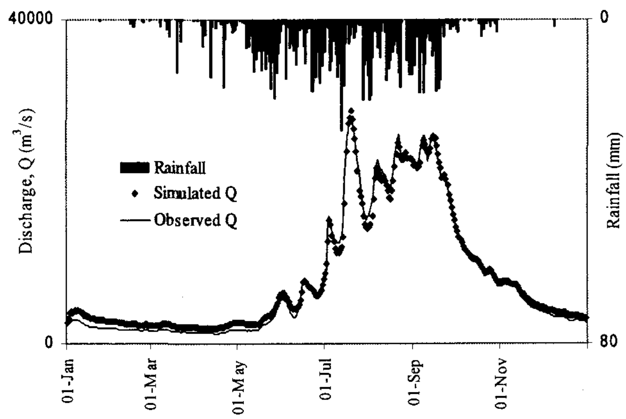

Fig. 4 Simulated hydrograph from Khong Chiam to Pakse (154,000 km^2 effective watershed)

3. MODEL APPLICATION

In this research, distributed BTOPMC model is used to model hydrological processes of the effective watershed from Luang Prabang to Pakse gauging station (**Fig. 3**). 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. 4.**

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

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

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.

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

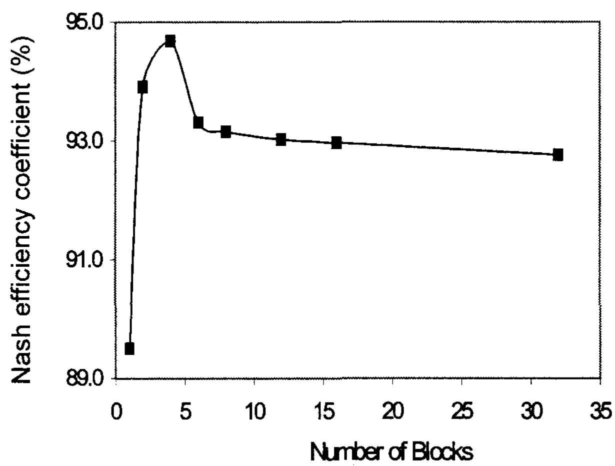

Fig. 5 The graph of Nash coefficient at Pakse against the number of blocks

4. EFFECT OF BLOCK SIZE ON ESTIMATION OF SATURATION DEFICIT

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

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

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. 5.**

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 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 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. 6 – Fig. 9** standard deviation is used to describe the parameter variations among blocks.

Soil topographic index is the controlling parameter governing hydrological processes in

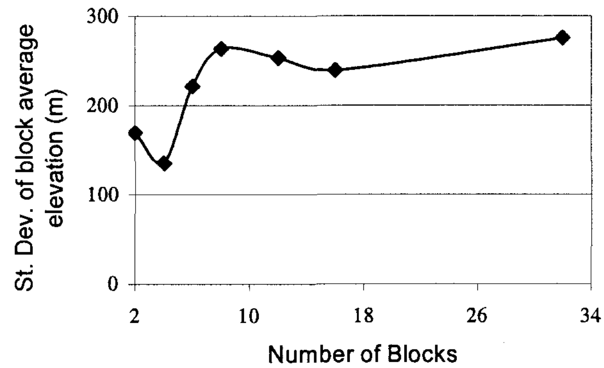

Fig. 6 Standard deviation of block average elevation versus number of blocks

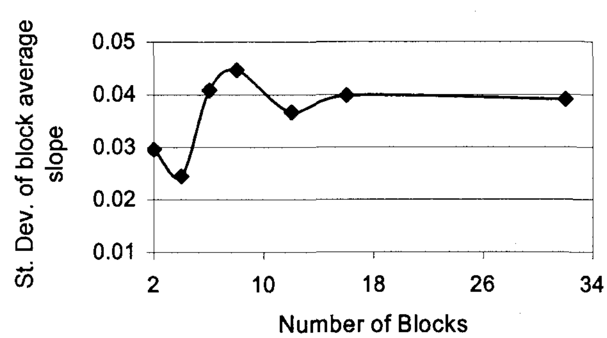

Fig. 7 Standard deviation of block average slope versus number of blocks

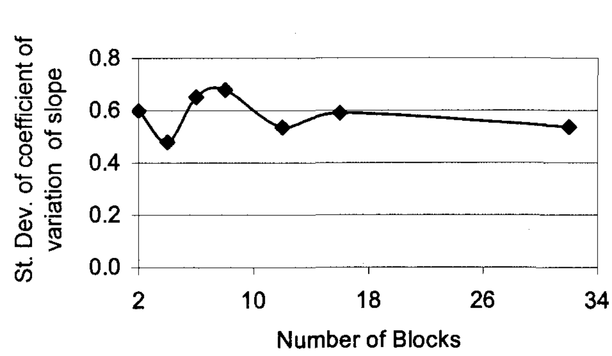

Fig. 8 Standard deviation of block average coefficient of variation of slope versus number of blocks

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. 6.** 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. 7**). 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 graph of coefficient of variation of slope over a block with number of blocks is shown in **Fig. 8.** The above mentioned figures show similar patterns and give the minimum values at 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 argued 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.

5. 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 modellers, 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. 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.

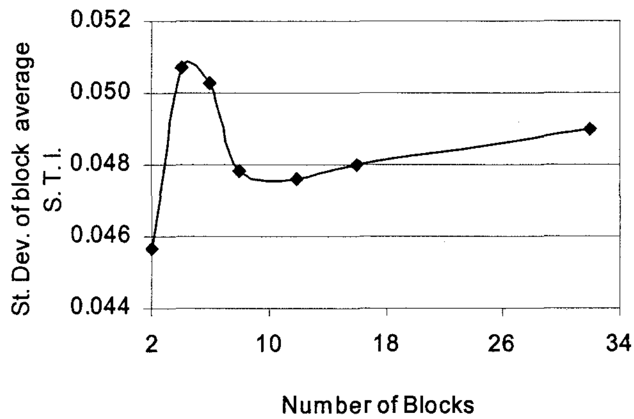

Fig. 9 Standard deviation of block average soil topographic index versus number of blocks

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