Hydrological modeling and flood simulation of the Fuji River basin in Japan

H. A. P. Hapuarachchi[*], A. S. Kiem, K. Takeuchi, H. Ishidaira , J. Magome and A. Tianqi

T 400-8511, Takeuchi-Ishidaira Lab, Department of Civil & Environmental Engineering, Yamanashi University, Takeda 4-3-11, Kofu City, Japan,
([*]E-mail: *hapuara@yamanashi.ac.jp*)

Abstract
Fuji River is located in the central area of Japan and originates from the Southern Alps. The river is one of the largest in Japan covering three prefectures (Nagano, Yamanashi, and Shizuoka) and having a basin area of about 3570 km^2. Due to the heavy rainfall over the basin and steep river bed slope, there is a high flood risk in the basin. Also the region is susceptible to sediment-related disasters like landslides and debris flows due to the presence of fragile rocks in this tectonic area. Therefore, hydrological modeling and flood simulation of the Fuji River basin is of great importance. This paper presents an application of a grid based distributed hydrological model BTOPMC (Block-wise use of TOPMODEL with Muskingum-Cunge method) to the Fuji River basin to simulate the river flow. The model is applied for simulating the daily discharge as well as flood discharge of the river. The results indicate that the model is capable of capturing the complex hydrological processes in the Fuji River basin and capable of predicting daily and hourly river flow correctly.

Key words
BTOPMC; TOPMODEL; flood simulation; distributed hydrological modeling; calibration

INTRODUCTION

Fuji River is one of the largest rivers in Japan covering three prefectures (Nagano, Yamanashi, and Shizuoka) and having a basin area of about 3570 km^2. It gathers water from Southern Alps, Yatsugtake, and Okuchichibu mountains and flows into the Suruga Bay (Fig. 1). The geological features in the basin are very complex and fragile due to the giant dislocation, Itori river-Shizuoka tectonic line. Due to the heavy rainfall over the basin and steep river bed slope, there is a high flood risk in the basin. The design flood discharge near the river mouth at Kitamatsuno (Fig. 1) is 16600m^3/s, which is the third largest amount in Japan.

Various ancient flood control facilities still exist along the river prove that the flooding is a regular feature in the river from the past. Three famous flood control facilities are the Shingen embankment, the Minriki forest, and the Karigane embankment. Therefore, accurate flood discharge modeling of the Fuji River basin is important though the flooding has been reduced during the past two decades (last recorded in 1982) due to the advance flood control measures implemented along the river. However hydrological modeling of the basin is also important for long term flow predictions and estimating water quality and sedimentation.

This paper presents an application of a grid based distributed hydrological model BTOPMC (Block-wise use of TOPMODEL with Muskingum-Cunge method) to the Fuji river basin to simulate the river flow. The results indicate that the model is capable of capturing the complex hydrological processes in the Fuji River basin and able to predict the river flow accurately.

THE BTOPMC MODEL

The BTOPMC is a grid based semi distributed hydrological model developed at the University of Yamanashi (Japan) for hydrological simulations in large river basins (Takeuchi, *et al.*, 1999; Ao, *et al.*, 2003). To facilitate the application of the model to large river basins, the total basin area is subdivided into natural sub-basins manually or automatically by the Pfafstetter numbering system (Verdin and Verdin, 1999). The three dimensional physiographic heterogeneity of the basin is considered in the model mutually in terms of topography, soil types, geology, vegetation cover, and rooting depth. The soil column is divided into three layers: root zone; unsaturated zone; and the saturated zone. The non uniformity of the root zone depth over the catchment is taken into account using the distribution of land cover. In the model, runoff generation is based on the TOPMODEL (e.g. Beven and Kirkby, 1979; Beven and Binley, 1992; Quinn *et al.*, 1995) concepts and flow routing is carried out using the Muskingum-Cunge method (Ao, *et al.*, 2003). The model parameters (Table 1) are calibrated either manually or automatically using the Shuffle Complex Evolution (SCE-UA) algorithm (Duan, *et. al.*, 1992). The inputs of the model are the land cover map, digital elevation model (DEM), soil map, precipitation, and potential evaporation data. It is possible to obtain the hydrological characteristics (e.g., depth to the water table, actual evaporation, overland flow, base flow etc.) at any location (grid cell) of the catchment as model output.

Table 1. Parameters of the BTOPMC model

Description	Parameter	Units
Block average Manning's coefficient	n_0	
Decay factor of lateral transmissivity	m	m
Lateral transmissivity under saturated conditions	T_0	m^2/h
Maximum root zone capacity	Sr_{max}	m

The BTOPMC has advantages of both lumped and distributed models. It has few parameters to be identified yet capable of assessing the effects of land use changes as well as water resource systems development. The model parameters have physical interpretations, representing the effects of topography, vegetation (Sr_{max}), soil properties (T_0, and m) and land uses (n_0). This implies that BTOPMC can make use of GIS and remotely sensed spatial information of physical basin characteristics without extensive ground observations, and has the potential to relate its parameters to basin features. Also the hydrological response processes (spatial and temporal distribution of saturated areas) in a basin can be easily visualized.

FUJI RIVER BASIN CHARACTERISTICS AND DATA

Fuji River originates from 3000 m high mountains in the central Honshu Island of Japan and flows south to the Pacific Ocean (Fig. 1). The river length is about 128 km and basin outlet is Kitamatsuno (Fig. 1). The catchment receives an average annual precipitation of approximately 2100 mm. There are four small size reservoirs which have a total storage capacity of less than 18.9 MCM along its tributaries (Jayawardena, *et al.*, 1997). The middle and lower stream produces a large amount of sediment because of the presence of fragile rocks in this tectonic area. From their water source on the top of the high mountains, the Fuji River and its tributaries flow rapidly eroding riverbanks and riverbeds. Under these circumstances, the region is susceptible to sediment-related disasters like landslides and debris flows.

There are nine precipitation gauging stations and four discharge gauging stations in the catchment. Precipitation and discharge records are available both in daily and hourly time intervals (the Automated Meteorological Data Acquisition System observations). The daily potential evaporation was calculated using the Priestley-Taylor method (Priestley *et al.*, 1972). Daily measured values of maximum and minimum temperature, wind speed and sun shine hours are used for calculating the potential evaporation.

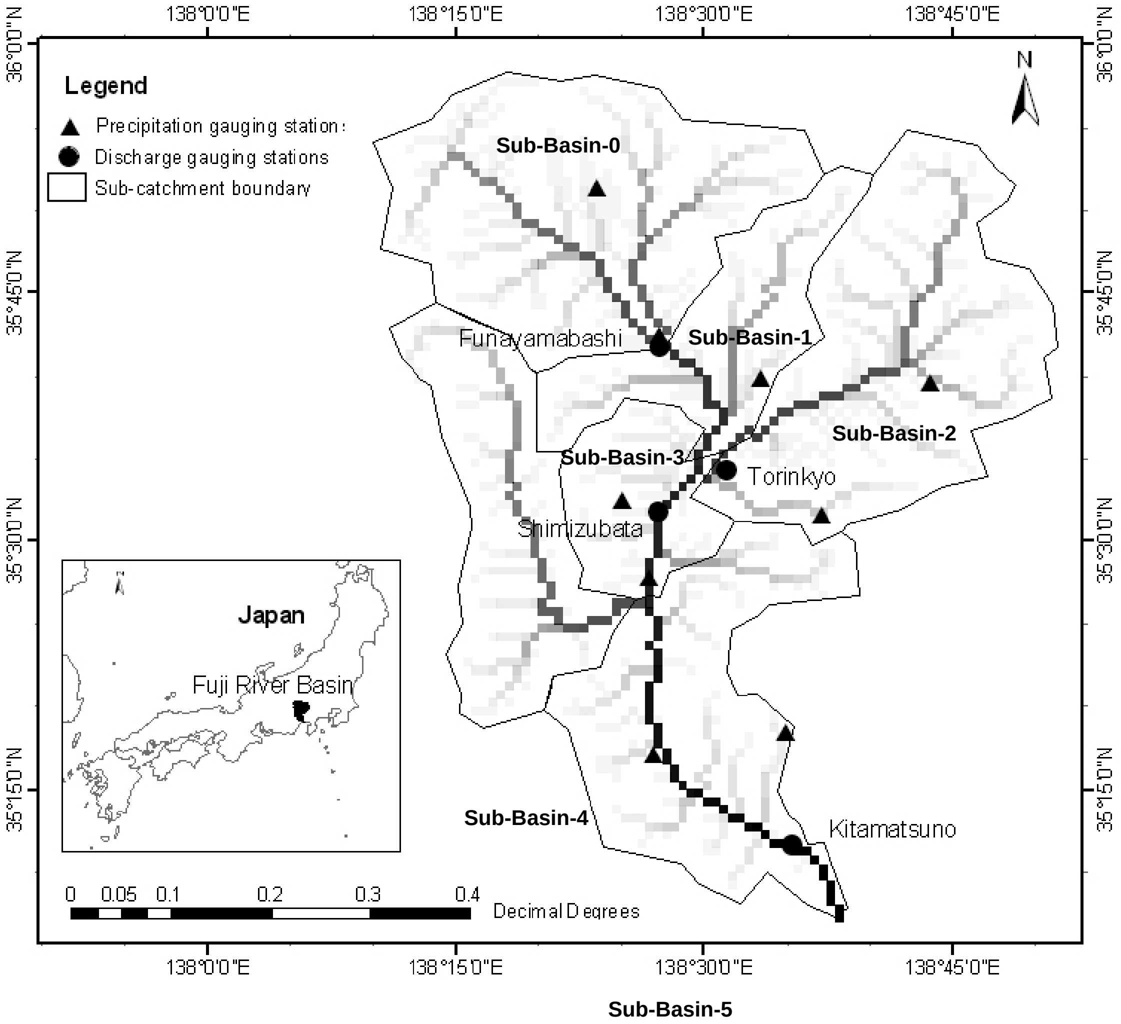

Figure 1 Fuji River Basin

In this application the soil properties of the catchment are obtained using the FAO (Food and Agriculture Organization) soil map and the DEM is generated from the USGS 30 arc second GTOPO30 data set (Table 2). The land cover data is prepared using IGBP (International Geosphere Biosphere Program) land cover map.

Table 2. Public data sets used in this study

Data set	Source	Spatial Scale	Coverage
DEM	GTOPO30, USGS	1 km	Global data
Land cover map	IGBP Version 2, USGS	1 km	Global data (1992-1993)
Soil map	FAO	5 km	Global data, 1995

MODEL SIMULATION

In this study, the total basin is divided into six natural sub-basins (Fig. 1) and the grid cell size is 1 km^2. The non-uniformity of the root zone moisture capacity (Sr_{max}) over the catchment is taken into account using the distribution of land cover and root depth. In the application of the BTOPMC model, the original land cover (IGBP-17 classes) is reclassified and reduced to four classes (impervious, shallow rooted, shallow rooted and irrigated, and deep rooted) in order to reduce the number of parameters (Sr_{max}) to be calibrated (Table 3). In order to incorporate the effects of actual soil properties of each grid cell in the calculation of groundwater flow, the T_0 value is assigned to each grid cell based on the following equation (Hapuarachchi, *et al.*, 2004):

$$T_0 = U_{clay} \times T_{0\ Clay} + U_{sand} \times T_{0\ sand} + U_{silt} \times T_{0\ silt} \quad (1)$$

Where U_{clay}, U_{sand}, and U_{silt} are the percentages of clay, sand, and silt present in each grid. It is assumed that the soil texture in a grid cell is homogeneous. $T_{0\text{-}clay}$, $T_{0\text{-}sand}$, $T_{0\text{-}silt}$ are parameters which represent the other soil textural properties (particle size, pore size etc.) present in the catchment. In this approach the number of coefficients to be determined is always three regardless of the number of sub-catchments or the heterogeneity of soil present in any study catchment and the actual soil texture of each sub-unit (e.g., grid, hydrological response unit) is uniquely considered.

In this application, first the BTOPMC model is applied to the Fuji River basin using daily data. Daily hydrological data from 1992 to 1995 are used for calibrating the model and 1996 to 1998 are used to validate the model (Table 4). Then the model is applied for flood event modeling (Fig. 2). In both applications, the model is calibrated using data from four discharge gauging stations Funayamabashi, Torinkyo, Shimizubata and Kitamatsuno (Fig. 1) in order to maintain equal accuracy all over the basin.

Table 3. Calibrated parameter values

Parameter	**Sub-Basin 0**	**Sub-Basin 1**	**Sub-Basin 2**	**Sub-Basin 3**	**Sub-Basin 4**	**Sub-Basin 5**
n_0	0.075 (0.400)	0.001 (0.100)	0.001 (0.850)	0.100 (0.100)	0.300 (0.300)	0.300 (0.200)
m	0.035 (0.019)	0.025 (0.010)	0.023 (0.006)	0.005 (0.010)	0.028 (0.010)	0.040 (0.010)
Sr_{max}-IMP	0.0001 (0.0001)	0.0001 (0.0001)	0.0001 (0.0001)	0.0001 (0.0001)	0.0001 (0.0001)	0.0001 (0.0001)
Sr_{max}-SRI	0.005 (0.030)	0.005 (0.030)	0.005 (0.030)	0.005 (0.030)	0.005 (0.030)	0.005 (0.030)
Sr_{max}-SR	0.009 (0.025)	0.009 (0.025)	0.009 (0.025)	0.009 (0.025)	0.009 (0.025)	0.009 (0.025)
Sr_{max}-DR	0.010 (0.060)	0.010 (0.060)	0.010 (0.060)	0.010 (0.060)	0.010 (0.060)	0.010 (0.060)
$T_{0\text{-Clay}}$	3 (6)	3 (6)	3 (6)	3 (6)	3 (6)	3 (6)
$T_{0\text{-Sand}}$	10 (21)	10 (21)	10 (21)	10 (21)	10 (21)	10 (21)
$T_{0\text{-Silt}}$	5 (10)	5 (10)	5 (10)	5 (10)	5 (10)	5 (10)

Note: IMP - Impervious area, SRI – Shallow Rooted & Irrigated, SR – Shallow Rooted, DR – Deep Rooted. The parameter values outside the brackets are calibrated values using daily data and in brackets are using hourly data.

RESULTS AND DISCUSSION

In this study, the BTOPMC model is applied to the Fuji River basin in Japan using daily and hourly input data and the model performance is shown in Tables 4 and 5. Table 3 shows the calibrated parameter values. The figures outside the brackets in table 3 are results obtained using daily data and figures in brackets are results obtained using hourly data. The parameter values Sr_{max} and T_0 do not depend on the number of sub-basins (Table 3) since they are assigned to each grid cell based on the distribution of land cover and soil types respectively. However it is clear that the parameter values calibrated using daily data and hourly data are different (Table 3). This implies that the calibrated parameter values depend on the temporal resolution of the model application. Therefore it is essential to find any relationship between model parameters and the temporal resolution of the model application, in the case of applying the model to ungauged or data poor regions. It is remarkable that the T_0 values calibrated using hourly data are almost double as that of calibrated using daily data (Table 3).

The BTOPMC is capable of generating the simulation results at any time anywhere in the basin. In this application, the model was calibrated using the observed discharge from four gauging stations. The model performance at each gauging station both in calibration and validation is acceptable (Table 4 and 5). The model performance using hourly data (Table 5) is excellent (Fig. 2, 3). Therefore the model can be successfully applied for hydrological simulations (flood forecasting, calculation of sedimentation, water use etc.) in the Fuji River basin. Importantly the model is capable of achieving equal accuracy all over the basin.

Table 4. Calibration and validation statistics of the BTOPMC (Daily data)

Daily	**Criteria**	**Funayamabashi**	**Torinkyo**	**Shimizubata**	**Kitamatsuno**
Calibration	Nash %	43.4	62.9	66.1	63.0
	Vol %	97.9	71.5	74.6	158.3
Validation	Nash %	28.3	66.6	59.2	68.6
	Vol %	87.5	68.4	98.4	133.7

Note: Nash is the Nash-Sutcliffe coefficient, Vol%=Q_s/Q_o, Q_o and Q_s are the observed and simulated discharges (m^3/s) respectively.

Table 5. Calibration and validation statistics of the BTOPMC (Hourly data)

Hourly	**Criteria**	**Funayamabashi**	**Torinkyo**	**Shimizubata**	**Kitamatsuno**
Calibration	Nash %	80.72	93.4	97.11	91.39
	Vol %	104.0	101.0	103.0	91.0
Validation	Nash %	68.8	90.4	95.7	95.8
	Vol %	107.3	95.9	95.6	98.3

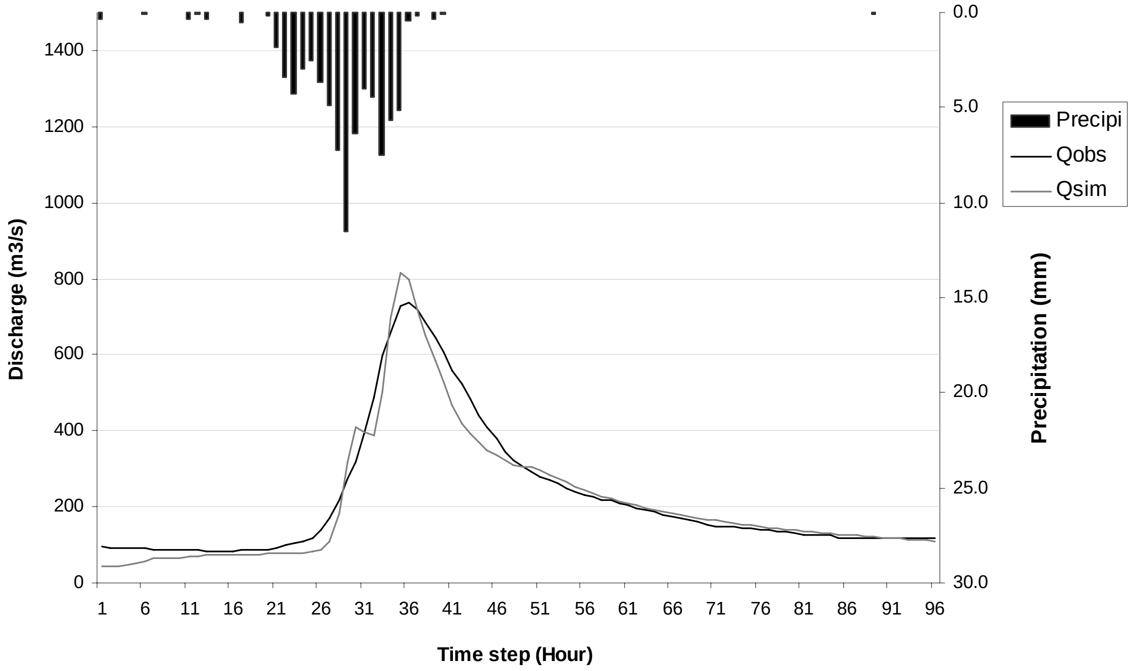

Fig. 2 Simulated and observed discharge at Shimizubata during the validation (hourly data) period (1993.09.03 00:00 to 1993.09.06 24:00).

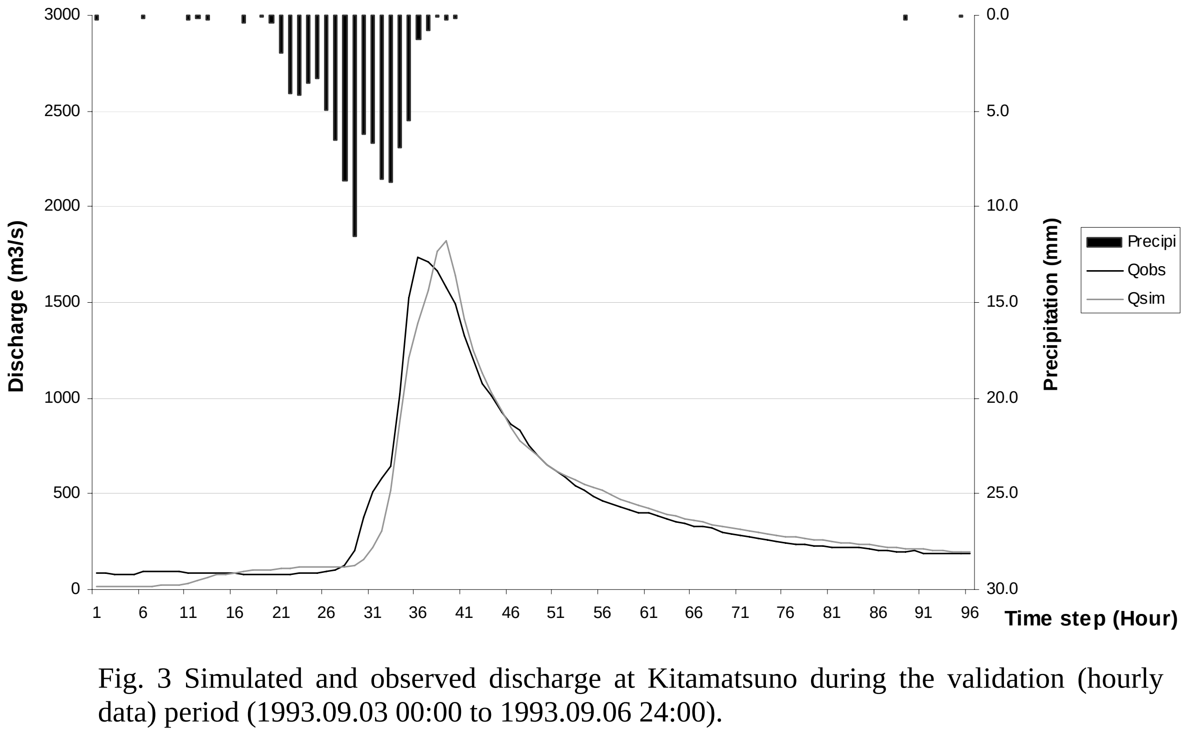

Fig. 3 Simulated and observed discharge at Kitamatsuno during the validation (hourly data) period (1993.09.03 00:00 to 1993.09.06 24:00).

CONCLUSIONS

In the present study, the BTOPMC model is applied to the Fuji River basin for simulating the daily and hourly flow. Results indicate that the model can be successfully applied for hydrological simulations (flood forecasting, accounting sedimentation, water use etc.) in the Fuji River basin. Importantly the model could achieve equal accuracy all over the basin. This fact is very important when modeling large catchments. However it is noted that the calibrated parameter set depends on the temporal resolution of the model application. Future research is necessary for finding relationships between calibrated parameter values and the physical catchment characteristics to enable the model to use without calibration which is extremely important in the case of applying the model to ungauged or data poor regions.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the 21st Century - Center of Excellence (COE) Program at the University of Yamanashi (H. A. P. Hapuarachchi) and the Japan Society for the Promotion of Science (Anthony Kiem) for their financial support and for the opportunity to work in Japan.

REFERENCES

1. Ao T. Q., Yoshitani J., Takeuchi K., Fukami K., Mutsura T. and Ishidaira H. (2003). Effects of sub-basin scale on runoff simulation in distributed hydrological model: BTOPMC. *Weather Radar Information and Distributed Hydrological Modeling* (*Proc. of symposium HS03 held during IUGG2003)*, Sapporo, IAHS Publ. No. 282.
2. Ao T. Q., Takeuchi T., Ishidaira H., Yoshitani J., Fukami K. and Matsuura T. (2003). Development and application of a new algorithm for automated pits removal for grid DEMs. *Hydrological Sciences Journal,* **48**(6), 985-997.
3. Beven K. J. and Kirkby M. J. (1979). A physically based, variable contributing area model of hydrology. *Hydrol. Sci. Bull*., **24**(1), 43-69.
4. Beven K. J. and Binley A. M. (1992). The future of distributed models: model calibration and predictive uncertainty. *Hydrol. Processes*, **6**, 279-298.
5. Duan Q., Sorooshian S. and Gupta V. K. (1992). Effective and efficient global optimization for conceptual rainfall-runoff models. *Water Resour. Res*., **28(**4), 1015-1031.
6. Hapuarachchi H. A. P., Kiem A. S., Ishidaira H., Magome J. and Takeuchi K. (2004) Eliminating uncertainty associated with classifying soil types in distributed hydrologic modeling. *Proc. of 2nd APHW conference*, Singapore, 592-600.
7. Jayawardena A. W., Takeuchi K. and Machbub B. (1997). *Catalogue of rivers for South East Asia and the Pacific*. UNESCO, vol. II, 115-126.
8. Priestley C. H. B. and Taylor R. J. (1972). On the assessment of surface heat flux and evaporation using large scale parameters, *Mon. Weather Rev*., **100**, 81-92.
9. Quinn P. F., Beven K. J. and Lamb R. (1995). The ln(a/tanâ) index: how to calculate it and how to use it in the TOPMODEL framework, *Hydrol. Processes*, **9**, 161-182.
10. Takeuchi K., Ao, T. Q. and Ishidaira H. (1999). Introduction of block-wise use of TOPMODEL and Muskingum-Cunge method for the hydro-environmental simulation of a large ungauged basin, *Hydrol. Sci. J.*, **44**(4), 633-646.
11. Verdin K. L. and Verdin, J. P. (1999). A topographical system for delineation and codification of the Earth's river basins, *J. Hydrol*., **218**, 1-12.