Evaluation of a physically based distributed hydrological model, BTOPMC, for different physiographic zones of Nepal

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Abstract: Many rivers in Nepal are ungauged and there is an urgent need to develop a model for those ungauged basins in order to properly use the vast natural resources of Nepal. The aim of this study is to evaluate the performance of the distributed hydrological model, BTOPMC (Block-wise use of TOPMODEL with Muskingum-Cunge method) for different physiographic zones of Nepal and then to develop a regional model, which can be used for prediction in ungauged basins. It is advantageous to use BTOPMC for poorly gauged or ungauged basins as it utilizes various global datasets available in public domain. In this study, except rainfall and discharge, all the inputs into the model were obtained from global data sets readily available in public domain. Considering the different features of the basins, seven basins used in this study were taken as a set of homogeneous basins. BTOPMC model was calibrated and validated for six basins. The result shows that the model performs reasonably well for most of the basins. Then, a simple regional model was developed. For evaluating the regional model, parameters of the regional model were applied to the seventh basin, which was not used for developing the regional model. The result shows that the parameters derived for the regional model give satisfactory performance. Therefore, BTOPMC model can be used for prediction in ungauged basins in Nepal. However, the application should be restricted to only the least impacted basins since the model is still under development for snow, reservoir and irrigation components.

***Keywords**:* Nepal, BTOPMC, Calibration, Regionalization

1. INTRODUCTION

Nepal is very rich in water resources. However, as a developing country, the natural resource could not be utilized properly to improve the life and economy of people. Nepal's rivers can be classified into three groups: rivers originating from Himalayas, rivers originating from Middle Mountains and rivers originating from Siwalik Hills. Although there are some gauging stations installed in some rivers, many river basins in Nepal are either ungauged or poorly gauged. Therefore, the prediction of flow in those rivers is one of the important tasks for the management of water resources in Nepal. Recently, IAHS (International Association of Hydrological Sciences) has initiated a research program in the name of IAHS decade on PUB (Sivapalan et al., 2003). The country's water resources management sector can benefit from PUB research.

Different kinds of hydrological models are used to predict runoff. According to the process description, these models can be classified into three categories: empirical (black box), conceptual and physically-based models. According to the spatial representation, the hydrological models are either lumped or distributed. However, in most applications, all are lumped temporally, e.g. when using daily or even hourly time steps. In Nepal, the use of distributed hydrological model for the prediction of runoff is still limited due to the difficulties in obtaining detailed local data required to run the model. There are only a few studies in this area of modeling for Nepalese context, e.g. Shrestha et al., 2005; Dulal et al., 2006. However, due to the advent of GIS and remote sensing technologies along with the immense utilization of computers in this field, many data which are required to run the model are available freely in the global public domain. The objective of this study is to utilize freely available global data set together with local available hydro-meteorological data to evaluate the performance of a distributed hydrological model BTOPMC for basins in Nepal located in different physiographic zones and to establish a regional model, which can be used for prediction in ungauged basins.

2. STUDY AREA AND DATA SETS

The study area consists of seven river basins in Nepal (Figure 1). The drainage area of the basins ranges from 427 km^2 to 5150 km^2. All of these rivers are located in the southern part of Nepal and originated from the Middle Mountains. The source of runoff for these rivers is monsoon rainfall and groundwater. About 80% of rainfall falls in monsoon period (July-Sep) and the rest of the period is very dry. The climate of these areas varies with altitude: tropical climate in the southern plain areas, sub-tropical climate in the Siwalik Hills and temperate climate in the Middle Mountains. The major land uses of the basins are cropland and forest. Some of the important characteristics of the basins are shown in Table 1.

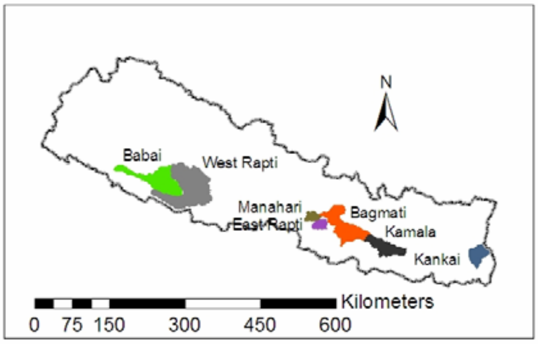


Figure 1. Locations of study basins in Nepal

Table 1. Characteristics of basins

Basin name	Drainage area (km^2)	Annual average rainfall (mm)	Average elevation (m)	Average topographic index
Bagmati	2700	1948	1043	9.4
West Rapti	5150	1580	1186	8.8
Kankai	1148	2689	1215	9.0
East Rapti	579	2549	857	9.8
Kamala	1450	1982	605	9.9
Manahari	427	2187	1135	8.4
Babai	3000	1445	956	10.0

Land use, topographic, soil and potential evaporation (PET) data were obtained from freely available global data set: specifically, topographic data from United States Geological Survey (GTOPO30), land use data from International Geosphere-Biosphere Programme (IGBP), soil data from Food and Agricultural Organization, (FAO), PET data from United Nations Environment Programme (UNEP), Global Resource Information Database. Rainfall and discharge data (DHM) were obtained from the Department of Hydrology and Meteorology, Kathmandu, Nepal. Data availability of the basins is shown in Table 2.

Table 2. Data availability of the basins

Basin name	No. of rainfall stations	No. of discharge stations	Available data period
Bagmati	16	1	1996-2002
West Rapti	5	3	1980-1993
Kankai	4	1	1995-1998
East Rapti	4	1	1995-1996
Kamala	4	1	2000-2002
Manahari	3	1	1996-1997
Babai	5	1	1977-1980

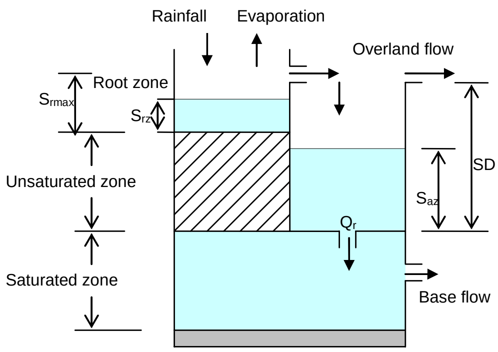
3. METHODOLOGY

3.1 Hydrological Model: BTOPMC

BTOPMC stands for "Blockwise use of TOPMODEL with Muskingum-Cunge routing". This is a distributed hydrological model developed at the University of Yamanashi, Japan (see Takeuchi et al., 1999; Ao, 2001; Hapuarachchi et al., 2004). BTOPMC is an extension of TOPMODEL concepts (Beven et al., 1995), which is developed in order to overcome the limitations of using the TOPMODEL for large river basins. For large river basins, spatial heterogeneity and timing of flow to outlet are the important factors. For representing spatial variability in BTOPMC, a basin is composed of grid cells, which can be divided into sub-basins, where each sub-basin is considered as a block or a unit. To consider timing of flow, flow from each grid cell is routed to the outlet using Muskingum-Cunge routing method.

The flow generation mechanism of BTOPMC is based on TOPMODEL concepts. TOPMODEL is based on a saturation-excess runoff mechanism, in which the saturation zone is called contributing area. The difference in TOPMODEL and BTOPMC is that in TOPMODEL the water table is spatially lumped over a basin, while in BTOPMC the lumping is done for a grid scale.

In BTOPMC, the soil profile of a grid cell is divided into three layers (root, unsaturated and saturated zones) as shown in Figure 2. Rainfall on the i^{th} grid cell is first received by the root zone storage which is subjected to evaporation. The unsaturated zone receives the overflow from the root zone storage and the saturated zone receives flow from the unsaturated zone. The outflow from the saturated zone constitutes base flow. The overland flow is generated when the unsaturated zone storage exceeds the local storage deficit. The discharge in each cell is composed of both overland flow and base flow. Both are dependent on local saturation deficit.



[S_{rmax}: Maximum root zone capacity. S_{rz}: Root zone storage, S_{az}: Unsaturated zone storage, Q_r: Recharge, SD: Local saturation deficit]

Figure 2. Structure of BTOPMC for a grid cell

The basic equations describing the concept of BTOPMC are presented below.

Within sub-basins, groundwater is mutually shared and discharges to nearby stream within grid cell *i*. The groundwater flow equation is

$$q_i = T_0 \exp(-SD_i / m) \tan\beta_i \qquad (1)$$

where T_0 is defined as saturated transmissivity (m^2/h), namely the lateral transmissivity when the soil profile is just saturated at the ground surface, SD_i is local saturation deficit (m), m is a decay factor of lateral transmissivity with respect to saturation deficit (m), β is the local slope angle, and $\tan\beta_i$ is the hydraulic gradient.

For each grid cell *i*

$$q_i = r.a_i \qquad (2)$$

where q_i is the groundwater flow per unit contour length, r is the recharge rate (m/h) and a_i is the upstream contributing area per unit contour length (m^2/m) that drains through point *i*.

From equation (1) and (2), the distribution of local saturation deficit, SD_i is derived as

$$SD_i = \overline{SD} + m(\gamma - \gamma_i) \qquad (3)$$

where $\overline{SD}$ is average saturation deficit in the catchment, γ_i is soil-topographic index ($\gamma_i = \ln(a_i / T_0 \tan\beta_i)$) and γ is the catchment average of the soil-topographic index.

The following are the parameters of BTOPMC model:

T_0: T_0 is saturated soil transmissivity, which describes the potential rate of lateral flow for a completely saturated soil for a given hydraulic gradient.
m: m is decay factor of transmissivity, which describes how the actual transmissivity decreases when the soil is not saturated.
S_{rmax}: S_{rmax} is the maximum root zone capacity, which represents the plant available soil moisture capacity as well as interception capacity of the canopy.
n_0: n_0 is roughness factor for a block, which is used as a scaling parameter to compute Manning's roughness for routing.

3.2 Model Parameter Estimation Procedure

It is difficult to implement an automatic optimization technique for a distributed hydrological model like BTOPMC. Therefore, parameters of the model in this study were estimated manually.

Parameters m and n_0 were calibrated for each sub-basin. For distributing n_0 value to each river segment, the following expression is used in BTOPMC.

$$n_i = n_0(\mathrm{k})[\tan\beta_i / \tan\beta_0(\mathrm{k})]^{1/3} \qquad (4)$$

where n_i is equivalent Manning roughness coefficient of river segment *i*, $\tan\beta_i$ is local topographic gradient and $\tan\beta_0$ is the topographic gradient at the outlet of sub-basin *k*. T_0 in BTOPMC is based on soil types, where weighted soil texture is used to represent spatial heterogeneity.

$$T_0 = T_0Cl \times U_{cl} + T_0Sa \times U_{sa} + T_0Si \times U_{Si} \qquad (5)$$

where T_0Cl, T_0Sa, T_0Si are T_0 value for clay, sand and silt, and U_{cl}, U_{sa} and U_{si} are the percentages of clay, sand and silt present in each grid, which was obtained from the FAO soil data. Calibrating T_0 for clay, sand and silt gives T_0 value of soil for each grid cell. S_{rmax} in BTOPMC is based on land use class. IGBP land use data was reclassified into four classes (deep rooted, shallow rooted, shallow rooted and irrigated, and impervious) in order to reduce equifinality and improve computation time, and S_{rmax} value for the reclassified land use was calibrated.

3.3 Approach for Regionalization

Considering physiography, temporal rainfall distribution (80% rainfall in summer monsoon period), climate zone (tropical to temperate) and land use (mainly agriculture and forest), the seven basins used in the study are taken as a set of homogeneous basins for developing regional model. The BTOPMC model is calibrated and validated for six basins, The Manahari basin is left out because it is comparatively poorly gauged having continuous data set of discharge for the year 1996-1997 only. Then, the parameters are regionalized. In most of the regionalization studies, a relationship between the parameters of the model and the catchment descriptors is developed (e.g. see Parajka et al., 2005 for different methods). However, this method is not applied in this study because the aim of this study is to evaluate the performance of the BTOPMC model for a set of homogeneous basins and to check the ranges of the parameters to see whether they are significantly different or not. In this study, simple average of each parameter of the six basins is taken as parameter for regional model. To evaluate the performance of the regional model, the parameters of the model are applied to the seventh basin, the Manahari basin, which is not used in the development of the regional model.

3.4 Model Performance Indicators

The first indicator for model performance is Nash-Sutcliffe Efficiency (NSE), which is given by

$$NSE = 1 - \frac{\sum (Q_{obs} - Q_{sim})^2}{\sum (Q_{obs} - Q_m)^2} \qquad (6)$$

where Q_{obs} = observed discharge, Q_{sim} = simulated discharge, Q_m = mean of observed discharge. NSE is widely used indicator of model performance for hydrological model. However, NSE should not be considered the only measure for evaluating the performance as it is more biased towards high flow values, i.e. it gives less weight to low flow errors. Therefore, to check the mass balance, another indicator, called Volume Bias (VB) is also computed, which is given by

$$VB = \frac{\sum (Q_{sim} - Q_{obs})}{\sum Q_{obs}} \qquad (7)$$

where Q_{obs} = observed discharge, Q_{sim} = simulated discharge.

4. RESULTS AND DISCUSSIONS

4.1 Single-site Model

Table 3 shows six basins used for developing regional model along with the period of time series data used for calibration and validation of BTOPMC model for each of the basins. Table 4 shows the calibrated parameters for each of the basins. Table 5 shows the performance of the model for the six basins for both calibration and validation. The observed and simulated hydrograph for validation for the six basins is presented in Figures 3 to 8.

Table 3. Calibration and validation data period

Basin name	Calibration data period	Validation data period
Bagmati	1996-1999	2000-2002
West Rapti	1980-1987	1988-1993
Kankai	1995-1997	1998
East Rapti	1995	1996
Kamala	2000-2001	2002
Babai	1977-1978	1979-1980

Looking at the performances of the model (Table 5), it is seen that NSE value is between 31%-70% for calibration and 43%-73% for validation, while VB value is between -15%-15% for calibration and -21%-43% for validation. In this study, the criteria set for evaluation of model are: excellent for NSE above 85% and VB below 5%, very good for NSE between 65%-85% and VB within 5%-10%, good for NSE between 50%-65% and VB within 10%-20%, poor for NSE between 20%-50% and VB within 20%-40% and very poor for NSE below 20% and VB below 40% (Henriksen et al., 2003). NSE for the Bagmati is very good, the West Rapti and the Kankai is good in the calibration data period, while it is poor for other three basins. For validation data period, NSE is very good for the Bagmati and the East Rapti, good for the West Rapti and the Kamala, while it is poor for other two basins. Looking at VB, the model performance is excellent for the west Rapti, very good for the Bagmti and the Kankai and good for the rest for calibration data period, while for validation data period the model performance is very good for the West Rapti and the Kankai, good for the Bagmati and the Kamala, poor for the East Rapti and very poor for the Babai. According to

Table 4. Calibrated parameters

Basin name	m (m)	n_0	S_{rmax}(m)				T_0(m^2/h)		
			DR	SR	SRI	IMP	Clay	Sand	Silt
Bagmati	0.03	0.005	0.03	0.02	0.01	0.0001	0.1	3	2
West Rapti	0.05	0.015	0.05	0.04	0.03	0.0001	0.5	7	3
Kankai	0.03	0.01	0.01	0.005	0.005	NA	1	4	2
East Rapti	0.10	0.006	0.03	0.02	0.01	NA	1	6	3
Kamala	0.07	0.02	0.02	0.01	0.005	NA	1	3	2
Babai	0.06	0.01	0.03	0.02	0.01	0.0001	0.5	4	2

(DR: Deep rooted, SR: Shallow rooted, SRI: Shallow rooted and irrigated, IMP: Impervious, NA: Not applicable)

Table 5, NSE for validation is better than that for calibration in five of the six basins, which is due to the quality and length of data set chosen for calibration and validation.

Comparison of the observed and the simulated hydrographs (Figures 3 - 8) shows that the model has reproduced the most parts of the observed hydrograph for most of the basins. The highest peak is underestimated for the Babai, the Kankai and the West Rapti. Low flows are captured well for five basins, while it is underestimated for the recession period in case of the East Rapti basin.

The possible reasons for the poor performance of the model are:

a. Uncertainty in data: There may be some errors in measurement of data, especially in rainfall and discharge data. In addition, there is uncertainty in spatial variability of precipitation due to the sparse network of rain gauge (e.g. 5 rain gauge stations for 5150 km^2 for the case of the West Rapti river basin) for most of the basins.

b. Uncertainty in parameters: There is some uncertainty in calibrated parameters due to the uncertainty in data and due to the inability of parameters to represent the heterogeneous nature of hydrological processes.

As the model structure is fixed in time, the uncertainty due to model structure is neglected here. This would still contribute to the performance, but maybe not the variation in performance between the catchments, providing that each catchment has similar processes driving the behaviour.

Table 5. Model performance

Basin name	Nash-Sutcliffe Efficiency (%)		Volume bias (%)	
	Calib-ration	Valid-ation	Calib-ration	Valid-ation
Bagmati	70	73	-5	13
West Rapti	60	65	-1	-8
Kankai	61	46	-5	-8
East Rapti	35	72	15	-21
Kamala	36	65	-15	-14
Babai	31	43	-12	43

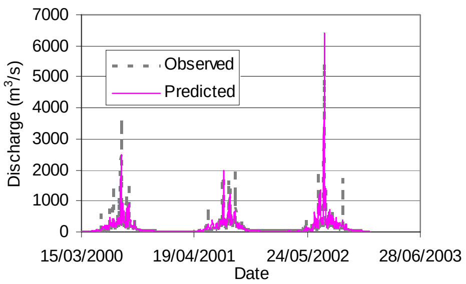


Figure 3. Validation for Bagmati

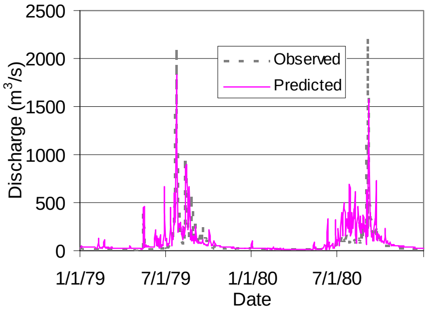


Figure 4. Validation for Babai

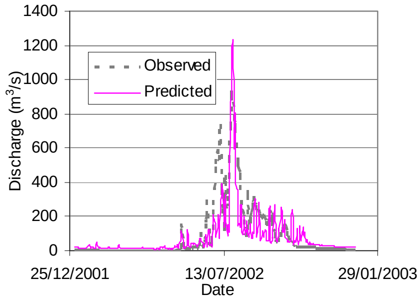


Figure 5. Validation for Kamala

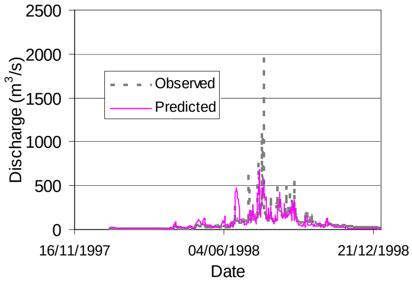


Figure 6. Validation for Kankai

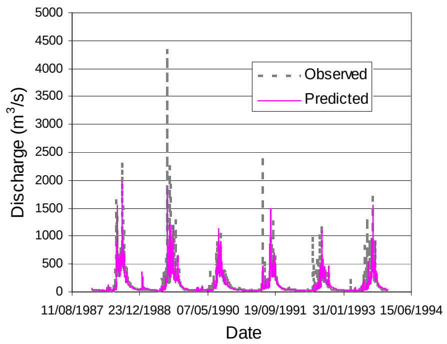


Figure 7. Validation for West Rapti

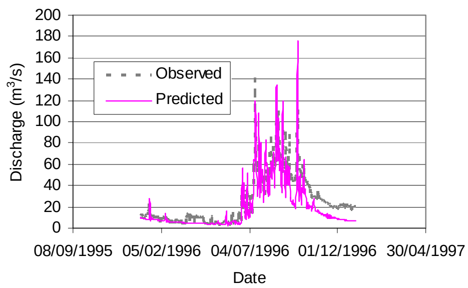


Figure 8. Validation for East Rapti

4.2 Regional Model

According to Table 4, the ranges of parameters found are: m from 0.03m-0.1m, n_0 from 0.005-0.02, S_{rmax} for DR from 0.01m-0.05m, S_{rmax} for SR from 0.005m-0.04m, S_{rmax} for DRI 0.005m-0.03m, S_{rmax} for IMP 0.0001m , T_0 for clay 0.1 m^2/h-1 m^2/h, T_0 for sand 3 m^2/h-7 m^2/h, T_0 for silt 2 m^2/h-3 m^2/h. The ranges of the parameters obtained are not wide. Therefore, the parameters of the regional model are derived by taking average of parameters for the six basins. The parameters of regional model are: m = 0.06m, n_0 = 0.011, S_{rmax} for DR = 0.03m, S_{rmax} for SR = 0.02m, S_{rmax} for DRI = 0.01m, S_{rmax} for IMP = 0.0001m, T_0 for clay = $0.7m^2/h$, T_0 for sand = $5m^2/h$, T_0 for silt = $2m^2/h$.

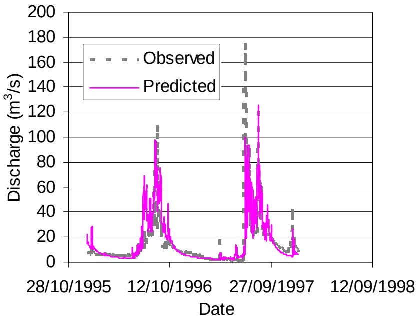


Figure 9. Validation of regional model for Manahari

The parameters of the regional model are applied to the Manahari river basin. Nash-Sutcliffe efficiency for this period was found to be 41% and the bias in runoff volume was found to be 9%. Although NSE in this case is below the good performance indicator set in the research, the VB is within the range.

The observed and simulated hydrograph for the basin for the year 1996-1997 is shown in Figure 9. The result shows that the parameters derived for the regional model give satisfactory performance as the simulated hydrograph closely resembles to the observed hydrograph.

5. CONCLUSIONS

This study attempted to evaluate the performances of the distributed hydrological model, BTOPMC for different physiographic zones of Nepal and then to develop a regional model. In this study, along with the hydrometerological data, freely available global data sets of topography, soil and land use were utilized for the model, BTOPMC. This feature of the model makes it more beneficial to use it for the prediction in ungauged basins. The result of the study shows that this model is able to predict the flow in poorly gauged basins in Nepal. However, the application should be restricted to only the least impacted basins since the model is still under development for snow, reservoir and irrigation components.

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