

An Application of Distributed Hydrological Model, YHyM/BTOPMC to Gin Ganga Watershed, Sri Lanka

T. N. Wickramaarachchi, H. Ishidaira and T. M. N. Wijayaratna

Abstract: Modelling approach is a useful tool which provides information on spatial distribution of basin hydrologic components. In that context distributed hydrological models play a vital role in efficient planning and managing water resources systems. But their applications are partly limited due to the requirement of large amount of data which are not always available and difficulties in obtaining such data due to bureaucratic constraints. Global public domain data sets have become increasingly available on the internet and it is appropriate to make use of such data which can often be supplemented for ground-based data. The objective of this study is to investigate the applicability of the distributed hydrological model, YHyM/BTOPMC to simulate the major hydrological characteristics in Gin ganga watershed utilizing the global data sets readily available in public domain along with the local available rainfall and discharge data. Gin ganga is a river which is one of the main sources of water supply to the southern region of Sri Lanka. It's catchment entirely lies within the wet zone of the country and frequently subjected to flooding during the rainy seasons. Hence, it is vital to comprehend the hydrology of the watershed in order to gain knowledge on current and future hydrological conditions. In the study, YHyM/BTOPMC model performance was evaluated by the Nash-Sutcliffe Efficiency (E) and the volume ratio of simulated discharge to observed discharge (Vr). The results show that the overall hydrological behaviour of the Gin ganga watershed is adequately simulated by the model. Further the results are discussed in the context of how the model simulation results replicate the temporal variation of basin hydrological characteristics such as ground water saturation deficit, soil moisture states, base flow etc.

Keywords: Watershed modelling, global public domain data, hydrological characteristics

1. Introduction

Hydrologic modelling is now well recognized as a powerful technique in land and water resources planning, development and management. Hydrological models can be classified according to the process description and spatial representation. According to the process description, models can be classified into three categories: metric, conceptual and physically-based models. According to the spatial representation, hydrological models are either lumped or distributed. Choice of a suitable model structure relies heavily on the function that the model needs to serve. Distributed models in hydrology are usually physically based in that they are defined in terms of theoretically acceptable continuum equations. Distributed hydrological models can fulfil the necessities of describing basin heterogeneity, and assessing the impact of natural and human induced changes. Furthermore they enable researchers to take advantage of currently available satellite observations, the quality of which is rapidly increasing (Virtual Academy, 2010). The University of Yamanashi Distributed Hydrological Model with Block-wise use of

TOPMODEL and Muskingum-Cunge method (YHyM/BTOPMC) was developed to cover most of the requirements for modelling hydrological responses of a basin, and has already been successfully applied to many catchments around the world. Most of the parameters to be identified in the YHyM/BTOPMC are related to physical basin features of land cover and soil.

The objective of this study is to investigate the applicability of the YHyM/BTOPMC to simulate the major hydrological characteristics in Gin ganga watershed utilizing the global data sets readily available in public domain along with the local available rainfall and discharge data.

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2. Study Area

Gin river is one of the main sources of water supply to the southern region of Sri Lanka. It is located roughly between longitudes 80°08" E and 80°40" E, and latitudes 6°04" N and 6°30" N. Gin river having a catchment area of about 932 km² includes Galle (83% of the basin area), Matara (9% of the basin area), Rathnapura (7% of the basin area), and Kalutara (1% of the basin area) administrative districts. The river originates from the Gongala mountains in Deniyaya having an elevation of over 1300 m and flows to the Indian Ocean in Ginthota area of Galle District. Rainfall pattern in the catchment is of bi-modal, falling between May and September (south west monsoon, which is the major rainfall event), and again between November and February (north east monsoon) followed by the inter-monsoon rains during the remaining months of the year. Rainfall varies with altitude with mean annual rainfall above 3500 mm in the upper reaches to less than 2500 mm in the lower reaches of the catchment. River Gin annually discharges about 1268 million cubic meters to sea (National Atlas, 2007). Average temperature in the catchment varies from 24°C to 32°C with high humidity levels and the dominant soil texture is sandy clay loam. The watershed of the river is rather a natural catchment in Sri Lanka which entirely lies within the wet zone of the country and having a natural rainforest covering considerable area in its upper catchment.

Since most of the low-lying areas in the Galle District are frequently subjected to flooding during the rainy seasons, problem of Gin river flooding is considered as leading to environmental hazard of the district. Due to rapidly growing population and development activities in some parts of the catchment, demand for water is likely to increase. Galle is the capital city in southern Sri Lanka and the city's main pipe-borne water supply system depends on the water resources in Gin catchment. Hence, it is vital to comprehend the hydrology of the catchment in order to gain knowledge on current and future hydrological conditions. Figure 1 shows the location of Gin ganga watershed.

3. Hydrological Simulation

3.1 Model Description

The University of Yamanashi Distributed Hydrological Model (YHyM) with Block-wise use of TOPMODEL and Muskingum-Cunge

method (BTOPMC) is a grid-based distributed hydrological model developed at the University of Yamanashi, Japan [Ishidaira *et al* (2000) and Takeuchi *et al* (1999 and 2008)]. Enabling easy and reliable application, many data which are required to run the model are available freely in the global public domain. The model is available for training at the University of Yamanashi Virtual Academy <http://www.coe.yamanashi.ac.jp/>

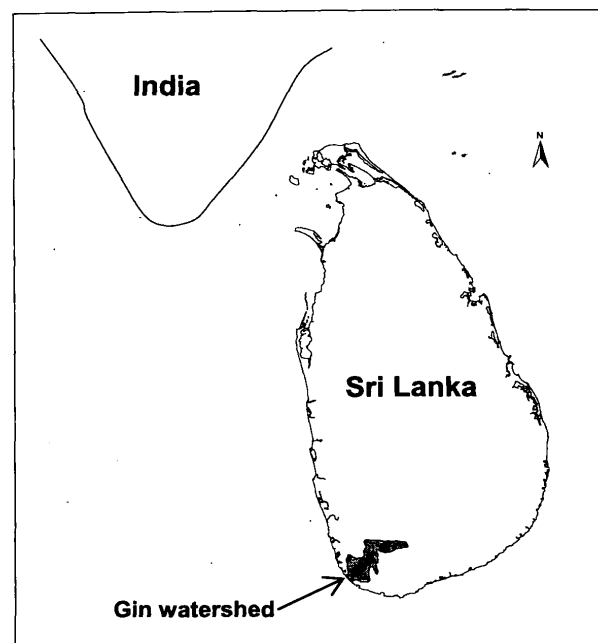


Figure 1 - Location of Gin ganga watershed

In the YHyM, runoff is generated based on the TOPMODEL concept (Beven and Kirkby, 1979) and flow routing is carried out using the Muskingum Cunge method (Cunge, 1969 and Ao *et al.*, 2003a,b). Core hydrological module included in the BTOPMC includes Topographic model, Runoff generation, Flow routing, and parameter identification.

The main features of Block-wise TOPMODEL (BTOP) include sub division of basin into a number of blocks, each of which may consist of several hillslopes and sub-surface water is assumed to be shared within each hillslope but not between blocks. After the holding capacity has been filled, the effective rainfall over a block discharges either as overland flow from each grid cell that is saturated, or as sub-surface flow to a local stream segment positioned in each grid cell in the block, or both. The hydrological processes in a grid cell in the BTOP model are illustrated in Figure 2 (Takeuchi *et al.*, 2008).

The watershed is described by drainage networks extracted from digital elevation models (DEMs), in which all pits are filled with

calculated small elevation increments (Ao et al., 2001, 2003b). The topographic index γ_i for the i^{th} grid cell is calculated using equation (1).

$$\gamma_i = \ln(\alpha_i / \tan \beta_i) \quad (1)$$

where, α_i is the drainage area per unit length of contour, $\tan \beta_i$ denotes the slope of grid cell, i .

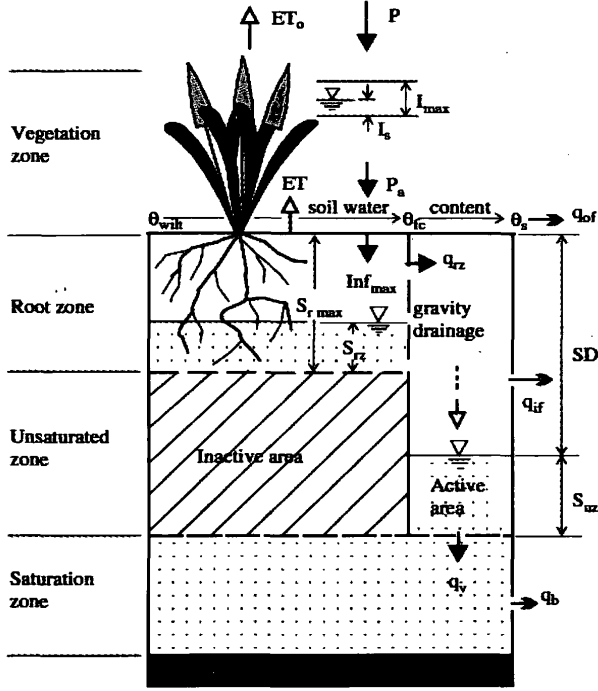


Figure 2 - Runoff generation in a grid cell in the BTOP model (the vertical profile).

In this diagram, P is the gross rainfall, ET_0 is the interception evaporation, $I_{\max}$ is the interception storage capacity, I is the interception state, $Inf_{\max}$ is the infiltration capacity, P_a is the net rainfall on the land surface, ET is the actual evapotranspiration, $S_{r\max}$ is the storage capacity of the root zone, S_{rz} is the soil moisture state in root zone, SD is soil moisture deficit in unsaturated zone, S_{uz} is the soil moisture state in unsaturated zone, q_{of} is the overland runoff, q_{if} is the saturation excess runoff, q_r is the groundwater recharge, and q_b is groundwater release. θ_{wilt} , θ_{fc} , θ_s are soil water content at wilting point, field capacity and saturation, respectively.

The runoff from a grid cell to the local schematic stream reach is the sum of saturation excess overland flow (q_{of}) and groundwater discharge (q_b) per unit length of contour line:

$$q_{of}(i, t) = \{S_{uz}(i, t) - SD(i, t)\} \quad (2)$$

where, S_{uz} is the unsaturated zone storage and SD is the saturation deficit for the i^{th} grid cell at time t .

$$q_b(i, t) = T_0(i) \exp\left(\frac{-SD(i, t)}{m(k)}\right) \tan \beta_i \quad (3)$$

where, SD indicates the saturation deficit, T_0 is the transmissivity, and $m(k)$ is the discharge decay factor in sub basin k .

In flow routing calculation using the Muskingum Cunge method, the river cross section is assumed to be rectangular and river width B (meters) is approximated by:

$$B(i) = C\sqrt{A(i)} \quad (4)$$

where, constant $C = 10$ and A is the drainage area in square kilometers (Lu et al., 1989).

The equivalent Manning's roughness coefficient of a grid cell is estimated as;

$$n_i = n_0(k) \left[\tan \beta_i / \tan \beta_0(k) \right]^{1/3} \quad (5)$$

where, n_0 and $\tan \beta_0$ are the equivalent roughness coefficient and slope at the outlet of sub-catchment k , respectively and n_0 is a model parameter to be calibrated.

The generated overland flow and groundwater flow of each cell will be added to the stream and then routed to the basin outlet. The maximum root zone storage is calculated considering the distribution of land cover and rooting depth. The spatial variation of soil transmissivity (T_0) over the catchment is considered based on the percentage of sand, silt, and clay present in each soil type.

In the BTOPMC, spatially distributed monthly average potential evapotranspiration is calculated using the Shuttleworth-Wallace (S-W) method (Shuttleworth and Wallace, 1985). In the S-W method, the evapotranspiration and the energy terms are related to:

$$\lambda ET = C_c ET_c + C_s ET_s \quad (6)$$

where, for the daily simulation, ET is the evapotranspiration (mm day^{-1}), λ is the latent heat of water evaporation (MJ kg^{-1}), ET_c and ET_s are terms similar to the transpiration and the evaporation by applying the Penman Monteith (P-M) equation to closed canopy and bare substrate, respectively, C_c and C_s are weighting coefficients as functions of resistances.

This article does not include a detailed description of the model and further references can be proposed as Ishidaira *et al* (2000) and Takeuchi *et al* (1999 and 2008).



Table 1 - Basic data required to run YHyM/BTOPMC and sources of data

Data-Set	Source
Digital Elevation Map (DEM)	Shuttle Radar Topography Mission (SRTM)
Soil Map	Harmonized World Soil Database (HWSD) V 1.1 by Food and Agricultural Organization (FAO)
Land Cover dataset	United States Geological Survey - International Geosphere Biosphere Programme (USGS - IGBP) Global Land Cover Characteristics Data Base Version 2.0
Data for Shuttleworth and Wallace (S-W) Simulation; - Normalized Difference Vegetation Index (NDVI) - Mean daily temperature - Diurnal temperature range - Vapour pressure - Cloud cover - Wind speed	Advanced Very High Resolution Radiometer-Global Inventory Modeling and Mapping Studies (AVHRR-GIMMS) Intergovernmental Panel on Climate Change - Climate Research Unit (IPCC-CRU) 2.0
Daily Discharge Data (From 1997 to 2006) at Tawalama and Agaliya gauging stations	Department of Irrigation, Sri Lanka
Daily Rainfall Data (From 1997 to 2006) at Anninkanda, Natagala, Pallegama, Baddegama, Labuduwa and Galle gauging stations	Department of Meteorology, Sri Lanka

3.2 Data Sets

Table 1 shows the basic data required to run the model and sources of data. Except rainfall and discharge, all the other inputs to the model were obtained from global data sets readily available in public domain.

DEM Data

DEM data was extracted from the SRTM data set which was having spatial resolution of 3" x 3" (Jarvis *et al.*, 2008). Due to computational limitations, it was scaled up to 30" x 30" when input to the model. While inputting to the model, this scaled-up DEM data was further compared with the DEM generated using the local available contour data of 1: 50,000 scale. Input of the scaled-up DEM data (from SRTM data set) to the model performed better in generating the stream network than the local available data and hence used as the topography data in this study. Figure 3 shows the stream network generated by the model using SRTM data set.

Discharge Data

Daily Discharge Data were obtained from the Department of Irrigation, Sri Lanka for the two

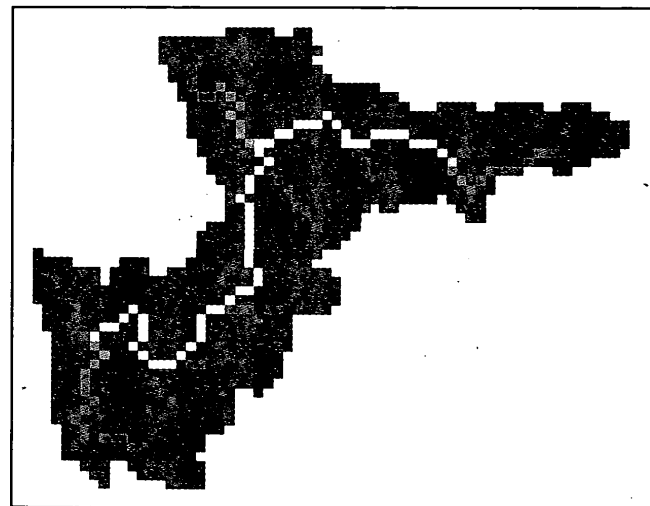


Figure 3 - Stream network generated by the model

discharge gauging stations located in Gin watershed (Figure 4). Agaliya station was established in lower reaches while Tawalama station was located in upper reaches of the catchment. The basin delineation was done based on the locations of discharge gauging stations. The whole catchment was divided to three sub catchments based on that (Figure 5). The total land areas of the upstream zone above

Agaliya and Tawalama stations are 780 km² and 470 km², respectively.

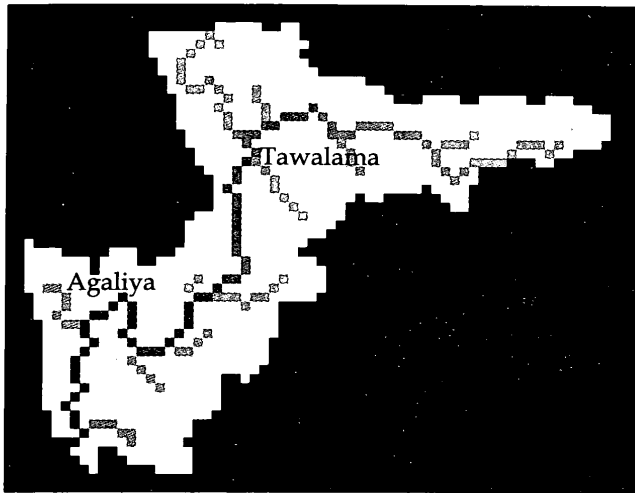


Figure 4 - Locations of discharge gauging stations

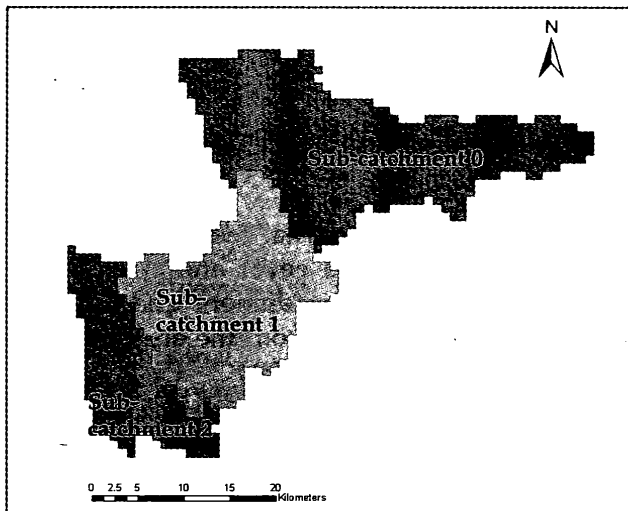


Figure 5 - Catchment sub-divisions

Rainfall Data

Six rain gauging stations were selected within the watershed and nearby locations considering the availability of long-term data. Daily rainfall data were obtained from the Department of Meteorology, Sri Lanka. Rainfall data were checked for missing data and it was noted that missing of few data, which could not be recorded during certain days. Since there existed a significant variation in the normal rainfall data of the above stations, according to Das (2009), the normal ratio method was applied to estimate the missing data. Spatial distribution of rainfall data was done by the model by using the Thession polygon method (Figure 6).

Soil Data

Soil map (Figure 7) was extracted from HWSD V1.1 produced by FAO which was having a resolution of 30" x 30" (FAO/ IIASA/ISRIC/ ISSCAS/JRC, 2009). Related soil properties and soil textures (Table 2) were identified in accordance with USDA soil triangle (Rawls *et al.*, 1982 and 1985).

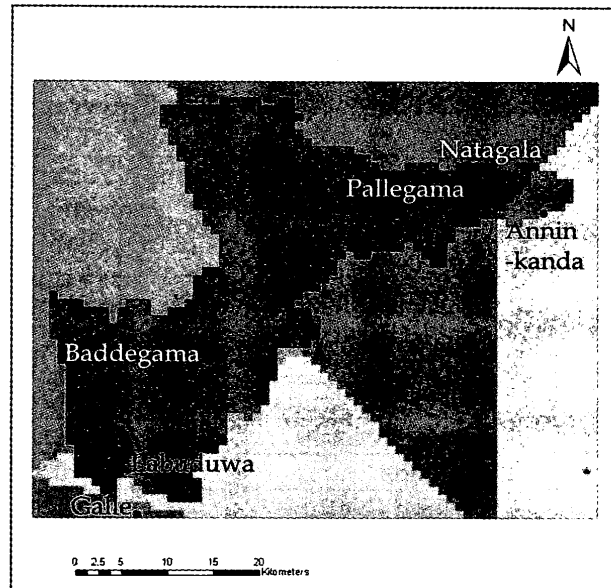


Figure 6 - Locations of the rain gauging stations and the Thession polygons generated

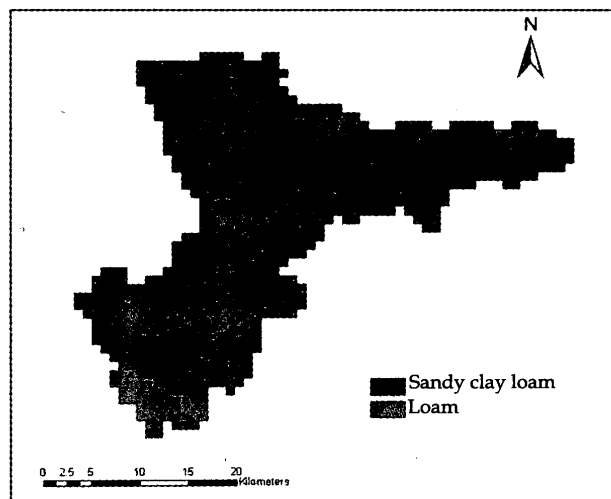


Figure 7 - Soil map (sub-catchment 0 and sub-catchment 1)

Land Cover Data

30" x 30" resolution IGBP V 2.0 (From April 1992 to March 1993) developed by USGS was used for land cover classification (USGS, 2008). Seven IGBP land cover classes presented in the area were reclassified to three classes based



Table 2 - Soil properties and distribution of soil textures

Soil ID/ Soil type	Texture	θ_{fc}	θ_{wilt}	(% area)	
				Sub-catchment 0	Sub-catchment 0 and sub-catchment 1
FAO ID_3641	Sandy Clay Loam	0.255	0.068	100.0	95.44
FAO ID_3645					
FAO ID_3778					
FAO ID_3654	Loam	0.270	0.027	0	4.56

Notes: θ_{fc} : Field capacity, θ_{wilt} : Soil moisture content at wilting point

Table 3 - Distribution of land cover according to IGBP classification and root depths

Original IGBP classification	Root depth (m)	Reclassified IGBP classes	% area	
			Sub-catchment 0	Sub-catchment 0 and sub-catchment 1
Evergreen Broadleaf Forest	2.5	Deep rooted Forest/Woodland	1.21	1.97
Deciduous Broadleaf Forest	2.5			
Mixed Forest	2.0			
Closed Shrublands	1.0	G/S/B/S	6.57	6.11
Woody Savannas	1.0			
Croplands	0.7	C/M	92.21	91.92
Cropland/Natural Vegetation Mosaic	1.0			

Notes: G/S/B/S: Grass/Savanna/Barren/Shrub, C/M: Crop/Mosaic

on the hydrological view point (Figure 8 and Table 3). Also the root depths for the land cover data (Sellers *et al.*, 1994 and 1996) are shown in Table 3.

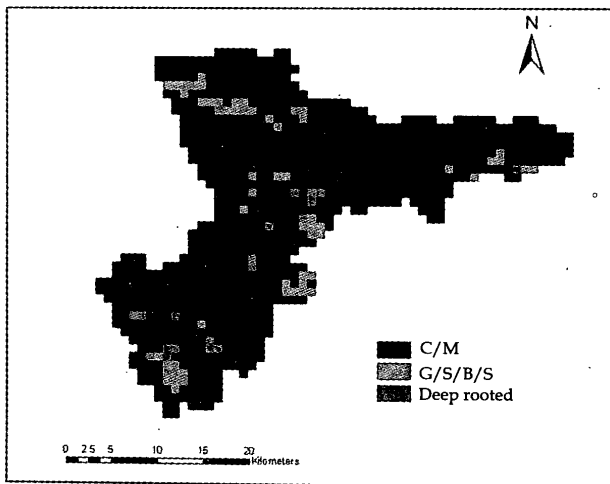


Figure 8 - Land cover map (sub-catchment 0 and sub-catchment 1)

Data for Shuttleworth and Wallace (S-W) Simulation

$0.5^\circ \times 0.5^\circ$ resolution, mean monthly climatology for 1961 - 1990 (30 year mean of the IPCC-CRU data) was used for the S-W potential evapotranspiration simulation in the YHyM/BTOPMC. These data included mean

daily temperature, diurnal temperature range, vapor pressure, cloud cover and wind speed. Also extraterrestrial radiation and daylight duration were derived from the above data by using the YHyM/BTOPMC Preprocessors. NDVI data used for S-W potential evapotranspiration module included monthly data from 1981 to 2006 with $4' \times 4'$ resolution (Tucker *et al.*, 2005).

3.3 Model Application

Most of the parameters to be identified in the model are related to physical basin features of land cover and soil. Parameters have been determined manually using the model parameter identification sub-module. Decay factor of transmissivity (m), Block average roughness coefficient (n_0), Saturated transmissivity (T_0) were identified through trial and error calibration while the maximum storage capacities at root zone were presumed based on literature values.

The effects of the actual soil properties of each grid cell are included by the T_0 value which is assigned to each grid cell based on the following equation;

$$T_0 = U_{clay} \times T_{0_clay} + U_{sand} \times T_{0_sand} + U_{silt} \times T_{0_silt} \quad (7)$$

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 inside each grid cell is homogeneous (Hapuarachchi *et al.*, 2004a).

The maximum storage capacity of the root zone ($S_{rz\ max}$) is assigned to each grid cell based on the soil properties and the root depths according to the land cover maps (Hapuarachchi *et al.*, 2004b).

$$S_{rz\ max} = (\theta_{fc} - \theta_{wilt}) \times \text{Root depth} \quad (8)$$

where, θ_{fc} (m/m) is the field capacity and θ_{wilt} (m/m) is the moisture content at wilting point of the top soil layer in each grid. Soil properties in the Table 2 and root depths in the Table 3 were used for the $S_{rz\ max}$ calculations.

Model performance was further improved by fine-tuning the parameter values. The calibrated parameter set used by the YHyM/BTOPMC is shown in Table 4.

Table 4 - Calibrated parameter set

Parameter	Value
Decay factor of transmissivity (m)	0.067 m
Block average roughness coefficient (n_0)	0.4
Saturated transmissivity (T_0)	T_{0_sand} : 12 m ² /h T_{0_silt} : 5 m ² /h T_{0_clay} : 1 m ² /h

Daily Discharge Data from 1997 to 2001 and from 2002 to 2006 were used for calibrating and validating the model, respectively. Model performance was evaluated by the Nash-Sutcliffe Efficiency (E) and the volume ratio of total simulated discharge to total observed discharge (Vr).

$$E = 1 - \frac{\sum_{i=1}^n (Q_{obs_i} - Q_{sim_i})^2}{\sum_{i=1}^n (Q_{obs_i} - \overline{Q_{obs}})^2} \quad (9)$$

Table 5 - Model performance

	Calibration		Validation	
	Agaliya	Tawalama	Agaliya	Tawalama
Nash-Sutcliffe efficiency (E)%	67.63	53.75	62.73	48.31
Ratio of total simulated discharge to total observed discharge (Vr)%	93.15	105.50	84.94	104.24

where, Q_{obs_i} is the observed discharge, Q_{sim_i} is the simulated discharge, $\overline{Q_{obs}}$ is the average observed discharge, and n is the number of time step.

$$V_r = \frac{\sum_{i=1}^n Q_{sim}}{\sum_{i=1}^n Q_{obs}} \quad (10)$$

where, Q_{sim} is simulated runoff volume and Q_{obs} is observed runoff volume.

4. Results and Discussion

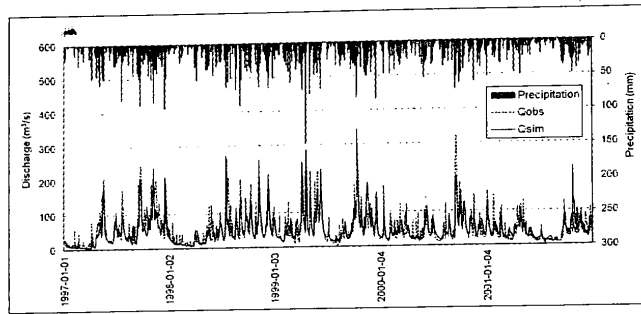
Table 5 shows the model performance during calibration and validation. Nash-Sutcliffe efficiencies in both calibration and validation at Agaliya (located downstream with 780 km² drainage area) are better than Tawalama (located upstream with 470 km² drainage area). Nash-Sutcliffe efficiency increases with the effective drainage area and this is further supported by Nawarathna *et al* (2001).

Figure 9 shows the observed and simulated discharge hydrographs during calibration and validation in Tawalama and Agaliya. According to Figure 9, the hydrographs show a good agreement between the observed and simulated discharges in Agaliya during both calibration and validation except for few extreme events. In particular, the low flows are simulated very well. Except for few years during which the simulated peaks are similar to the observed ones, most of the peak flows are underestimated. The reliability of the simulation results depends also upon the availability and quality of the input data. The deviation of simulated discharge from the observed is believed to be due to the overall error in the catchment rainfall estimation and uncertainty associated with the river discharge observations during peak flows. Catchment rainfall varies with altitude with mean annual rainfall above 3500 mm in the upper reaches, 2500-3500 mm in the middle reaches and less than 2500 mm in the lower reaches of the catchment. Most of the rain gauging stations lie in the upper and the lower reaches of the

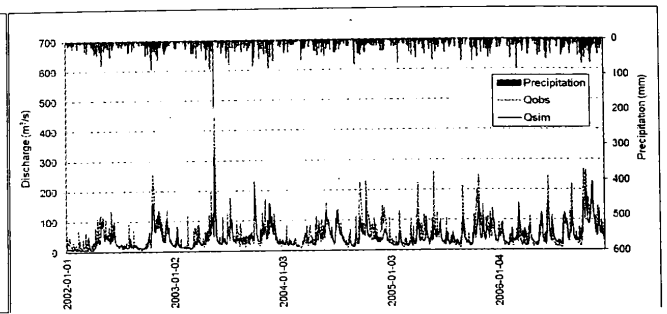


(a)

Calibration



Validation



(b)

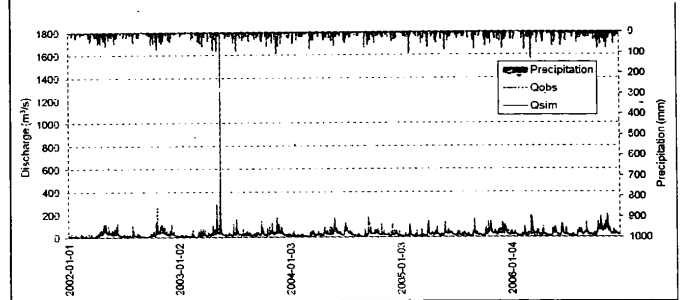
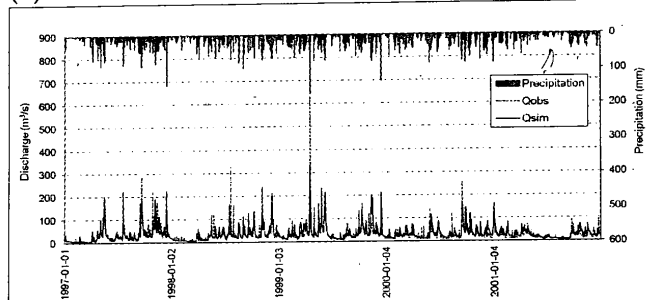


Figure 9 - Observed and simulated discharge hydrographs

Q_{obs} is the observed discharge and Q_{sim} is the simulated discharge during calibration and validation in (a) Tawalama and (b) Agaliya

catchment. Rainfall estimations in the middle reaches are based on the approximations using the nearest stations. This leads to formation of large Thiessen polygons in the middle reaches of the basin (Figure 6) in resulting less accurate rainfall estimations. The main storm runoff generation process considered by the YHyM/BTOPMC is surface runoff due to saturation excess overland flow. Hence the peak flow estimations during the monsoon seasons with high rainfall intensities might have been affected due to the lack of ability of the model to incorporate the infiltration excess runoff mechanism.

The model validation results at Agaliya during 2002–2006 are shown in Figure 10 for which the Nash-Sutcliffe efficiency is 62.73% and volume ratio is 84.94% (Table 5). According to Figure 10(b), in response to the rainfall, base flow shows rather direct action due to the sandy textured soils present in substantial area of the catchment. Considering Figure 10(a) and Figure 10(d), it can be shown how the model output simulates variation of the soil moisture condition of the catchment. Just after a dry season, with the start of rainfall [shown by rising limbs of the hydrographs in Figure 10(a)], SD begins to decrease from its maximum. With the continuation of rainfall, S_{rz} is increasing and S_{uz} also begins to increase. During a peak flow

event, both S_{rz} and S_{uz} achieve their maximum values. At the end of the peak flow event, with the decrease of rainfall, S_{uz} decreases with a gradual increase of SD . When S_{uz} achieves its minimum, S_{rz} begins to decrease and SD further increases. ET is considered to occur from the root zone according to the EP and the availability of water in the root zone. The variation of ET [Figure 10(c)] follows the pattern of S_{rz} change [Figure 10(d)] in accord with the fact that the evaporation takes place basically from the root zone. When there is enough rainfall, ET reaches nearly to its potential value which is EP .

5. Conclusions

According to the results, YHyM/BTOPMC model simulation adequately represented the major hydrological characteristics in Gin ganga watershed including runoff volume, base flow and soil moisture states of the catchment. The study utilized the global data sets readily available in public domain along with the local available rainfall and discharge data as input to the model. This suggests the applicability of YHyM/BTOPMC model for hydrologic simulations in data-poor (limited availability of local data) watersheds for which most of the required datasets could be acquired from global archives.

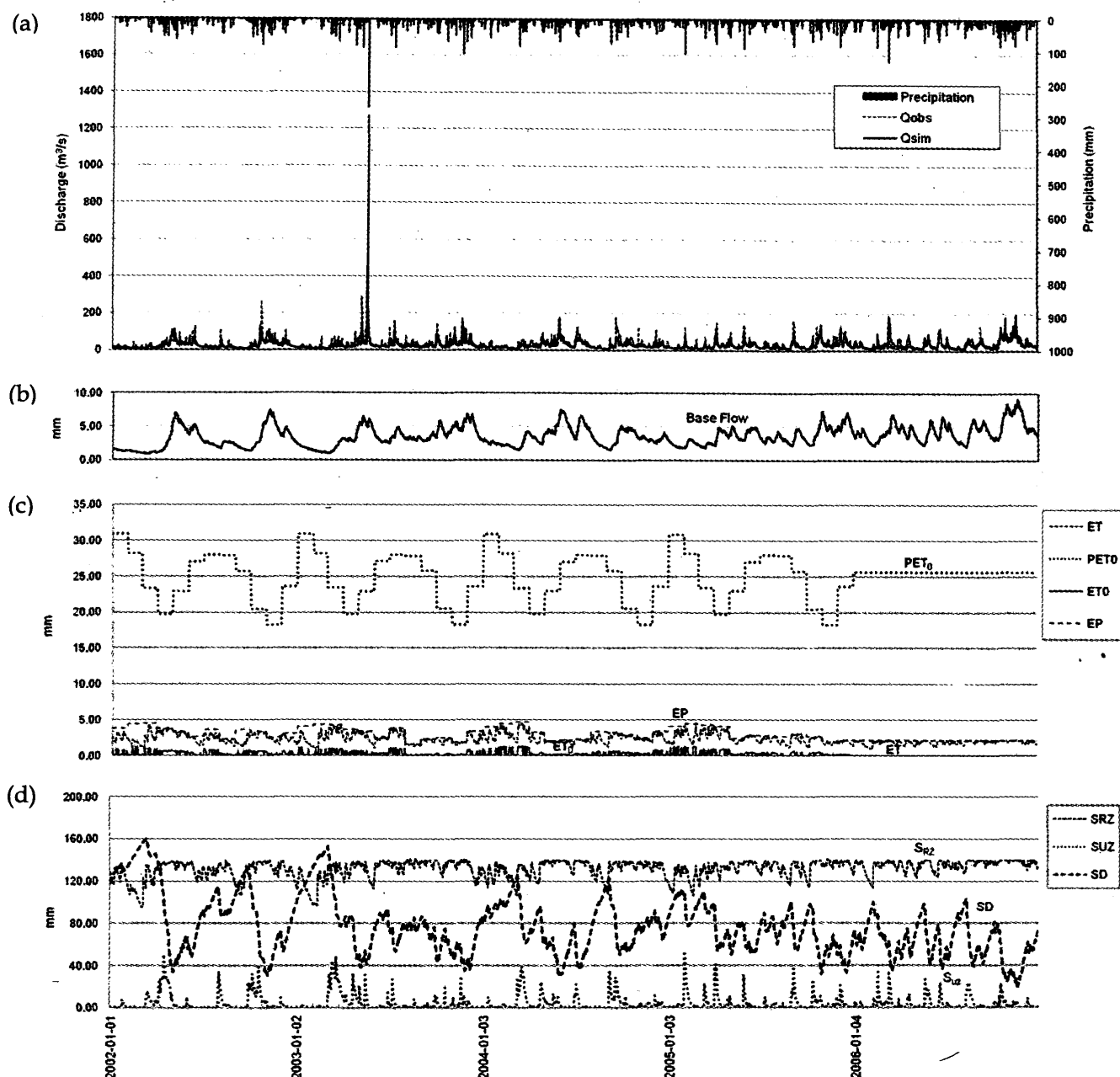


Figure 10 - Model validation results at Agaliya discharge gauging station during 2002-2006.

(a) Observed (Q_{obs}) and simulated discharge (Q_{sim}) hydrographs; (b) estimated base flow; (c) estimated average evapotranspiration (PET_0 is the potential evaporation from interception, EP is potential evapotranspiration from root zone, ET_0 is the actual evaporation from interception, and ET is the actual evapotranspiration from root zone); (d) Variation of estimated soil moisture (SD is the average saturation deficit, S_{rz} is the average storage in the root zone and S_{uz} is the average storage in unsaturated zone)

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