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Semi-distributed Rainfall-runoff Modeling utilizing ASTER DEM in Pinang Catchment of Malaysia

(Model Separa Edaran Curahan Hujan-Aliran menggunakan ASTER DEM di Kawasan Tadahan Pinang Malaysia)

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ABSTRACT

This paper presents the application of TOPMODEL in the Pinang catchment of Malaysia for stream flow simulation. An attempt has been made to use remote-sensing data (ASTER DEM of 30 m resolution) as a primary input for TOPMODEL in order to simulate the stream flow pattern of this tropical catchment. A calibration period was executed based on 2007-2008 hydro-meteorological dataset which gave a satisfactory Nash-Sutcliffe model (NS) model efficiency of 0.749 and a relative volume error (RV_E) of -19.2. The recession curve parameter (m) and soil transmissivity at saturation zone (T_o), were established as the most sensitive parameters through a sensitivity analysis processes. Hydro-meteorological datasets for the period between 2009 and 2010 were used to validate the model which resulted in satisfactory efficiencies of 0.774 (NS) and -19.84 (RV_E), respectively. This study demonstrated the ability ASTER DEM acquired from remote sensing to generate the required TOPMODEL parameters for stream flow simulation which gives insights into better management of available water resources.

Keywords: ASTER DEM; Pinang; remote sensing; sensitivity analysis; topographic index (TI) tropical area

ABSTRAK

Kertas kerja ini membentangkan penggunaan TOPMODEL di kawasan tadahan Pinang, Malaysia bagi simulasi aliran sungai. Percubaan telah dibuat untuk menggunakan data penderiaan jauh (ASTER DEM resolusi 30 m) sebagai input utama bagi TOPMODEL untuk mensimulasikan corak aliran sungai tadahan tropika ini. Tempoh penentukuran telah disempurnakan berdasarkan dataset meteorologi hidro 2007-2008 yang memuaskan model Nash-Sutcliffe (NS); model kecekapan 0.749 dan relatif jumlah kesilapan (RV_E)-19.2. Parameter lengkung kemelesetan (m) dan kememancaran tanah di zon tepu (T_o), telah ditubuhkan sebagai parameter yang paling sensitif melalui proses analisis sensitiviti. Meteorologi hidro dataset untuk tempoh antara tahun 2009 dan 2010 telah digunakan untuk mengesahkan model yang mengakibatkan kecekapan yang memuaskan masing-masing 0.774 (NS) dan-19.84 (RV_E). Kajian ini menunjukkan keupayaan yang diperoleh ASTER DEM daripada teknologi pengesanan jarak jauh untuk menjana parameter TOPMODEL yang diperlukan untuk simulasi aliran sungai yang memberikan pemahaman lebih baik tentang pengurusan sumber air sedia ada.

Kata kunci: Analisis sensitiviti; DEM ASTER; indeks topografi (TI); kawasan tropika, pengesanan jarak jauh; Pinang

INTRODUCTION

There has been growing concern along many river systems due to the enormous floods in Malaysia that resulted in significant loss of life and property (Izham et al. 2011). The Pinang catchment area located on Penang Island is dominated by flash floods. Flash floods are the result of the sloped area and high rainfall as well as the cross-section capacity of the river networks feeding into this catchment. Flood management depends among other things on the relationship between rainfall and runoff. This relationship would provide basic information regarding the stream flow patterns in the study area in a way that would assist water resource managers. Modeling runoff is an important issue in the field of hydrology and in the tropics and it is one of the most complex hydrological phenomena (Güntner 1999) because of limited data on hydrological parameters as well as the scarcity of the spatial landform data required for remote sensing analysis and geographic information system (GIS) processing (Sigdel et al. 2011).

Efforts have been made to understand the nonlinearity of the relationship between rainfall and runoff. This study adopted a topographic-based model (TOPMODEL), developed by Beven and Kirkby (1979) to understand this kind of relationship by simulating the streamflow of the main river in the tropical catchment area of Penang Island. TOPMODEL is appropriate for data poor regions because it requires less data and minimal computation (Beven et al. 1995; Chappell et al. 1998; Gumindoga et al. 2011; Sigdel et al. 2011). It is widely used in various regions of the world (Beven 1997a; Campling et al. 2002; Chappell et al. 2006; Chen et al. 2010; Fleischbein et al. 2006; Kavetski et al. 2003; Kwanyuen & Pooworakulchai 2003; Molicova et al. 1997; Pradhan et al. 2008; Quinn et al. 1991; Vongtanaboon & Chappell 2009) and it has provided satisfactory results, especially for stream flow simulation. It has also been used for different purposes that address environmental (Huang & Jiang 2002), water balance assessment (Kinner & Stallard 2004) and agricultural water pollution issues (Quinn et al. 2008).

TOPMODEL is an investigative model (O'Connell 1991) that consists of a number of areas that cover two types of runoff and the flow base with underground operations. One of the key inputs of TOPMODEL is its topographic index map. It is obtained from a elevation maps such as digital elevation models (DEMs). An accurate representation of catchment topography is required with a fine resolution DEMs. Numerous of TOPMODEL studies have observed the effect of DEM resolution on catchment simulation results found that higher resolved grids gave better results. Bruneau et al. (1995), Gallant and Hutchinson (1996), Jing et al. (2012), Lin et al. (2010), Moore et al. (1993), Quinn et al. (1996, 1991), Wolock and McCabe (2000), Wolock and Price (1994), Zhang and Montgomery (1994) and Zhang et al. (1999) showed how DEM resolution affected the topographic computation features and outflow. Quinn et al. (1995) noted that different DEM resolutions can create different spatial patterns of the topographic index. Zhang and Montgomery (1994) stated that the mean of the topographic index distribution increased as data resolution became coarser. Moreover, Gallant and Hutchinson (1996) found that the DEM spatial resolution affects topographic characteristics through terrain discretization and smoothing. Fine resolution DEMs provide the specifications related to watersheds and the paths which affect the results of the simulation (Beven 1997b; Quinn et al. 1995). Due to its ability to play an important role in rainfall runoff modeling (Lee & Kim 2011), the advanced spaceborne thermal emission reflection radiometer (ASTER) DEMs were employed in this study. The accuracy of the ASTER DEMs was evaluated based on control points on the ground by LPDAAC (2001). It was used to estimate the hydrological parameters required as model inputs. Gumindoga et al. (2011) concluded that remote-sensing created by DEMs can be combined with TOPMODEL to predict stream flow in regions with poor data.

The main focus in this paper was to highlight the possibility of applying ASTER DEM based satellite imagery in a semi distributed model (TOPMODEL) to simulate the stream flow of the main river in the tropical catchment area of Penang Island.

METHODS, DATA COLLECTION AND ANALYSIS

STUDY AREA

This study examined the Pinang catchment area (Figure 1). The Pinang catchment area is located in the northern part of Penang Island and it includes the largest river basin on the Island. The geographical coordinates of the area are 5º 21' 32'' to 5º 26' 48'' N latitude and 100º 14' 26'' to 100º 19' 42'' E longitude. The study area (34km^2) is a humid tropical area with a mean annual rainfall ranging from 1800 to 3000 mm in the lowlands and highlands, respectively (Ismail 2000). The area also consists of 4 tributaries: Sungai Pinang, Sungai Air Itam, Sungai Dondang and Sungai Air Putih. The elevation ranges from 2 to 785 m above sea level.

TOPMODEL BACKGROUND AND ITS PARAMETERS

Several TOPMODEL versions have been produced in different program environments such as Matlab, Fortran and interactive data model (IDL). This study employed the IDL TOPMODEL because of the availability and its ability to deal with the topographic index histogram of the small catchment certainly. It consists of three dynamic zones, which are the root, gravity and saturated zones as shown in Figure 4. The root zone receives precipitation (P) and releases moisture at a potential rate (E_p) of evaporation until it is empty. Runoff from the contributing areas and infiltration occurs once the first zone is full. The third zone of the soil profile is assumed to have exponential outflow represented by (Figure 2).

TOPMODEL's important assumption is the similarity between the water table and ground surface slopes (hydraulic gradient approximated with ground surface slope). The direction of subsurface flow and surface flows are parallel based on topography. The subsurface flow is described by (1) (Beven et al. 1995; Romanowicz 1997). Equation 2 shows the runoff production areas calculation for the catchment area.

$$Q_b(t) = T_o e^{-\lambda} e^{-\bar{S}(t)/m}, \tag{1}$$

$$\Delta S_i = \left(S_i - \bar{S}(t)\right) = m\left(\bar{\lambda} - \lambda_i\right), \tag{2}$$

where, Q_b is the subsurface flow, $\bar{S}$ is the average soil moisture deficit, ΔS_i is the difference between the average area deficits and local area deficits, S_i is the saturation deficit at any point in the catchment area, $\bar{S}$ is the average deficit of soil at saturation for the catchment, λ_i is local topographic index and $\bar{\lambda}$ is the average catchment topographic index.

Equation 3 describes the balanced equation used to calculate the change in the soil deficit over time:

$$\frac{d\bar{S}_3(t)}{dt} = Q_b(t) - Q_v(t), \tag{3}$$

where, Q_v is an incremental flow rate which inter the third storage and $\bar{S}_3$ is the average deficit of soil at saturation for the catchment.

HYDRO-METEOROLOGICAL DATA COLLECTION

A daily inputs and outputs time step was used in this study. The Jln. P. Ramlee gauging station was the catchment outlet. The water level data sets (2007-2010) were provided by Malaysia's Department of Irrigation and Drainage (DID). The data from 2007-2008 and 2009-2010 were used as calibration and validation periods, respectively. To calculate discharge, a river cross-section was observed at

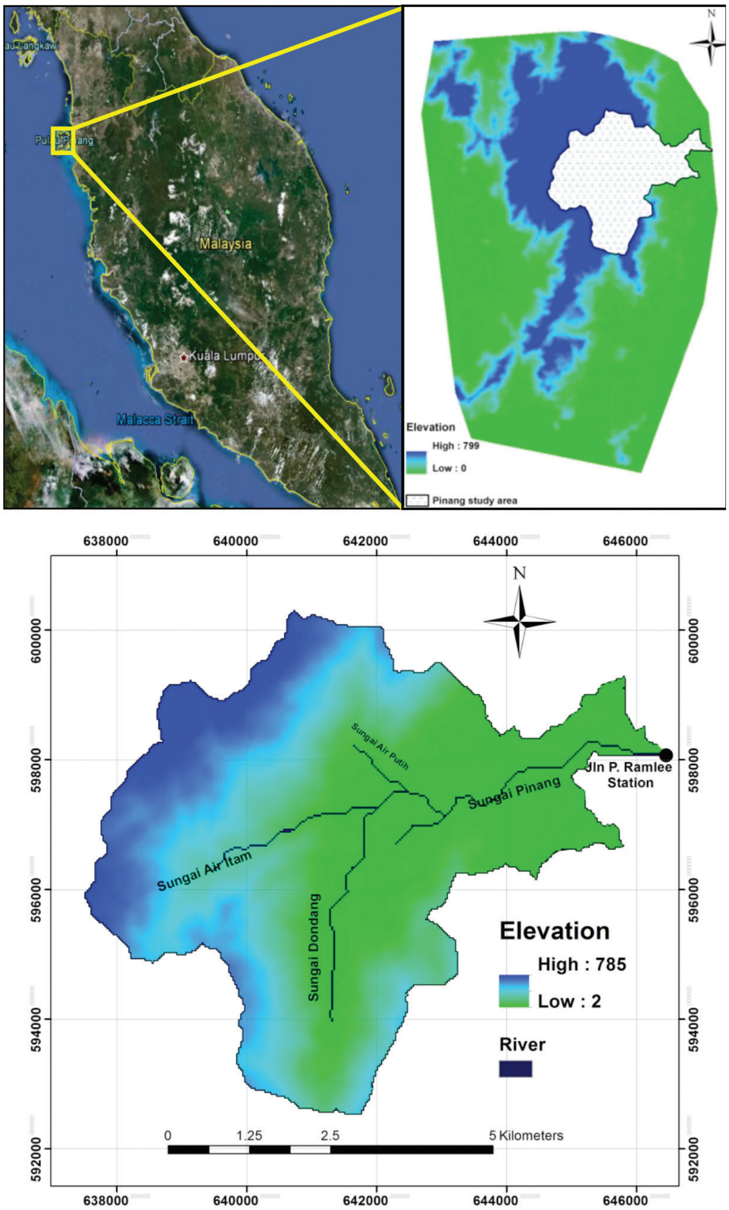

FIGURE 1. Location of Pinang catchment area in Pulau Pinang, Malaysia

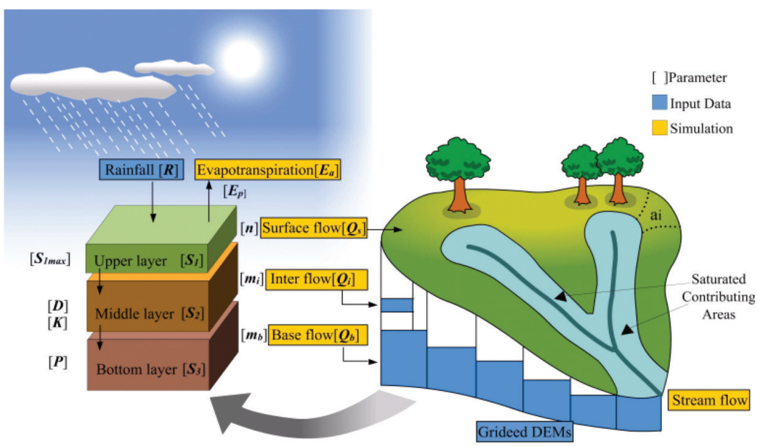

FIGURE 2. TOPMODEL scheme represents the three soil areas (Huang et al. 2009)

the outlet station using fixed surface water width (w). Since the channel is quite shallow, the side slope is considered as presented in Figure 3 and thus the estimation of channel flow based on channel's cross-section is close to accurate. The river depth (y) was assumed to vary based on the available water level datasets.

One of the issues that affected the performance of the model was rainfall heterogeneity (Candela et al. 2005). For that reason, rainfall was calculated for the study area using the Thiessen Polygons method (Figure 4). As small catchment area, the three stations Kolam Bersih, Bukit Bendera, and Kolam Air Itam were sufficient relatively to be used for areal precipitation based on Thiessen Polygon calculation shown in Table 1.

ROUTING OF OVERLAND FLOW

To implement flow routing, a delay approach was used that employed a fractional area of the catchment area for each $ln(\alpha/tan\beta)$ class (Gumindoga et al. 2011). Fractional areas helped predict the time water would take to reach the outlet. Figure 5 shows the routing of overland flows generated in a GIS. The fractional area and its distance from the outlet as well as channel velocity were used as inputs.

TOPOGRAPHIC INDEX MAP TI

A 30 m ASTER DEM for Penang Island was collected from NASA/METI from the ASTER global digital elevation model (GDEM) website. The accuracy of the elevation data of the

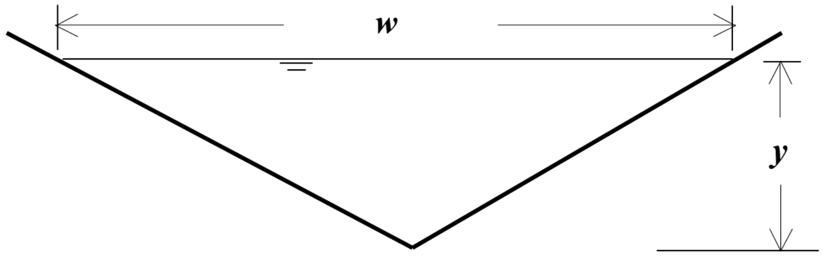

FIGURE 3. Hydraulic cross-section used for discharge calculation

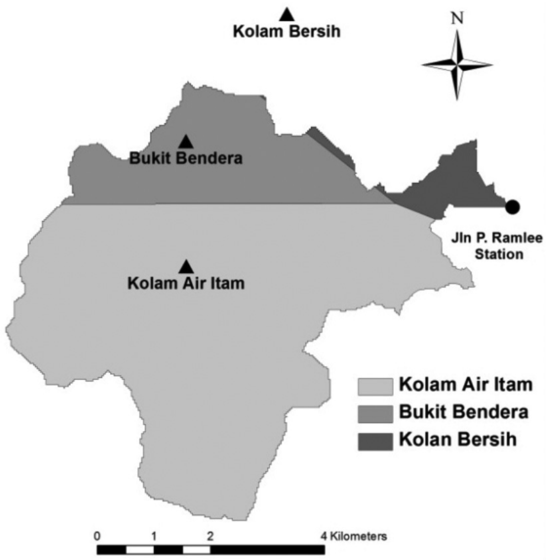

FIGURE 4. Areal precipitation estimation through Thiessen polygons with its weights

TABLE 1. Rainfall stations in UTM coordinates and Thiessen polygon weights

No.	Station name	Location X	Location Y	Covered area (km^2)	Thiessen weights
1	Kolam Air Itam	640708	597027	25.75	0.753
2	Bukit Bendera	640703	599238	6.96	0.293
3	Kolam Bersih	642483	601484	1.48	0.043

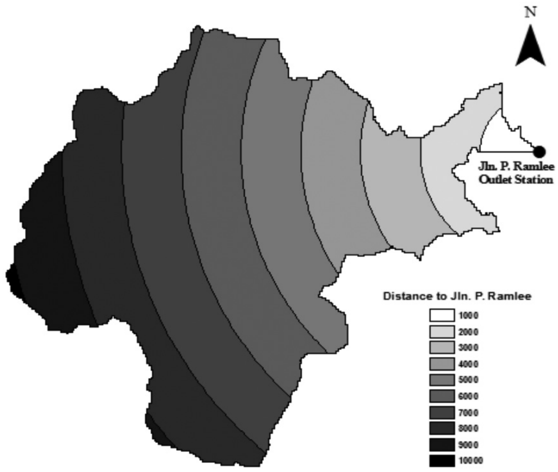

FIGURE 5. Distance map used for overland flow routing of Pinang catchment area

study area was assessed, including experimental points to show that the ASTER DEM was able to provide hydrological parameters (Vithanage 2009).

TI was introduced by Beven and Kirkby (1979) and has since then been used as a key driver in TOPMODEL simulations. The DEM hydro-processing technique in the integrated water and land information system (ILWIS) was used to remove the local depressions in the DEM before the flow direction was computed. A computation of the flow accumulation then followed. The topographic index map was produced using (4):

$$TI = \ln(\alpha / \tan\beta) \tag{4}$$

where, α is the contributing area (flow accumulation * DEM pixel area), $\tan\beta$ is the local slope of the cell and the drained area per unit of contours length in (m), respectively (Beven 1997a; Qin et al. 2007).

RESULTS AND DISCUSSION

LAND SURFACE PARAMETERIZATION

GIS and remote sensing tools are able to be used for obtaining the input parameters of TOPMODEL (Chen et al. 2003; Sigdel et al. 2011). Penang Island DEM hydro-possessing was applied to obtain a topographic index map through flow direction and flow accumulation calculations. Figure 6 shows the topographic index map produced for the Pinang catchment area. The number of pixels versus the values of topographic index map is also illustrated as a histogram. The topographic index map value was high when there was a large amount of runoff. The highest numbers of pixels found in the map were equal to 10 and this area was located inside and around the channels. It included a few north, west and south regions of Pinang catchment area, which are mountainous.

SENSITIVITY ANALYSIS

Several parameters can affect the simulation of stream flow. Some of these parameters are described as sensitive (Beven & Kirkby 1979; Beven & Freer 2000; Gumindoga et al. 2011) depending on the conditions of the catchment areas in the study. The most sensitive TOPMODEL parameter was the recession parameter m, which was described by Gallart et al. (1994) and Romanowicz (1997). During the pre-calibration process, the parameter's influences were observed. Their ranges were specified based on trial and error. From the pre-calibration process and based on current relevant literature, specific parameters were selected for sensitivity analysis. However, the efficiency of the model was calculated in terms of Nash Sutcliffe (NS) (Nash & Sutcliffe 1970) and relative volume error (RV_E) (Janssen & Heuberger 1995) (5) and (6), respectively. The result of this process, the recession curve parameter m, and the soil transmissivity at saturation zone T_o (shown in (1)) were selected as the most sensitive parameters for their sensitivity in order to create a simulation of the period from 2007 to 2008.

$$NS = 1 - \frac{\sum_{i=1}^{n}\left(Q_{obs} - Q_{sim}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs} - \bar{Q}_{obs}\right)^2}, \tag{5}$$

$$RV_E = \left[\frac{\sum_{i=1}^{n}\left(Q_{sim} - Q_{obs}\right)}{\sum_{i=1}^{n} Q_{obs}},\right] * 100\%, \tag{6}$$

where, n is the total number of time steps, Q_{obs}, Q_{sim}, $\bar{Q}_{obs}$ are observed, simulated and mean observed discharges, respectively.

Sensitivity Analysis for M Parameter Effect The recession curve parameter m was chosen to be a significant

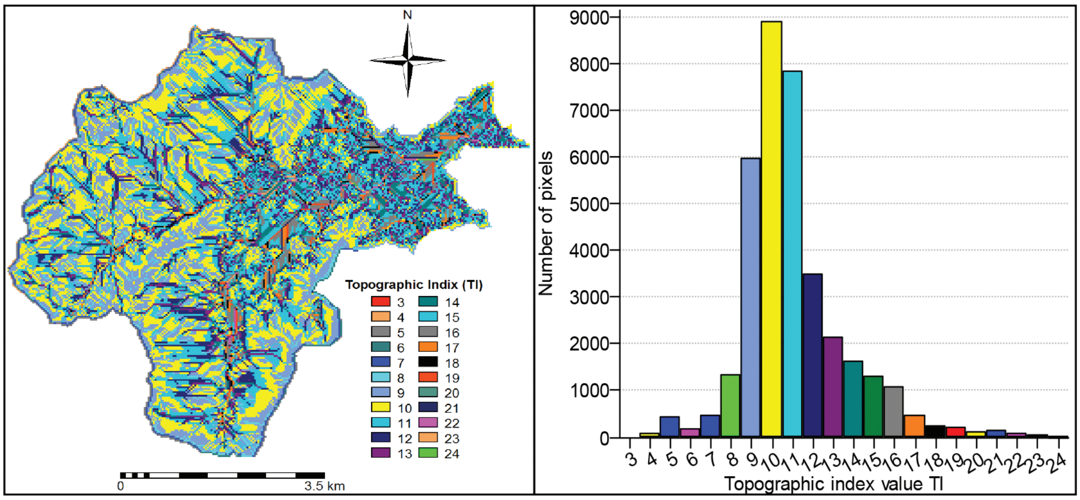

FIGURE 6. The topographic index map and the topographic index value distribution

TOPMODEL input parameters. It was analyzed and reviewed by Tallaksen (1995). It describes the behavior of soil transmissivity by depth and for different discharge values, which were assumed to be an exponential profile. This parameter was evaluated through recession curve analysis. Recession curve parameter *m* can be used for subsurface drainage prediction as shown in (1). It is also used as scaling parameter for regions that contribute runoff, as shown in (2) (Romanowicz 1997). It assumes that the transmissivity effectiveness at saturation over all catchment areas is homogeneous.

The parameter *m* influences the simulated of surface saturation for a given zone and the amount of area required in a zone to achieve a given increase in runoff for a contributing area. A high *m* value reflects a deep infiltration rate and slow response to rainfall (Beven & Kirkby 1979). The values of the TOPMODEL parameters were fixed to range between 0.1 and 0.9. Figure 7 shows the relationship between *m* and the chosen efficiencies. The lowest values for NS and RV_E were set to 0.384 and 13.467 for and these represent the lowest values for parameter *m*. This meant that NS increased and RV_E decreased when the *m* values increased. The highest value of efficiency for NS was 0.748, which was found when *m* was equal to 0.7. This was unlike the RV_E efficiency, which was -19.202, at the same *m* value. Significant water balance errors can be found from increasing RV_E with smaller values of *m* (Gumindoga et al. 2011).

Sensitivity Analysis to T_o Parameter Effect All values for the TOPMODEL parameters were fixed during the sensitivity analysis for the T_o parameter. The impervious characteristic of the study area was represented by T_o. It simulated hydrograph, especially on the rising and falling limb, without affecting the baseflow (Sigdel et al. 2011). Figure 8 shows the relationship between the T_o parameter with each NS and RV_E change. The T_o parameter values ranged between 4 and 12. NS efficiency values ranged from the lowest value of 0.656 to its highest value of 0.748 when T_o was equal to 7.

Unlike the RV_E efficiency values, which ranged from 14.112 to -19.43 when T_o was equal to 4 and 12, respectively. Deep effective soil was generated whenever a high value of the *m* parameter was coupled with small value of for the T_o parameter. In this study, a high T_o value was investigated with high *m* value to accommodate for the high percentage urbanized area in the Pinang catchment area. This produced a simulation with a quick response to runoff with low transmitting capacity and water holding.

RESULTS OF THE CALIBRATION PROCESS

Based on the sensitivity analysis of the parameters *m* and T_o, the results of the calibration period were executed. In terms of matches, the calibration period was weak. Figure 9 shows that the baseflows for the months from February to May and from July and August of 2007, as well April, July and August of 2008, were underestimated. This reflected an unsatisfactory performance of the baseflow simulation. The baseflow was overestimated for November and December of 2007 and 2008. Using the sensitivity analysis process, the optimization improved the hydrograph by the increasing the NS and RV_E efficiencies to 0.749 and -19.2, respectively. TOPMODEL tends to underestimate the simulation of overall period and its performance is fairly well. Figures 7 and 8 show the relationship between the parameters and the values that were optimized. The priority was given to NS. The critical values were calculated and are shown in Table 2. These were used in the validation period as fixed parameters with the hydro-meterlogical data sets.

RESULTS OF THE VALIDATION PROCESS

The hydro-meteorological datasets of 2009-2010 were applied using the optimized parameters transferred from a calibration period to validate the model. Figure 10 shows the result of the validation period. Accurate matches were shown for rising limbs and the recession portion of the simulated hydrograph for May until October of 2009. Good matches were found between June, July, August, November and December of 2010. However, it failed to match the peak for October 2009 and the results were overestimated until May 2010. The simulated discharge from January to April 2009 and for a few months in 2010 was underestimated. Furthermore, the overestimation

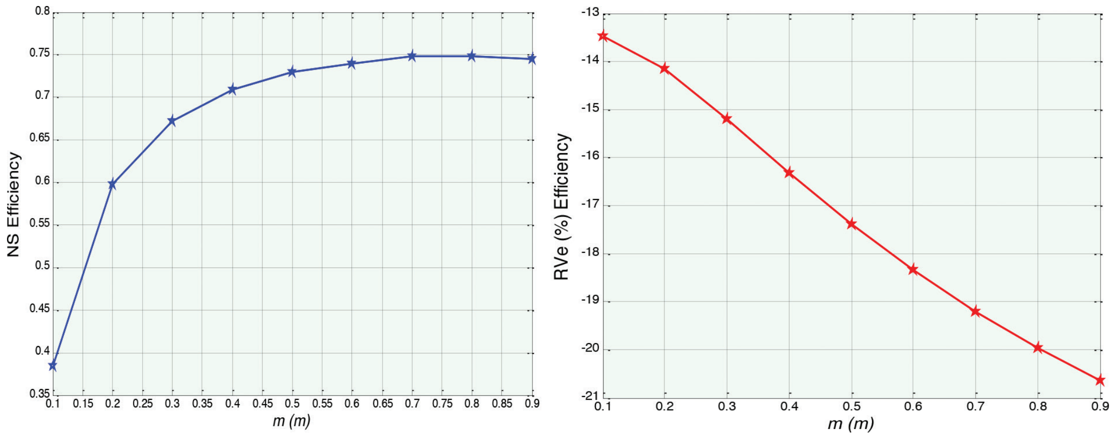

FIGURE 7. The effect of *m* parameter on NS and RV_E efficiencies

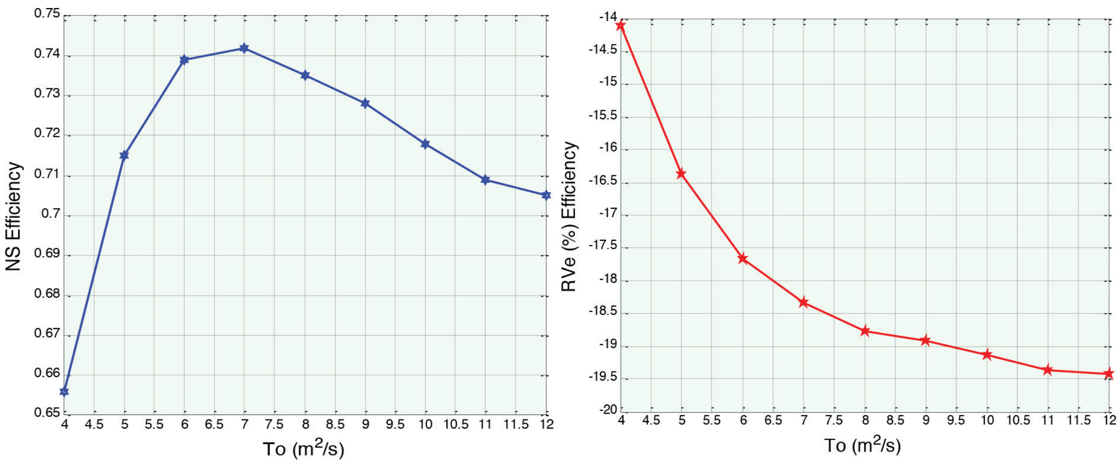

FIGURE 8. The effect of T_o parameter on NS and RV_E efficiencies

TABLE 2. Parameters values used in calibration period process and their significance

Parameter	Descriptions	Impact	Value
m (m)	Control the rate of exponential decrease of transmissivity with increasing soil moisture and infiltration characteristics	highly sensitive	0.7
T_o (m^2/h)	Control the peak flow and shape of storm hydrograph	highly sensitive	7
$SR_{max}(m)$	Maximum root zone storage, physically based, control Evaporation and local saturation deficit	sensitive	0.0015
Td (h)	Time delay constant, control the recharge rate from unsaturated to saturated zone	sensitive	2
Q_O *(m/timestep)*	Initial observed discharge	sensitive	0.0048
SR_O *(m)*	Initial root zone storage value	sensitive	0.055
CHV (m/h)	Control surface routing velocity, physically based	less sensitive	500
RV (m/h)	Stream velocity	less sensitive	250
INFEX	An infiltration flag	insensitive	1
Ko (m/h)	Hydraulic conductivity at surface	insensitive	0.008
Δ_ψ	Effective suction head	insensitive	0.14
$\Delta\theta$	Moisture deficit	insensitive	0.360

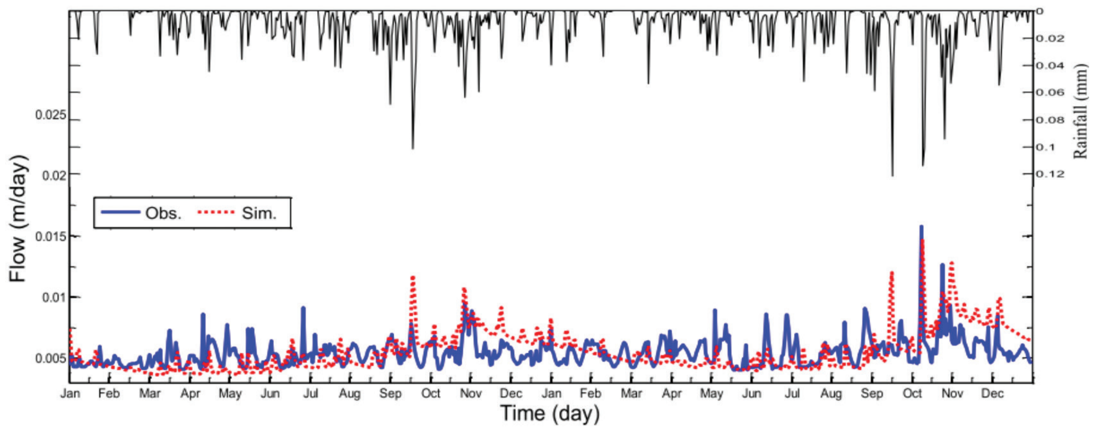

FIGURE 9. Simulated and observed discharge for calibration period, 2007-2008 at Pinang catchment area, Malaysia

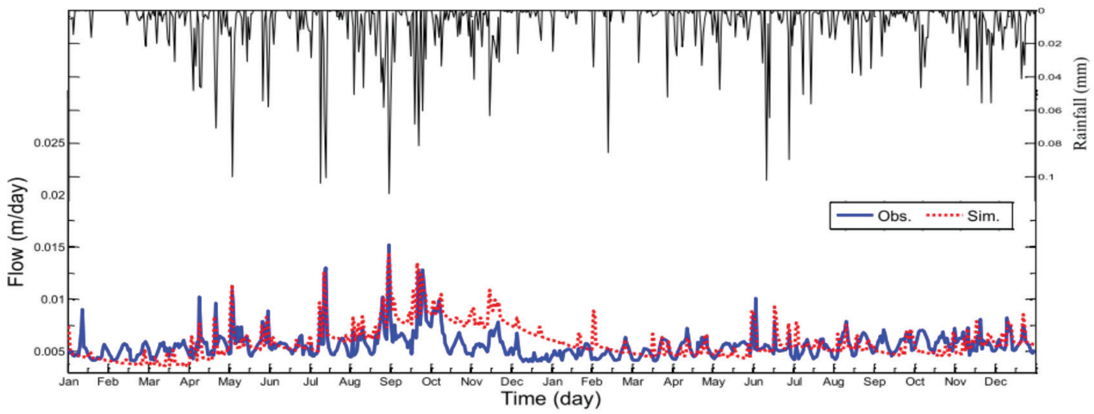

FIGURE 10. Simulated and observed discharge for validation period, 2009-2010 at Pinang catchment area, Malaysia

of baseflow was due to the spatial distribution of the rainfall may have been inaccurately represented as a result. Another contributing factor may have been errors in the input data for such a data poor area such as the Pinang catchment area. The model itself may also have been at fault. A satisfactory level of performance was obtained through NS and RV_E efficiencies of 0.774 and -19.84, respectively (Elsner et al. 2010; Freer et al. 2004) (Table 3). Due to the superior quality of the data, a better result of the validation period was found in terms of NS efficiency. Likewise, the RVE efficiency was less when compared with the calibration period.

CONCLUSION

TOPMODEL is used in this paper to simulate the stream flow of the small Pinang catchment area located in tropics. However, the following conclusions were drawn. Firstly, TOPMODEL was successfully applied in a tropical catchment area to simulate the stream flow. The efficiencies for NS and RV_E were 0.749 and -19.2 for calibration period (2007-2008) and 0.774 and -19.84 for the validation period (2009-2010). Secondly, the two parameters, m and T_o were more sensitive to the simulated discharge hydrograph based on the efficiency of NS and RV_E. In addition, this study used the capabilities of a remote sensing ASTER 30

TABLE 3. Results obtained from calibration and validation processes

Periods	Calibration 2007 - 2008	Validation 2009 - 2010	Importance
NS	0.749	0.774	Quantitatively describes the model accuracy for time scale models
RV_E	-19.2	-19.84	Measuring volume errors by assessing the mass balance error between the observed and the simulated discharges

m DEM provided by METI/NASA to transfer the study area topography to simulate the flow of streams.

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REFERENCES

Beven, K. & Freer, J. 2000. A dynamic TOPMODEL. *Hydrological Processes* 15(10): 1993-2011.

Beven, K. 1997a. TOPMODEL: A critique. *Hydrological Processes* 11: 1069-1085.

Beven, K.J. 1997b. *Distributed Hydrological Modelling: Applications of the TOPMODEL Concept*. Chichester, U.K.: John Wiley and Sons Ltd.

Beven, K.J., Lamb, R., Quinn, P.F., Romanowicz, R. & Freer, J. 1995. TOPMODEL. In *Computer Models of Watershed Hydrology*, edited by Singh, V.P. Water Resources Publications. pp. 627-668.

Beven, K.J. & Kirkby, M.J. 1979. A physically based variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin* 24(1): 43-69.

Bruneau, P., Gascuel-Odoux, C., Robin, P., Merot, P. & Beven, K. 1995. Sensitivity to space and time resolution of a hydrological model using digital elevation data. *Hydrological Processes* 9: 69-81.

Campling, P., Gobin, A., Beven, K. & Feyen, J. 2002. Rainfall-runoff modelling of a humid tropical catchment: the TOPMODEL approach. *Hydrological Processes* 16: 231-253.

Candela, A., Noto, L.V. & Aronica, G. 2005. Influence of surface roughness in hydrological response of semiarid catchments. *J. Hydrol*. 313(3): 119-131.

Chappell, N.A., Vongtanaboon, S., Jiang, Y. & Tangtham, N. 2006. Return-flow prediction and buffer designation in two rainforest headwaters. *Forest Ecology and Management* 224: 131-146.

Chappell, N.A., Franks, S.W. & Larenus, J. 1998. Multi-scale permeability estimation in a tropical catchment. *Hydrological Processes* 12: 1507-1523.

Chen, X., Cheng, Q., Chen, Y.D., Smettem, K. & Xu, C. 2010. Simulating the integrated effects of topography and soil properties on runoff generation in hilly forested catchments, south China. *Hydrological Processes* 24(6): 714-725.

Chen, Y., Zhu, D. & Zhao, J. 2003. Small basin flash flood simulation with TOPMODEL. In *GIS and Remote Sensing in Hydrology, Water Resources and Environment (IAHS Proceedings & Reports*) vol. 289, edited by Chen, Y., Takara, K., Cluckie, I.D. & De Smedt, F.H. IAHS Publication. pp. 41-49.

Elsner, M.M., Cuo, L., Voisin, N., Deems, J.S., Hamlet, A.F., Vano, J.A., Mickelson, K.E.B, Lee, S.Y. & Lettenmaier, D.P. 2010. Implications of 21st century climate change for the hydrology of Washington State. *Climatic Change* 102(1-2): 225-260.

Fleischbein, K., Wilcke, W., Valarezo, C., Zech, W. & Knoblich, K. 2006. Water budgets of three small catchments under montane forest in ecuador: Experimental and modelling approach. *Hydrological Processes* 20(12): 2491-2507.

Freer, J.E., McMillan, H., McDonnell, J.J. & Beven, K.J. 2004. Constraining dynamic TOPMODEL responses for imprecise water table information using fuzzy rule based performance measures. *Journal of Hydrology* 291(3-4): 254-277.

Gallant, J. & Hutchinson, M. 1996. Towards an understanding of landscape scale and structur. In *Proceedings, Third International Conference/Workshop on Integrating GIS and Environmental Modelling,* Santa Fe, NM. pp. 21-26.

Gallart, F., Llorens, P. & Latron, J. 1994. Studying the role of old agricultural terraces on runoff generation in a small Mediterranean mountainous basin. *Journal of Hydrology* 159: 291-303.

Gumindoga, W., Rwasoka, D.T. & Murwira, A. 2011. Simulation of streamflow using TOPMODEL in the upper save river catchment of Zimbabwe. *Physics and Chemistry of the Earth* 36: 806-813.

Güntner, A., Uhlenbrook, S., Seibert, J. & Leibundgut, C. 1999. Multi-criterial validation of TOPMODEL in a mountainous catchment. *Hydrological Processes* 13(11): 1603-1620.

Huang, B. & Jiang, B. 2002. AVTOP: A full integration of TOPMODEL into GIS. *Environmental Modeling and Software* 17(3): 261-268.

Huang, J.C., Lee, T.Y. & Kao, S.J. 2009. Simulating typhoon-induced storm hydrographs in subtropical mountainous watershed: An integrated 3-layer TOPMODEL. *Hydrology and Earth System Sciences* 13: 27-40.

Ismail, W.R. 2000. The hydrology and sediment yield of the Sungai Air Terjun catchment, Penang Hill, Malaysia. *Journal of Hydrological Sciences* 45(6): 897-910.

Izham, M.Y., M. Uznir, U., Alias, A.R., Ayob, K., W. Ruslan, I. 2011. Influence of geo-reference for saturated excess overland flow modeling using 3D volumetric soft geo-objects. *Computers & Geosciences* 37(4): 598-609.

Janssen, P.H.M. & Heuberger, P.S.C. 1995. Calibration of process-oriented models. *Ecol. Model*. 83(1-2): 55-66.

Jing Xu, Liliang Ren, Fei Yuan & Xiaofan Liu. 2012. The solution to DEM resolution effects and parameter inconsistency by using scale-invariant TOPMODEL. *Hydrology Research* 43(1-2): 146-155.

Kavetski, D., Kuczera, G. & Franks, S.W. 2003. Semidistributed hydrological modeling: A 'saturation path' perspective on TOPMODEL and VIC. *Water Resour.* Res. 39 art.no. 1246.

Kinner, D.A. & Stallard, R.F. 2004. Identifying storm flow paths in a rainforest catchment using hydrological and geochemical modelling. *Hydrological Processes* 18: 2861-2875.

Kwanyuen, B. & Pooworakulchai, C. 2003. Comparison of HEC-HMS model and Topmodel for runoff prediction in Lampachi Basin. *Kamphaengsaen Acad. J.* 1: 49-55.

Lee, Giha & Kim, Joo-Cheol. 2011. Comparative analysis of geomorphologic characteristics of DEM-based drainage networks. *Journal of Hydrologic Engineering* 16(2): 137-147.

Lin, Kairong, Qiang Zhang & Xiaohong Chen. 2010. An evaluation of impacts of DEM resolution and parameter correlation on TOPMODEL modeling uncertainty. *Journal of Hydrology* 394(3-4): 370-383.

LPDAAC. 2001. ASTER Digital Elevation Model (DEM) Product Description, http://asterweb.jpl.nasa.gov/ content/03_data/01_Data_Products/DEM.

Molicova, H., Grimalidi, M., Bonell, M. & Hubert, P. 1997. Using TOPMODEL towards identifying and modelling the hydrological patterns within a headwater, humid tropical catchment. *Hydrological Processes* 11: 1169-1196.

Moore, I.D., Lewis, A. & Gallant, J.C. 1993. Terrain attributes: Estimation methods and scale effects. In *Modelling Change in Environmental Systems,* edited by Jakeman, A.J., Beck, M.B. & McAleer, M.J. New York: John Wiley and Sons Ltd. pp. 189-214.

Nash, J.E. & Sutcliffe, J.V. 1970. River flow forecasting through conceptual models. Part I: A discussion of principles. *Journal of Hydrology* 10: 282-290.

O'Connell, P.E. 1991. A historical perspective. In *Proc. NATO Advanced Institute on Recent Advances in the Modeling of Hydrologic Systems* (Sintra, Portugal, 10-23 July 1988), edited by Bowles, D.S. & O'Connell, P.E. The Netherlands: Kluwer, Dordrecht.

Pradhan, N.R., Ogden, F.L., Tachikawa, Y. & Takara, K. 2008. Scaling of slope, upslope area, and soil water deficit: Implications for transferability and regionalization in topographic index modeling. *Water Resources Research* 44(12): DOI: 10.1029/2007WR006667.

Qin, X., Ahn, S., Speed, T.P. & Rubin, G.M. 2007. Global analyses of mRNA translational control during early Drosophila embryogenesis. *Genome Biol*. 8, R63.

Quinn, P.F., Mewett, C.T.M. & Dayawansa, N.D.K. 2008. TOPCAT-NP: A minimum information requirement model for simulation of flow and nutrient transport from agricultural systems. *Hydrological Processes* 22: 2565-2580.

Quinn, P., Cummins, M., Kase, J., Martin, E. & Weissman, S. 1996. Development of categorical representations for above and below spatial relations in 3- to 7-month old infants. *Developmental Psychology* 32(5): 942-950.

Quinn, P.F., Beven, K.J. & Lamb, R. 1995. The Ln(a/TanB) Index: How to calculate it and how to use it within the Topmodel framework. *Hydrological Processes* 9: 161-182.

Quinn, P.F., Beven, K.J., Chevallier, P. & Planchon, O. 1991. The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. *Hydrological Processes* 5: 59-79.

Romanowicz, R. 1997. A MATLAB implementation of TOPMODEL. *Hydrological Processes* 11: 1115-1129.

Sigdel, Abinashi., Jha, Raghunath, Bhatta, Dhruba, Abou-Shanab, Reda A.I., Sapireddy, Veer Raghavulu and Byong-Hun Jeon. 2011. Applicability of TOPMODEL in the catchments of Nepal: Bagmati River Basin. *Geosystem Engineering* 14(4): 181-190.

Tallaksen, L.M. 1995. A review of baseflow recession analysis. *Journal of Hydrology* 165: 349-370.

Vithanage, Bihawala I.C. 2009. Analysis of nutrient dynamics in Roxo catchment using remote sensing data and numerical modeling. MSc Thesis, ITC, Educational material (unpublished).

Vongtanaboon, S. & Chappell, N.A. 2009. Validation and interpretation of spatial soil-water modelling in the tropical subcatchments of maechaem basin. Paper presented at the IAHS-AISH Publication 326: 174-180.

Wolock, D.M. & McCabe, G.J. 2000. Differences in topographic characteristics computed from 100- and 1000 m resolution digital elevation model data. *Hydrological Processes* 14(6): 987-1002.

Wolock, D.M. & Price, C.V. 1994. Effects of digital elevation model map scale and data resolution on a topography based watershed model. *Water Resour. Res*. 30(11): 3041-3052.

Zhang, W. & Montgomery, D.R. 1994. Digital elevation model grid size, landscape representation, and hydrologic simulations. *Water Resour. Res*. 30: 1019-1028.

Zhang, X., Drake, N.A., Wainwright, J. & Mulligan, M. 1999. Comparison of slope estimates from low resolution DEMs: Scaling issues and a fractal method for their solution. *Earth Surface Processes and Landforms* 24: 763-779.

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