JOURNAL OF FLOOD ENGINEERING
5(1-2) January-December 2014; Pp. 17–37

ISSN : 0976-6219

DISTRIBUTED FLOOD SIMULATIONS ON A SMALL TROPICAL WATERSHED WITH THE TREX MODEL

J. Abdullah[1] and P. Y. Julien[2]
[1]*Graduate Student, Department of Civil and Environmental Engineering, Colorado State University Fort Collins, Colorado 80523, and Lecturer, Faculty of Civil Engineering, UniversitiTeknologi MARA 40450 Shah Alam, Selangor, MALAYSIA*
[2]*Professor, Department of Civil and Environmental Engineering, Colorado State University Fort Collins,Colorado 80523, USA*

ABSTRACT: Estimating the peak discharge and time to peak are two most important factors in the design of flood control structures. This article focuses on two-dimensional (2D) hydrological modeling application in Malaysia. The objectives of this study are: (1) to evaluate the model performance in simulating the rainfall-runoff relationship, (2) to compare the simulated peak discharge $Q_p$from 1D and 2D models with a flood frequency analysis and (3) to conduct a sensitivity analysis mainly to evaluate Q_p and the runoff coefficient C. A 2D distributed model to simulate infiltration, overland flow and channel runoff was successfully applied to a small tropical watershed in Malaysia. A grid size analysis considers the time to prepare the input data, simulation time, model performance and post-processing of the results. It is found thata resolution smaller than 90 m is bestto simulate runoff from small watersheds. A comparison with a 1D model showed that the 2D model parameters better represent the field conditions. The flood frequency analysis alsoshows that the TREX model is beneficial in extending the results to extreme rainfall-runoff conditions.The runoff coefficient C increased significantly by a factor of three from the 100-year rainfall event to the PMP and the world's largest events (C_{PMF},C_{WMF}> 0.6).

Keywords: TREX Model,Small Tropical Watershed,Grid Analysis, Sensitivity and Uncertainty Analyses.

1. INTRODUCTION

Malaysia consists of two geographical regions divided by the South China Sea. Peninsular Malaysia shares a land border on the north with Thailand and is connected by the two bridges on the south with Singapore. The temperature in the tropics rarely exceeds 35°C because sun heat generates the evaporation and rain formation. At night, the abundant cloud cover restricts heat loss and minimum temperatures fall no lower than about 22°C. Peninsular Malaysia receives an average rainfall of 2,500 mm.

In Malaysia, models from the United Kingdom (UK), United States of America (USA) and Australia are widely used for rainfall-runoff simulations. Mah *et al.* (2007, 2010 and 2011), Said *et al.* (2009) and Ali and Ariffin (2011) used the commercial software InfoWorks River Simulation (IWRS) and Siang *et al.* (2007) used InfoWorks Collection System (IWCS) from the UK to simulate rainfall-runoff. Hydrological models from the USA such as HEC group model (i.e. HEC-RAS and HEC-HMS) (Yusop *et al.,* 2007; Razi *et al.,* 2010; Mohammed *et al.,* 2011), L-THIA program (Izham, 2010), MIKE (Billa *et al.,* 2004 and 2006; Lim and Cheok, 2009) and MAYA 3D (Ghazali and Kamsin, 2008) have been used to simulate flood events.

Teo *et al.* (2009) and Toriman *et al.* (2009) used the 2DSWAMP and XP-SWMM models from Australia to simulate runoff. Except for the L-THIA and HEC group models, the other models listed are not publicly available. Most hydrological modeling studies in Malaysia were carried out using a one-dimensional (1D) approach. While modelers are aware of the advantages of two-dimensional models, the lack of reliable information is the main reason why modelers avoid using them (Eslamian, 2014).

The ability of the distributed two-dimensional (2D) TREX model to work with raster GIS database and to go beyond the stochastic approach with 1D model provides the motivation for this study. This model was applied on a small tropical watershed in Malaysia. The objectives of this study are: (1) to evaluate the application of the TREX model into small tropical watershed, (2) to determine the best grid size to represent the water depth, (3) to compare the estimated peak discharge between flood frequency analysis, 1D model and 2D model and (4) to describe the entire set of possible discharges and runoff coefficients for extreme events. For this study, the classifications of the watershed size as defined by Singh (1995) will be used. He categorized the area of a watershed that is less than 100 km^2 is small.

2. TWO-DIMENSIONAL DISTRIBUTED PHYSICALLY-BASED TREX MODEL

TREX is a fully-distributed, physically-based model that can be used to simulate precipitation, overland runoff, channel flow, soil erosion, stream sediment transport and chemical transport and fate at the watershed scale (Velleux *et al.* 2008; England *et al.* 2007; Velleux *et al.* 2006; Velleux 2005). This framework is based on the CASC2D watershed model (Julien *et al.* 1995; Johnson *et al.* 2000; Julien and Rojas 2002). TREX has three main components which are hydrology, sediment transport and chemical transport and fate. The hydrological processes simulated are rainfall (England *et al.* 2007; Velleux 2005; Velleux *et al.* 2006; Velleux *et al.* 2008; Abdullah 2013) and snowfall (precipitation), interception, snowmelt (Kang 2005), and surface storage, infiltration and transmission loss and overland and channel flow. Precipitation can be uniform or distributed in both time and space (Jorgeson 1999; Ogden 1992; Ogden and Julien 1993, 1994 and 2002; Ogden *et al.* 2000; Richardson *et al.* 1983) and can also be specified using several grid-based formats to facilitate radar precipitation data use. Infiltration and transmission loss rates are simulated using the Green and Ampt (1911) relationship. Flow on overland and in the channel is simulated using the diffusive wave approximation in two- and one-dimensional, respectively. The selection of the computational time step was done by satisfying the Courant Condition. There are four main processes in the TREX hydrological sub-model: (1) precipitation and interception, (2) infiltration and transmission loss, (3) depression storage and (4) overland and channel flow as shown in Figure 1.

3. SITE DESCRIPTION

Located in the State of Selangor in Malaysia, the Lui (small) watershed covers 68 km^2 (Figure 2). The lowest elevation at the outlet is 80 m above sea level (ASL) while the highest point reaches 1,200 m at the upstream end of the watershed. Approximately 87% of the area is mountainous, and valleys cover 13% of the watershed area. The flow depth in the small watershed ranges from 0.23 m to 0.99 m. The top width of the main channel is constant at 16 m

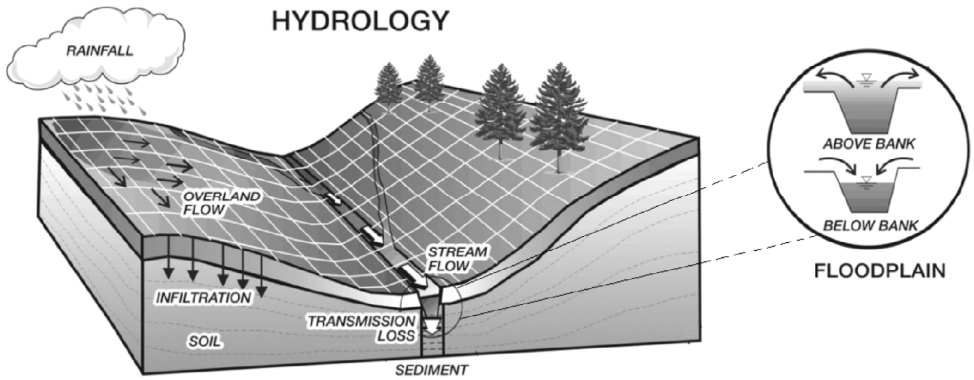

Figure 1: Overview of hydrological processes in TREX model

along the river. The average channel bed slope was 0.04. The maximum observed discharge in the main channel ranged from 0.74 to 17.17 cms during normal flow. The watershed is used for agriculture and the residential area. Located near the equator, the watershed climate is categorized as equatorial, being hot and humid throughout the year. The average rainfall precipitation reaches 2,500 mm per year and the average temperature is 27 °C. Influenced by the southwest and northwest monsoon, the study area falls into the west coast rainfall region, where June and July are the driest months and November is the wettest.

4. MODEL PERFORMANCE EVALUATION

The Nash-Sutcliffe Efficiency Coefficient (NSEC) and Percent BIAS (PBIAS). The NSEC and PBIAS will be used to evaluate the hourly value of discharges and volumes from the simulated result, respectively. The value of NSEC can be between $-\infty$ and 1.0, with NSEC = 1.0 being the optimal value (i.e. very good). PBIAS measures the tendency of the simulated data (i.e. volume in cubic meter) to be larger or smaller than the observed data (Gupta *et al.* 1999). The optimal value of PBIAS is 0.0. In this study, the classifications for NSEC and PBIAS defined by Moriasi *et al.* (2007) were used to determine whether the simulation results is satisfactory, good or very good. The Relative Percentage Different (RPD) method is used to evaluate the total volume, peak discharge and time to peak by comparing between observed and simulated results. Positive and negative values indicate a model underestimated and overestimated, respectively.

5. CALIBRATION AND VALIDATION

The small watershed hydrology was simulated using the TREX model. The Digital Elevation Model (DEM) data for the site (Figure 3a) was obtained from the Department of Surveying and Mapping Malaysia (DSMM) and resampled from 20 m (i.e. original resolution) to 90 m resolution. The DEM also allowed a delineation of the channel network with the watershed. The channel network includes 1 link (i.e. channel) and 66 nodes for a total stream length of approximately 6 km. The soil types and land use are shown in Figures 3b and 4, respectively.

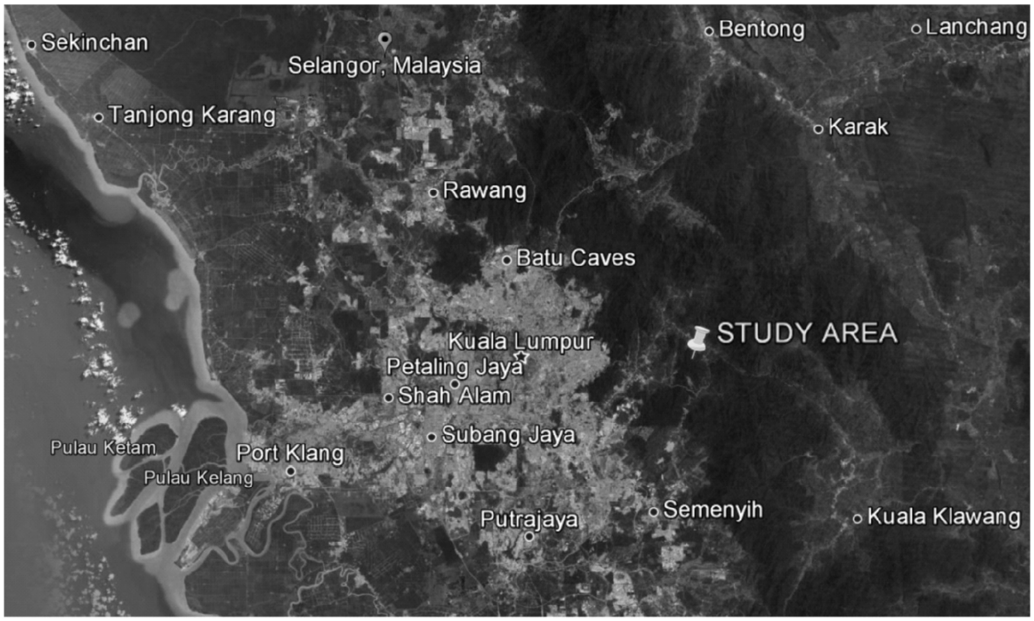

Figure 2: Location of the small watershed on Malaysia's map

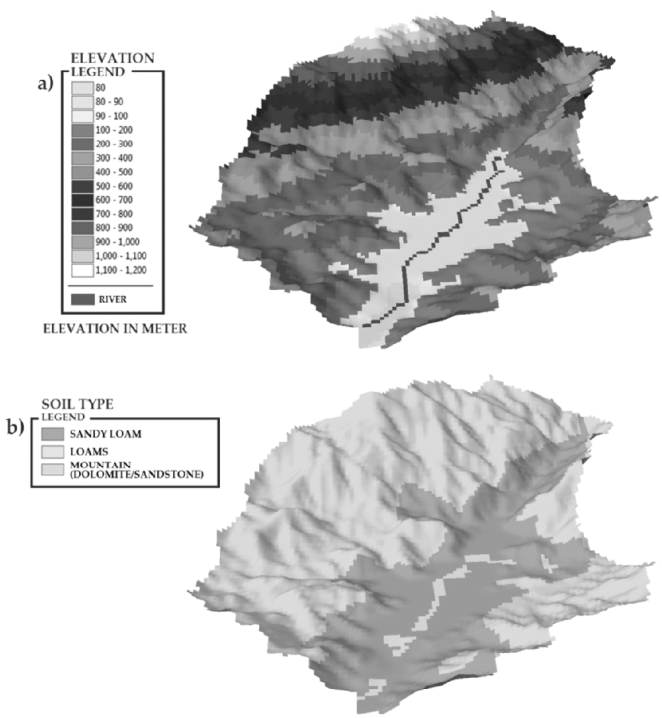

Figure 3: Input data for the small watershed (a) DEM and (b) soil type

The storm of May 14, 2009 storm is the largest recorded event and was used for model calibration using the precipitation and flow records collected by the Department of Irrigation and Drainage (DID). The calibration procedure focused on properly simulating peak flow, time to peak and discharge volume at the main outlet. Model parameters subjected to calibration were the effective hydraulic conductivity (K_h), and roughness (i.e., Manning's n) (Abdullah, 2013). The values of the calibrated parameters are summarized in Table 1. These values were adjusted during calibration to achieve good agreement between measured and simulated discharge.

The TREX model parameterization for the calibration on May 14, 2009 shows that peak flow and time to peak were all accurately simulated at the outlet (Figure 5). A calibrated channel Manning's n (0.04) was within the range proposed by Zakaria *et al.* (2010). The RPD for peak flow, time to peak and total volume was -16.8%, 4.2% and -3.2%, respectively. This statistical metric indicates that the model performance is very good. The NSEC and PBIAS value for the peak discharge and total volume were 0.8 and -11.1%, respectively.

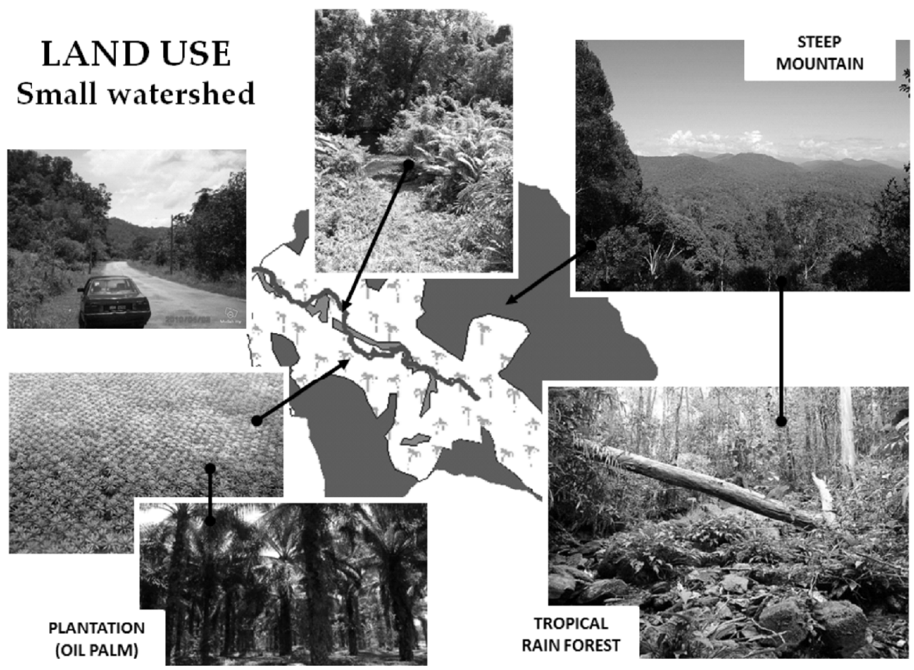

Figure 4: Land use at study area

For the validation events (refer Table 2), the peak discharge, time to peak and total volume found to be near-perfectly simulated with an average RPD value -4.6%, -5.44% and 8.1%, respectively. The model is numerically very stable and matches the peak discharge, time to peak and total volume. Performance evaluations for these simulations are presented in Table 2. Rainfall events recorded in the wettest months (i.e., October, November and December) were selected for the validation process and model performance evaluation. These scenarios were selected in order to observe the capabilities of the model to simulate high rainfall volumes under Malaysia's climate.

Table 1
Summary of Model Parameter (from Rawls *et al*. 1982 and 1993 and Maidment 1993)

Parameter	*Value*	*Application*
Interception depth (mm)	2.0	Agriculture
	0.05	Urban / Commercial
	5.0	Forest
Soil moisture deficit (-)	0.29	Sandy loam
		Loams
		Mountain – limestone
Capillary suction head (m)	0.14	Sandy loam
	0.22	Loams
	0.17	Mountain – limestone
Hydraulic conductivityK_h (m/s)	$1.81 \times 10^{-8} – 1.14 \times 10^{-4}$	Sandy loam
	$9.44 \times 10^{-9} – 3.67 \times 10^{-4}$	Loams
	$3.20 \times 10^{-11} – 3.20 \times 10^{-6}$	Mountain – limestone
Manning's n	0.02 – 0.20	Agriculture
	0.01 – 0.08	Urban / Commercial
	0.11 – 0.40	Forest
	0.02 – 0.08	Main channel

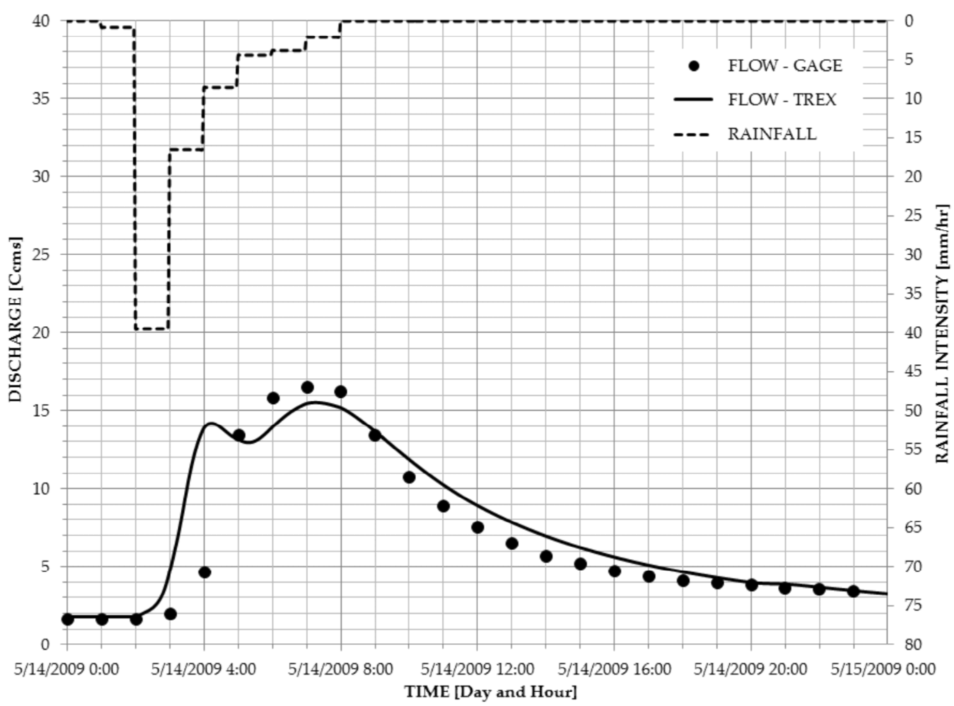

Figure 5: Hydrologic parameter calibration hydrograph for the storm event on May 14, 2009

Table 2
Summary of the Evaluation of Hydrologic Model Performance for the Small Watershed (Lui)

Date of event	Total volume (x 1,000 m^3)			Peak flow (cms)			Time to peak (24 hours)			Model's performance	
	Obs.	*Sim.*	*RPD (%)*	*Obs.*	*Sim.*	*RPD (%)*	*Obs.*	*Sim.*	*RPD (%)*	*NSEC*	*PBIAS*
CALIBRATION											
05/14/09	592	573	- 3.2	16.51	13.74	- 16.8	07:00	07:18	4.2	0.8	- 11.1
VALIDATION											
11/14/10	520	577	10.9	13.36	13.67	2.3	21:00	20:36	- 1.9	0.5	29.3
10/20/09	470	495	5.3	16.60	17.00	2.4	22:00	20:35	- 6.4	0.8	- 11.4
01/03/09	526	442	- 16.0	14.67	13.37	-8.8	18:00	14:42	- 18.3	0.7	- 7.6
11/13/10	227	205	- 10.0	5.99	4.25	- 29.1	23:00	22:00	- 4.3	0.7	4.4
02/26/10	203	141	- 30.6	6.86	7.58	10.4	17:00	17:39	3.7	0.7	21.4

Note: Obs. = Observed; Sim. = Simulated; RPD = Relative Percentage Different; NSEC = Nash-Sutcliffe Efficiency Coefficient; PBIAS = Percentage BIAS

6. GRID SIZE ANALYSIS

Different model grid sizes have a significant impact on simulation results (Blöschl *et al.*, 1997). Therefore, an appropriate grid size should be considered carefully to reduce the difficulty in obtaining results (Grayson and Blöschl, 2000; *Wu et al.*, 2007). Grid sizes ranging from 30 to 330 m were used to analyze the performance of the TREX model in estimating the peak discharge, time to peak and total volume at a small watershed. The analysis of this watershed was conducted by applying the calibrated and validated hydrologic parameters from Table 1. The interception depth, soil moisture deficit and capillary suction head were same as shown in Table 1. Only the hydraulic conductivity and Manning's n were chosen because these values control the peak discharge, time to peak and volume of the water (Velleux, 2005).

Figure 6 shows the hydrographs of the observed and simulated discharge at different sizes of grid. This figure is used to evaluate the performance of the model graphically. The hydrograph reveals that the model performed *very good* in estimating the peak discharge, time to peak and rising and falling limbs grid size of 30 and 90 m and good for 150 m grid size. At a grid size more than 150 m, the simulation results changed obviously. Time to peak simulated by the model was clearly three hours earlier than observed. The estimated peak discharge and volume of water were larger than observed. The rising and falling limbs indicated that the model did not show at least the minimum level to be accepted.

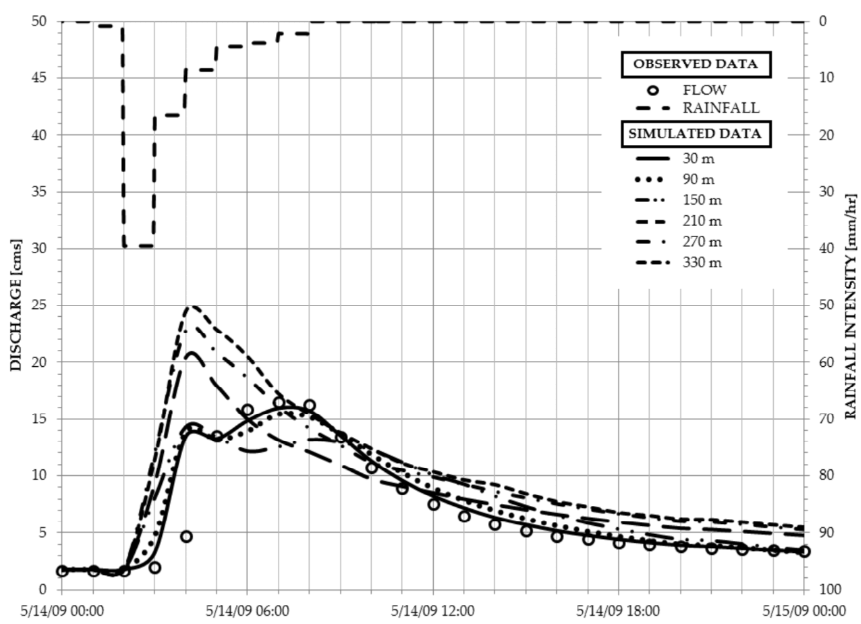

Figure 6: Comparison of discharge hydrograph at difference grid sizes

Three statistical methods were calculated and plotted in Figure 7. The calculated NSEC values for hourly discharges show that the model performance is very good for grid sizes of 30 and 90 m and good at grid sizes 150 and 210 m (Figure 7– diamond symbol line). However, by increasing the grid size from 210 to 330 m led to decreasing the NSEC values (unsatisfactory). The performance of the model in estimating the total volume was compared to observed data using the PBIAS method. The model showed a very good and good performance, as indicated in Figure 7 (square symbol line), for grid sizes of 30 and 90 m and 150 m, respectively. The application of the model using different grid sizes then becomes less significant as the hourly volume estimated has not reached the minimum rating, i.e. satisfactory, for grid size coarser than 210 m. The estimated volume decreased as coarser grid sizes were applied. The RPD method indicated that the estimation of the peak discharge (Figure 7– triangle symbol line) and time to peak at grid sizes up to 90 m is very good. However, for grid sizes of more than 90 m, the discrepancies of simulated and observed time to peak increased from -9% to 33%.

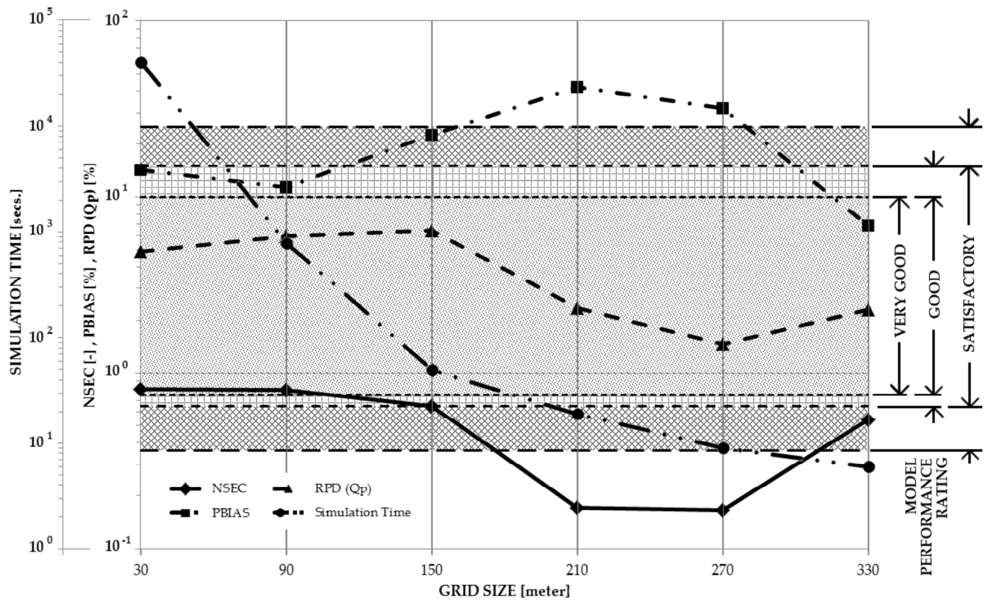

Figure 7: The model performance rating as a function of grid sizes

The temporal and spatial distributions of water depth at various grid sizes were visualized in 3D as shown in Figure 8. From this figure, water depth distributions are uncertain for grid sizes larger than 150 m. Increasing the grid size from 30 to 330 m resulted in the inaccuracy of input data such as DEM, land use and soil type (Abdullah, 2013).

7. ONE- AND TWO-DIMENSIONAL ANALYSIS

The comparison between 1D (HEC-HMS) and 2D (TREX) models was made. In Malaysia, there were several studies conducted to simulate rainfall-runoff and rainfall-water surface profile relationships. The most common software from HEC group was applied, i.e., the HEC-HMS (Yusop *et al.*, 2007; Razi *et al.*, 2010) and HEC-2 (Mohammed *et al.*, 2011). Both models are capable of simulating the rainfall-runoff relationship in Malaysia, based on the historical events. The HEC-HMS model gives the simulation results in terms of a hydrograph, while the HEC-2

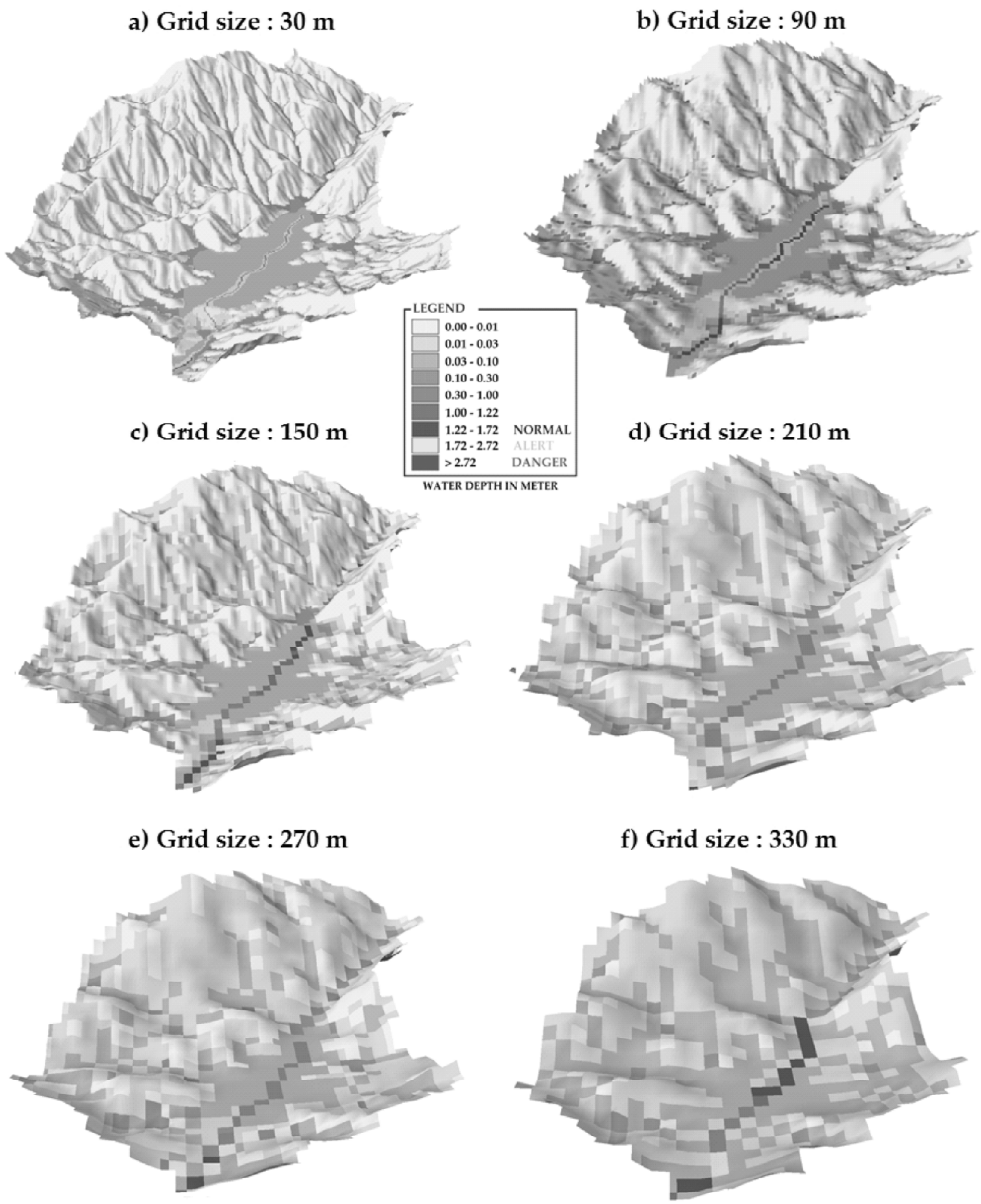

Figure 8: Comparison of the maximum water depth distribution for different grid sizes

model produced the water level of the study area. Since the TREX model (2D) is capable of producing a hydrograph of the study area, therefore HEC-HMS (1D) was chosen in this study because a more meaningful comparison between both models can be made.

Table 3 shows the estimated peak discharge for the 100-year, PMF and world maximum flood (WMF) events on the small watershed. The 1D model has the ability to estimate the peak discharge for the 100-year and PMF events. However, the peak discharges estimated by the 1D model for the WMF event are less than the 2D model. The difference between these two models is 25%. In this study, the estimated peak discharges from a 2D model were assumed to be reliable because the model use grid to represent the land use, soil type and elevation of the watershed. In addition to that, the formulations to solve the hydrologic cycles are based on the physically-based model which includes the mass balance and momentum equations. Whereas the 1D is a lumped model which the properties of the watershed is presented as an average across the watershed. Another reason that the 1D model cannot estimate peak discharge for the WMF event is because the model assumed a linear relationship between Q_p and rainfall intensity, *i*. The 2D model performs much better in simulating the nonlinear relationship between Q_p and *i*.

Table 3
Comparison of Simulated Peak Discharges (cms), Q_p, between 1D (HEC-HMS) and 2D (TREX) Models for Different Watershed Sizes

Rainfall events	*Small tropical watershed*		
	Rainfall intensity, i(mm/hr)	*Peak discharge, Q_p (cms)*	
		1D	*2D*
100-year	38	101	21
PMP	43	421	520
WGR	86	1,027	1,358

Another significant topic that should be included when comparing the 1D and 2D models is the calibrated and validated model parameters. Both models use the Green and Ampt method to calculate infiltration. The 2D diffusive wave approximation is used to calculate the overland flow, while 1D diffusive wave approximation is used to estimate the channel flows in the 2D model. However, these flows are calculated using only the 1D kinematic wave approximations in the 1D model. The storm event on May 14, 2009 was chosen to compare between the observed flow gage measurement, 1D model and 2D model. The allowable upper and lower limits of the hydraulic conductivity and roughness were derived from the suggested values by Rawls *et al.*, (1982 and 1993) and Maidment (1993). These values are 100 times higher and lower (as suggested by Liong *et al.,* 1989) for the upper and lower limits, respectively. The calibrated and validated roughness's are within the acceptable limit using 2D model but not for 1D model (Table 4). This is because the 1D model use 1D kinematic wave approximation which force the overland flow to be in one-direction, i.e., only flow in y-direction, by assuming that the channel flow is in x-direction from upstream to downstream. Additionally, the 1D simulation is unable to estimate the flooding area as compared to the 2D model, especially on the flood plains.

Figure 9 shows the comparison of the hydrograph produced by both 1D and 2D models. The hydrograph simulated using calibrated and validated model parameters for 1D (dotted)

Table 4
Calibrated and Validated Hydraulic Conductivity, K_h, and Manning's n using 1D (HEC-HMS) and 2D (TREX) Models

SOIL TYPE	*SUGGESTED VALUE (Rawls et al. (1982,1993); Maidment (1993))*		*Hydraulic Conductivity, K_h*		*LAND USE*	*SUGGESTED VALUE (Chow et al. (1988))*		*Manning's n*	
	Lower	*Upper*	*1D*	*2D*		*Lower*	*Upper*	*1D*	*2D*
Sandy loams	1.81×10^{-8}	6.06×10^{-4}	9.12×10^{-2}	1.14×10^{-7}	Main Channel*	0.02	0.08	0.04	0.04
Loams	9.44×10^{-9}	3.67×10^{-4}		1.31×10^{-7}	Urbanization	0.01	0.08	0.04	0.05
Mountain (Limestone)	3.20×10^{-11}	3.20×10^{-6}		4.34×10^{-7}	Agricultural	0.02	0.20		0.17
					Forest	0.11	0.40		0.40

Note: *Suggested value for roughness at main channel obtained from Zakaria *et al.*, (2010) and 2D (solid line – 30 m grid size and dotted and dashed – 90 m grid size) models are comparable to the observed data (black dots). However, the calibrated and validated model parameters are off from the acceptable limit for 1D model, as discussed in the previous paragraph. When the acceptable model parameters were applied to the 1D model, the peak discharge is 5 times larger than the observed data (Figure 9 – dashed line).This is because the 1D model used linear relationship between rainfall and discharge. The representations of the land use and soil type are uniform through the watershed area.

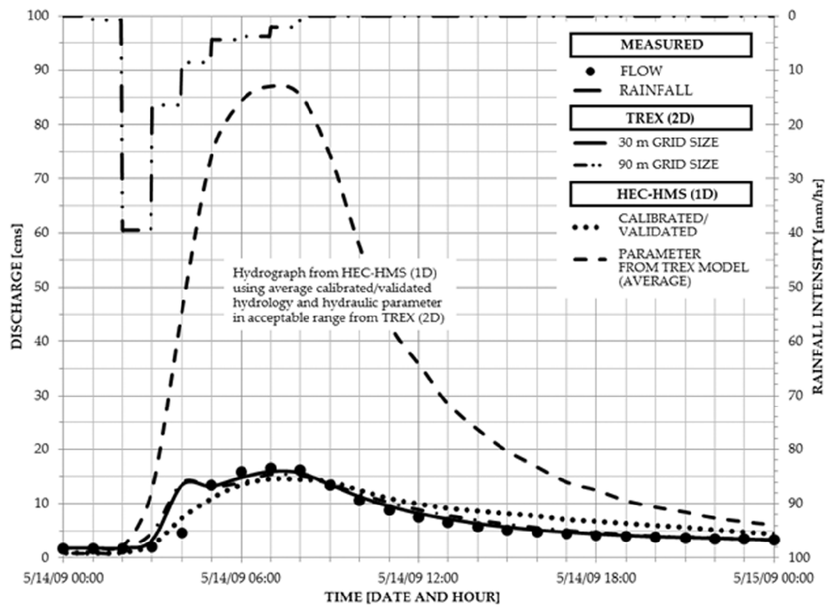

Figure 9: Comparison of the hydrograph produced by the 1D (HEC-HMS) and 2D (TREX) models

8. FLOOD FREQUENCY ANALYSIS

Data were assumed to follow the Gumbel model distribution. This distribution model was used for fitting the frequency distribution of extreme natural events at study areas. This model is oneof the most recommended to analyze the frequency of floods (e.g. Reich, 1972; Lettenmaier and Burges, 1982). The moment method was used to estimate Gumbel's parameters as suggested by Raynal and Salas (1986).

Peak discharge probabilities from the measured data are calculated using Weibull (1939). Figure 10 was plotted on semi-log graph from the calculated values using Gumbel (1958) equations for observed and fitted data, respectively. The 5% and 95% confidence limit were calculated and plotted as a lower and upper limit, respectively. These graphs indicated that the model can be used to estimate the peak discharges for the large event (*i.e.*, from 2- to 100-year return periods) as well as the stochastic approach. However, there are several advantages by using the TREX model as compared to the stochastic approach. First, the simulated result can be extended to the map and animation created aided by using any animation software such as ArcGIS to determine the distribution of the area that likely would be flooded. From this map

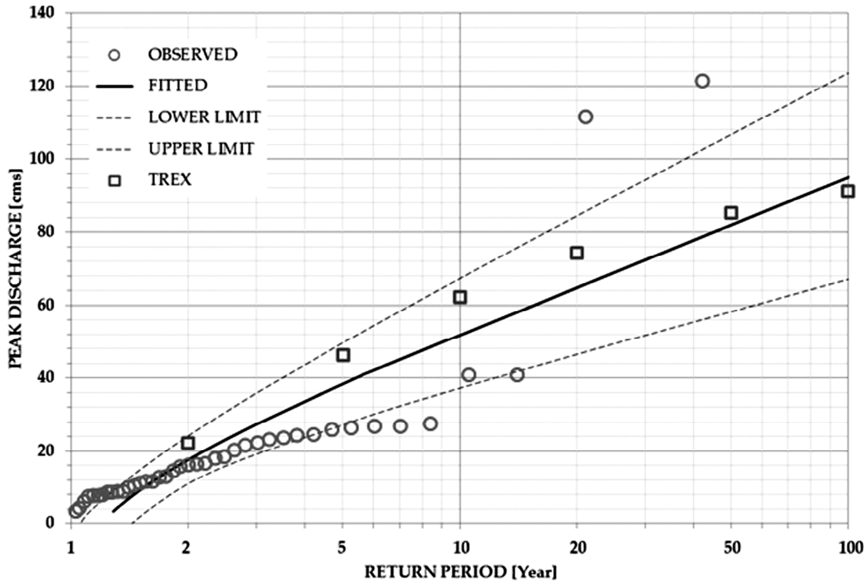

Figure 10: Comparison the daily maximum discharge between flood frequency analysis and TREX model at small watershed

and animation, the contingency plan can be managed to evacuate people from the flooded area by knowing the distribution of water depth spatially and temporally.

Secondly, the stochastic approach can only estimate the discharge for the year of N+1. This means, for instance from Figure 10, the maximum year is 42 (N = 41 years of sample data). When the TREX model has been calibrated and validated, the accuracy of the estimated peak discharge can be beyond what the stochastic approach can provide. The extrapolation in estimating peak discharge can be either high or low. This prediction will affect the cost of any construction. For instance, to design a dam, the designs factor for discharge from return periods should be longer than 50 years. If the stochastic approach cannot produce reliable results, the cost for this project would increase by over predicting the peak discharge and vice versa. The peak discharge that is simulated using the TREX model take into account the physical topography such as the elevation, land use and soil type. The rainfall amount was applied from the recorded data. For these watersheds, the quality of the rainfall data is more reliable when compared to flow data. As a result, the estimated discharge by the model is more reliable.

9. SENSITIVITY ANALYSIS OF PEAK DISCHARGE AND RUNOFF COEFFICIENT

Sensitivity analysis was conducted to describe the entire set of possible discharges and runoff coefficients, C, based on several combinations of upper, lower limits and calibrated/validated values. From the sensitivity analysis, the uncertainty of the water depth distribution across the watershed during these rainfall events (i.e., large and extreme events) will also be highlighted. The upper and lower limits for each parameter are presented in Table 5.There are several sources that contributed to the uncertainty of discharge, which includes the measurement error in rainfall and discharge and the estimation of hydrological and hydraulic parameters in the hydrologic model. However, in this study, the uncertainty analysis of discharge was evaluated using only hydrological and hydraulic parameters. The measurements of rainfall and flow are assumed to be error free in this study. The K_h and Manning's n vary widely between soil classes and land covers, respectively. The variation of the Manning's n depends on the type and condition of vegetative cover, as well as the flow condition (laminar or turbulent). Upper (UL) and lower (LL) limits of K_h and Manning's n values were assumed to be 50% larger and lower than the calibrated value. To simplify the analysis, only the variation of the overland roughness was explored. These limits correspond to the maximum and minimum permissible values of hydrology and hydraulic parameters (will be referred to as the model parameters in the following paragraph) in a hydrological model as suggested by Liong *et al.* (1989).

Table 5
Parameter Bound for Uncertainty Analysis at Small Watershed: Hydraulic Conductivity and Manning's n

Parameter	*Lower Limit*	*Upper Limit*	*Application*
Hydraulic Conductivity, K_h (m/s)	5.70×10^{-8}	1.71×10^{-7}	Sandy loam
	6.55×10^{-8}	1.97×10^{-7}	Loams
	2.17×10^{-7}	6.51×10^{-7}	Mountain - limestone
Manning's n	0.085	0.255	Agricultural
	0.025	0.075	Urban / Commercial
	0.2	0.6	Forest

The Logic Tree Analysis (LTA) approach as described by Mishra (2009) was used. The author suggests that this approach is particularly useful for uncertainty propagation when parameter uncertainty is described using a limited number of possibilities (*e.g.*, upper and lower limit, and calibrated and validated parameter values). The ± 50% limits were chosen to depict the plausible and realistic range of parameter uncertainty for the key inputs to assess variability in the system outputs. However, in this study, there are some of the model parameters exceed the Liong's limit. In this case, the exceeding values are used and assumed to be valid.

The watershed runoff coefficients C are calculated using the rational method shown in equation 1.

$$C = \frac{Q_p}{iA} \tag{1}$$

Where C is a runoff coefficient; Q_p is a peak discharge [L^3T^{-1}]; i is rainfall intensity [LT^{-1}] and A is a watershed area [L^2]. This method was used with the assumptions that (1) the peak flow is reached when the entire watershed is contributing to the runoff, (2) the rainfall intensity is assumed to be uniform across the watershed and over a time duration, and (3) the peak discharge recurrence interval simulated is equal to the rainfall intensity recurrence interval (*i.e.*, the 100-year rainfall intensity is assumed to produce 100-year flood discharge and so forth).

The simulated peak discharges obtained using combination parameters from Table5and the result were tabulated in Table 6. Figure 11 shows the box plot of the peak discharges for return period events from 2- to 100-year and extreme events, i.e., PMP and world's largest

Table 6
The Hydrologic Parameter Combination, Discharge and Runoff Coefficient

Hydrologic parameters				*Rainfall Events*															
				Large Events												*Extreme Events*			
				2-year		*5-year*		*10-year*		*20-year*		*50-year*		*100-year*		*S-PMP*		*World*	
				Q_p	*C*	Q_p	*C*	Q_p	*C*	Q_p	*C*	Q_p	*C*	Q_p	*C*	Q_p	*C*	Q_p	*C*
Hydraulic conductivity	LL	Manning's n	LL	48	0.1	77	0.2	88	0.2	95	0.2	106	0.3	111	0.3	661	0.8	1516	0.9
	UP		UP	14	0.0	25	0.1	41	0.1	55	0.1	67	0.2	76	0.2	342	0.4	1092	0.7
	LL		UP	20	0.1	49	0.1	62	0.1	71	0.2	80	0.2	86	0.2	413	0.5	1174	0.7
	UP		LL	25	0.1	57	0.1	72	0.2	84	0.2	95	0.2	101	0.3	583	0.7	1449	0.9
	CV		LL	18	0.0	65	0.2	81	0.2	89	0.2	100	0.3	106	0.3	615	0.8	1481	0.9
	CV		UP	34	0.1	37	0.1	54	0.1	65	0.2	76	0.2	84	0.2	421	0.5	1223	0.8
	LL		CV	18	0.0	58	0.1	72	0.2	81	0.2	90	0.2	95	0.2	534	0.7	1385	0.9
	UP		CV	31	0.1	35	0.1	53	0.1	66	0.2	80	0.2	88	0.2	459	0.6	1299	0.8
			CV	22	0.1	46	0.1	62	0.1	74	0.2	85	0.2	91	0.2	520	0.6	1358	0.8

Note: LL = Lower Limit Value; UP = Upper Limit Value; CV = Calibrated / Validated Value; Q_p = Peak discharge in cms;C = Runoff-coefficient

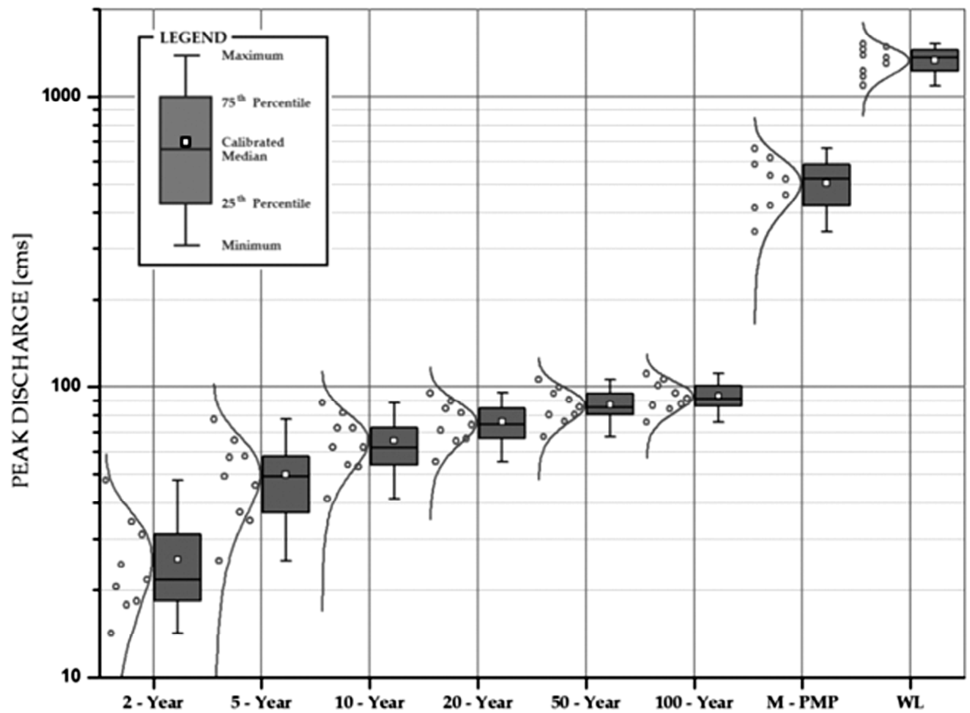

Figure 11: Box-plot the uncertainty for peak discharge, Q_p

rainfall events. The calibrated/validated (CV) values are presented with white box. The distribution of the peak discharges are presented in the forms of box-plot, red-dotted, and line.

Table 6 shows discharges and runoff coefficients for different combinations of hydrologic parameters. The peak discharges, as tabulated in the Table6, indicated that the possible peak discharge value of small watershed is normally distributed for large events (Figure 11). The same trend also can be found for extreme events. This trend indicates that during extreme events, the Manning's n do not affect the discharge. This happens because after a certain period of rainfall, soil becomes fully saturated and roughness become smooth very fast as compared to during large events. All rainfall becomes runoff and flows directly to tributaries and the main channel. The runoff coefficient, C, value for the calibrated hydrologic parameters is between 0.1 and 0.3 for large events (see Table 6 and Figure 12). However, the coefficient drastically increased for extreme event, which was between 0.4 and 0.9. The maximum runoff coefficient for the small watershed was calculated when the lower limit of Manning's n is applied.

10. CONCLUSIONS

The two-dimensional physically-based TREX model was successfully applied to a small tropical watershed to simulate the large and extreme events. A grid size analysis indicates that as the grid size increases beyond 100 m, the simulated results become less significant. Simulation

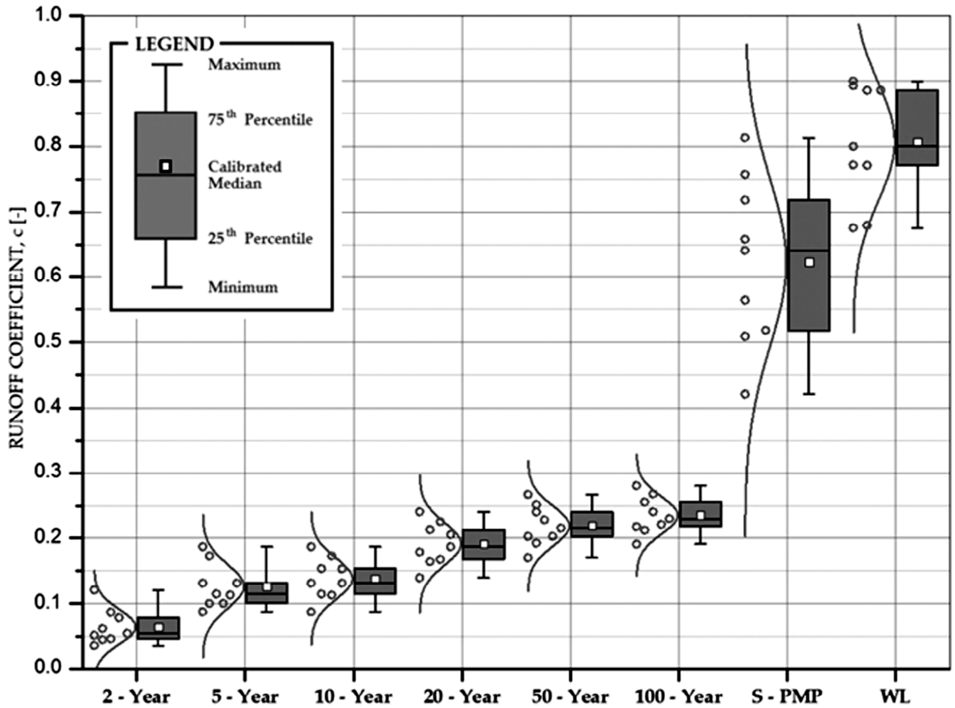

Figure 12: Box-plot the uncertainty for runoff coefficient, C

time required by the TREX model decreased significantly when coarser grid size is used. This study suggests that grid sizes between 30 m and 90 m is best to represent the water depth distribution across the watershed. The flood frequency analysis can be extended by using the TREX model with the PMP and the WMP events. The advantages of using this model as compared to other approaches are: (1) the simulated results can be presented with maps and animation, (2) the peak discharge that is simulated using the TREX model takes into account the physical topography (i.e., the elevation, land use and soil type), and (3) the model use gridded DEM, soil type and land use data to represent the physical topography. The runoff coefficient C increased significantly (i.e., a factor of three) from the 100-year rainfall event to the PMP and the world's maximum precipitation events for all watersheds (C_{PMP},C_{WMP}> 0.6).

Acknowledgements

Financial support of the first author was granted through the Ministry of Higher Education (MOHE), Malaysia and the UniversitiTeknologi MARA (UiTM) Malaysia. Data for this watershed application were provided by Mohd Rozi Talib, Nor Haslinda Mohamed Yusop and Arshad Mohd Isa from the Department of Survey and Mapping Malaysia and LizawatiTuri, Abu Salim Abd. Aziz, Khairul Fadzilah Mohd Omar, MohdShawalAbd. Wahid and Azmi Md. Jafri from the Department of Irrigation and Drainage. We also appreciate the assistance of Junaidah Ariffin, Joe Nyuin, Azmi Ibrahim and Norizan Ismail from UniversitiTeknologi MARA, Nur Shazwani Muhammad and Othman Jaafar from National University of Malaysia to provide us some useful information regarding this watershed. Additional support from James Halgren (Riverside, Fort Collins, Colorado) and Mark Velleux (HydroQual, New Jersey) in using TREX software is also gratefully acknowledged.

References

[1] Abdullah, J. (2013), Distributed runoff simulation of extreme monsoon rainstorm in Malaysia using TREX.Ph.D dissertation, Department of Civil and Environmental Engineering, Colorado State University, CO.

[2] Ali, A.N.A., and J. Ariffin, (2011), Model reliability assessment: A hydrodynamic modeling approach for flood simulation in Damansara catchment usinhInfoWorks RS.*Advanced Materials Research*, **250-253**, 3769-3775.

[3] Billa, L., Mansor, S., and A.R. Mahmud, (2004), Spatial information technology in flood early warning systems: An overview of theory, application and latest developments in Malaysia. *Disaster Prevention Management*, **13**(5), 356-363.

[4] Billa, L., Mansor, S., Mahmud, A.R., and A. Ghazali, (2006), Hydro-meteorological modeling and GIS for operational flood forecasting and mapping. The 2nd International Conference on Water Resources and Arid Environment, 1-16.

[5] Blöschl, G., Sivapalan, M., Gupta, V.K., and K.J. Beven, (1977), Scale problems in hydrology. *Water Resources Research*, **33**(12), 2881-2999.

[6] Chow, V. T., Maidment, D., and L.W.Mays, (1988), *Applied hydrology*, McGraw Hill Publication.

[7] England, J., Velleux, M., and P. Y. Julien, (2007), Two-dimensional simulations of extreme floods on a large watershed. *Journal of Hydrology*, **347**(1), 229-241.

[8] Eslamian, S. (2014), Handbook of Engineering Hydrology, Vol. 2: Modeling, Climate Change and Variability, Taylor and Francis, 646Pages.

[9] Ghazali, J. N., and A. Kamsin, (2008), A real time simulation of flood hazard. Fifth International Conference on Computer Graphics, Imaging and Visualization, 393-397.

[10] Grayson, R. B., and G. Blöschl, (2000), CHAPTER 14: Summary of pattern comparison and concluding remarks. Spatial Patterns in Catchment Hydrology: Observations and Modelling, Grayson, R. B. and G. Blöschl, (eds.), Cambridge University Press: Cambridge, (2000), 355-367.

[11] Green, W.H., and G.A. Ampt, (1911), Studies on soil physics, 1: the flow of air and water through soils. *Journal of Agricultural Sciences*, **4**(1), 11-24.

[12] Gupta, H. V., Sorooshian, S., and P. O. Yapo, (1999), Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydrology Engineering*, **4**(2), 135-143.

[13] Gumbel, E. J. (Ed.). (1958), Statistic of extreme. Columbia University Press, New York, 375.

[14] Izham, M.Y., Md. Uznir, U., Alias, A.R., and K. Ayob, (2010), Georeference, rainfall-runoff modeling and 3D dynamic simulation: Physical influence, integration and approaches, COM. Geo. First International conference on computing for geospatial research and application, Washington D. C., 1-8.

[15] Julien, P. Y., and R. Rojas, (2002), Upland erosion modeling with CASC2D-SED.*International Journal of Sediment Research*, **17**(4), 265-274.

[16] Julien, P. Y., Saghafian, B., and F. L. Ogden, (1995), Raster-Based hydrologic modeling of spatially-varied surface runoff. *Water Resources Bulletin*, AWRA, **31**(3), 523-536.

[17] Johnson, B. E., Julien, P. Y., Molnár, D. K., and C. C. Watson, (2000), The two-dimensional upland erosion model CASC2D-SED." *Journal of the American Water Resources Association*, **36**(1), 31-42.

[18] Jorgeson, J. J., (1999), Peak flow analysis using a two-dimensional watershed model with radar precipitation data. Ph.D. Thesis, Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, Colorado.

[19] Kang, D. K., (2005), Distributed snowmelt modeling with GIS and CAS2D at California Gulch, Colorado. M.S. thesis, Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, Colorado.

[20] Lettenmaier, D. P. and S. J. Burges, (1982), Gumbel's extreme value I distribution: A new look. *Journal of Hydrology Division ASCE*, 108(HY4), 502-514.

[21] Liong, S.Y., Selvalingam, S. and D. K. Brady, (1989), Roughness values for overland flow in subcatchments. *Journal of Irrigation and Drainage Engineering*, **115**(2), 203-214.

[22] Maidment, D. R. (1993). Handbook of hydrology, Mc-Graw Hill, 1424.

[23] Mah, D. Y., Outuhena, F. J., and S. Said, (2007), Use of Infoworks River Simulation (RS) in Sungai Sarawak Kanan modeling. *Journal of Institute of Engineers*, Malaysia, **68**(1), 1-9.

[24] Mah, D. Y., Lai, S. H., Chan, R. B., and F. J. Putuhena, (2010), Investigative modeling of the flood bypass channel in Kuching, Sarawak, by assessing its impact on the inundations of Kuching-BatuKawa-Bau Expressway.*Structure and Infrastructure Engineering*, 1-10.

[25] Mah, D. Y. S., Hii, C. P., Putuhena, F. J., and S. H. Lai, (2011), River modeling to infer flood management framework. Technical Note.

[26] Mishra, S. (2009), Uncertainty and sensitivity analysis techniques for hydrologic modeling. *Journal of Hydroinformatics*, 11.3-4, 282-296.

[27] Mohammed, T. A., Said, S., Bardaie, M. Z., and S. N. Basri, (2011), Numerical simulation of flood levels for tropical rivers. IOP Conference Series: Materials Science and Engineering, **17**, 1-10.

[28] Moriasi, D. N., Arnold, J. G., Van-Liew, M., W., Bingner, R. L., Harmel, R. D. and T. L. Veith, (2007), Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *American Society of Agricultural and Biological Engineers*, **50**(3), 885-900.

[29] Ogden, F. L., (1982), Two-dimensional runoff modeling with weather radar data. Ph.D. Thesis, Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, Colorado.

[30] Ogden, F. L., and P. Y. Julien, (1993), Runoff sensitivity to temporal and spatial rainfall variability at runoff plane and small basin scales.*Water Resources Research*, **29**(8), 2589-2597.

[31] Ogden, F. L., and P. Y. Julien, (1994), Runoff model sensitivity to radar rainfall resolution.*Journal of Hydrology*, **158**, 1-18.

[32] Ogden, F. L., Sharif, H. O., Senarath, S. U. S., Smith, J. A., Baeck, M. L., and J. R. Richardson, (2000), Hydrologic analysis of the Fort Collins, Colorado, flash flood of 1997. *Journal of Hydrology*, **228**, 82-100.

[33] Rawls, W. J., Brakensiek, D. L. and K. E. Saxton, (1982), Estimation of soil water properties. *Soil and Water Division of ASAE*, 81-2510, 1316-1328.

[34] Rawls, W. J., Brakensiek, D. L. and S. D. Logsdon, (1993), Predicting saturated hydraulic conductivity utilizing fractal principles. *Journal of Soil Science Society of America*, **57**, 1193-1197.

[35] Raynal, J. A. and J. D. Salas, (1986), Estimation procedures for the type-I extreme value distribution." *Journal of Hydrology*, **87**, 315-336.

[36] Razi, M. A. M., Ariffin, J., Tahir, W., and N. A. M. Arish, (2010), Flood estimation studies using hydrologic system (HEC-HMS) for Johor River, Malaysia.*Journal of Applied Sciences*, **10**(11), 930-939.

[37] Reich, B. M., (1972), Log-Pearson type III and Gumbel analysis of floods. Proceedings of the Second International Symposium in Hydrology, Fort Collins, CO, USA, 291-303.

[38] Richardson, W. L., Smith, V. E., and R. Wethington, (1983), Dynamic Mass Balance of PCB and Suspended Solids in Saginaw Bay – A Case Study.*Physical Behavior of PCBs in the Great Lakes*, Mackay, D., Patterson, S. and Eisenreich, S. J. (eds.), Ann Arbor Science Publishers, Ann Arbor, Michigan, (1983), 329-366.

[39] Said, S., Mah, D. Y. S., Sumok, P., and S. H. Lai, (2009), Water quality monitoring of Maong River, Malaysia. Proceedings of the Institute Civil Engineers, Water management, **162**, 35-40.

[40] Siang, L. C., Abdullah, R., Zakaria, N. A., Ghani, A. A., and C. C. Kiat, (2007), Modelling urban river catchment: A case study of Berop River, TanjongMalim, Perak. *2nd International conference on managing rivers in the 21st century: Solution towards sustainable rivers basin*, 165-171.

[41] Singh, V. P. (1995), *Computer models of watershed hydrology*, Water Resources Publication.

[42] Teo, F. Y., Falconer, R. A., and B. Lin, (2009), Modelling effects of mangroves on tsunamis. Proceedings of the Institute Civil Engineers, Water Management, **162**, 3-12.

[43] Toriman, M. E., Hassan, A. J., Gazim, M. B., Mokhtar, M., Sharifah-Mastura, S. A., Jaafar, O., Karim, O., and N. A. Abdul-Aziz, (2009), Integration of 1-d hydrodynamic model and GIS approach in flood management study in Malaysia.*Research Journal of Earth Sciences*, **1**(1), 22-27.

[44] Velleux, M., (2005), Spatially distributed model to assess watershed contaminant transport and fate.Ph.D Thesis, Department of Civil and Environmental Engineering, Colorado State University, Colorado.

[45] Velleux, M., Julien, P. Y., Rojas-Sanchez, R., Clements, W., and J. England, (2006), Simulation of metals transport and toxicity at a mine-impacted watershed: California Gulch, Colorado.*Environmental Science and Technology*, **40**(22), 6996-7004.

[46] Velleux, M., England, J., and P.Y. Julien, (2008), TREX: spatially distributed model to assess watershed contaminant transport and fate. *Science of the Total Environment*, **404**(1), 113-128.

[47] Weibull, W., (1939), A statistical theory of the strength of materials. Ingeniörsvetenskapsakademiens Handlingar Nr 151, GeneralstabensLitografiskaAnstaltsFörlag, Stockholm, (English version).

[48] Wu, S., Li, J., and G. H. Huang, (2007), Modeling the effects of elevation data resolution on the performance of topography-based watershed runoff simulation.*Environmental Modelling and Software*,**22**, 1250-1260.

[49] Yusop, Z., Chan, C. H., and A. Katimon, (2007), Runoff characteristics and application of HEC-HMS for modeling stormflow hydrograph in oil palm catchment.*Water Science Technology*, **56**(8), 41-48.

[50] Zakaria, N. A., Azamathulla, H. M., Chang, C. K., and A. Ab. Ghani, (2010), Gene expression programming for total bed material load estimation – a case study. *Science of the Total Environment*, **408**, 5078–5085.