Hydrologic Modeling of Extreme Events

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Abstract

The TREX watershed model has become a very powerful tool to simulate floods from extreme rainstorms. Malaysia experiences some of the world's most devastating floods and the Semenyih watershed has been selected for this study. Approximately half of this 236 km^2 watershed is covered with forest under rapid development for agriculture and urbanization. The TREX model has been calibrated using precipitation data from April 13, 2003 and has been validated with several other storms. The model is numerically very stable and matches both the peak discharge and the time to peak very well. The potential effects of the world's greatest precipitation at 68 mm/hr for 16 hours have been simulated to represent the case of long monsoon precipitation on the Semenyih watershed. The model results provide a dynamic illustration of the magnitude and duration of the vast flooding area with flow depths in excess of 6.0 m which would occur in the relatively flat and wide agricultural and urbanized areas. These flood mapping results should facilitate the analysis of flood hazards and disaster prevention.

INTRODUCTION

The simulation of extreme floods is one of the main concerns for public safety and hydrologic engineering.[1] In the analysis of extreme floods, the concepts of Probable Maximum Flood and paleohydrology are very useful.[2] In the United States, the models HEC-1 and HEC-HMS are used by the U.S. Army Corps of Engineers, whereas the Flood Hydrograph and Runoff (FHAR) model is promoted by the U.S. Bureau of Reclamation. The major advances in Geographical Information System (GIS)-based computer models in the past two decades offer a new perspective on the simulation of extreme flood events. We explore the use of a physically based and distributed model to simulate floods on a watershed under monsoon precipitation in South-East Asia.

The objectives of this research are to test the potential of GIS-based rainfall-runoff modeling to simulate extreme floods; and demonstrate modeling applicability through calibration, validation, and simulation of extreme floods. The Two-dimensional Runoff, Erosion and EXport (TREX) model has been selected for the analysis and is tested at Sungai Semenyih in Malaysia where the 236 km^2 watershed can be subjected to some of the highest precipitation levels ever recorded world-wide.

TREX MODEL

The physically based TREX model is fully distributed and simulates rainfall-runoff, sediment transport, and chemical fate and transport at the watershed scale.[3] TREX uses a GIS-based raster format combining the CASC2D surface runoff model,[4–7] and the water quality WASP/IPX model.[8] TREX is classified as an event model as it simulates the Hortonian overland flow and the watershed responses from a single storm with no soil infiltration capacity recovery between events. The selection of the computational time step was done by satisfying the Courant Condition.

Upland Processes

The hydrologic processes in the model are as follows: 1) rainfall, interception, and surface storage; 2) infiltration and transmission loss; and 3) overland and channel flow. The model state variables are water depth in the overland plane and stream channels. Rainfall can be uniform or distributed in both time and space and can also be specified using several grid-based formats for point rain gauges or radar rainfall data.[9] Rainfall can be representing as the gross volume of water that reached the near surface as:

$$\frac{\partial V_g}{\partial t} = i_g \; A_s \tag{1}$$

where V_g = gross rainfall water volume [L^3]; i_g = gross rainfall rate [L/T]; A_s = surface area over which rainfall occurs [L^3]; and t = time [T]. The model calculates the volume of interception as:

$$V_i = \left(S_i + Et_r\right) A_s \tag{2}$$

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where V_i = interception volume [L^3]; S_i = interception capacity of projected canopy per unit area [L^3/L^2]; E = evaporation rate [L/T]; and t_r = precipitation event duration [T].

Infiltration and transmission loss rates are simulated using the Green and Ampt relationship[10]:

$$f = K_h \left(1 + \frac{\left(H_w + H_c\right)\left(1 - S_e\right)\theta_e}{F} \right) \tag{3}$$

where: f = infiltration or transmission loss rate [L/T]; K_h = effective hydraulic conductivity [L/T]; H_w = hydrostatic pressure head (pond water depth) [L]; H_c = capillary pressure (suction) head at the wetting front [L]; θ_e = $(\varphi - \theta_r)$ effective soil porosity [-]; φ = total soil porosity [-]; θ_r = residual moisture content [-]; S_e = effective saturation [-]; and F = cumulative infiltrated depth (depth to wetting front) [L].

Overland Flow

Overland flow is two dimensional and simulated using the diffusive wave approximation. Flow occurs when the water depth exceeds the storage depth: [4,10]

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = i_n - f + W = i_e \tag{4}$$

$$q_x = \alpha_x \; h^{\beta} \tag{4a}$$

$$q_y = \alpha_y \; h^{\beta} \tag{4b}$$

where: h = surface water depth [L]; q_x, q_y = unit flow discharge in the x- or y-direction = Q_x / B_x, Q_y / B_y [L^2/T]; Q_x, Q_y = flow in the x- or y-direction [L^3/T]; B_x, B_y = flow width in the x- or y-direction [L]; i_n = net precipitation rate (gross rainfall minus interception) [L/T]; W = flow point source (unit discharge) [L/T]; i_e = excess precipitation rate [L/T]; α_x, α_y = resistance coefficient for flow in the x- or y-direction = $\left|S_{fx}\right|^{1/2} \big/ n_M$, $\left|S_{fy}\right|^{1/2} \big/ n_M$ [L$^{1/3}$/T]; n_M = Manning roughness coefficient [T/L$^{1/3}$]; S_{fx}, S_{fy} = $S_{0x} - dh/dx$, $S_{0y} - dh/dy$ friction slope (energy grade line) in the x- or y-direction [-]; S_{0x}, S_{0y} = ground surface slope in the x- or y-direction [-] and β = exponent of the stage-discharge relationship. To solve the resistance coefficient equations for α_x and α_y, the absolute value of S_f is used and the sign of S_f indicates the flow direction.

Channel Flow

Channel flow is one dimensional and simulated using the diffusive wave approximation. Flow occurs when the water depth exceeds the storage depth and the friction slope is not zero[4,10]:

$$\frac{\partial A_c}{\partial t} + \frac{\partial Q_x}{\partial x} = q_l + W \tag{5}$$

$$Q_x = \frac{1}{n_M} A_c \; R_h^{2/3} \left|S_{fx}\right|^{1/2} \tag{6}$$

where A_c = cross-sectional area of flow [L^2]; Q = total discharge [L^3/T]; q_l = lateral unit flow (into or out of the channel) [L^2/T]; W = unit discharge from/to a point source/sink (including direct rainfall to the channel) [L^2/T]; R_h = hydraulic radius = A_c / P_c [L]; P_c = wetted perimeter of channel [L]. To solve Eq. (5), the absolute value of S_f is used and the sign indicates the flow direction.

In floodplain areas, water and any transported constituents are transferred between the overland plane and channel network based on the difference in water surface elevations. Floodplain transfers are bi-directional. Water and transported constituents move into stream channels by overland flow and can return to the overland plane when water levels in the stream exceed bank height. Similarly, materials can be moved from the sediment bed and can be delivered to the land surface by floodwaters.[11,12]

SITE DESCRIPTION AND MODEL CALIBRATION

Site Description

Located in the state of Selangor in Malaysia, the Semenyih watershed covers 236 km^2 (Fig. 1). The lowest elevation at the outlet is 40 m above sea level, whereas the highest point reaches 1100 m at the upstream end of the watershed. The average terrain slope is about 45% and ranges between 4% and 85% with very steep mountains overhanging flat and wide valleys (Fig. 2a). The length and width of the watershed are 17.7 km and 23.9 km, respectively. The average normal depth of the main channel in Sungai Semenyih ranges between 0.8 m and 2.49 m. The watershed is partly used for agriculture and the urbanization through residential and industrial development has rapidly transformed the area in the past 20 yr.

Located near the equator, the watershed climate is categorized as equatorial, being hot and humid throughout the year. The average rainfall precipitation reaches 2500 mm/yr and the average temperature is 27°C. Influenced by the southwest and northwest monsoons, the study area falls into the west coast rainfall region, where June and July are the driest months and November is the wettest.

Model Organization and Parameterization

The Semenyih watershed was simulated using the TREX watershed model. To resolve surface topography, the watershed was discretized at a 90-m × 90-m grid scale. This should yield satisfactory results according to the grid size analysis

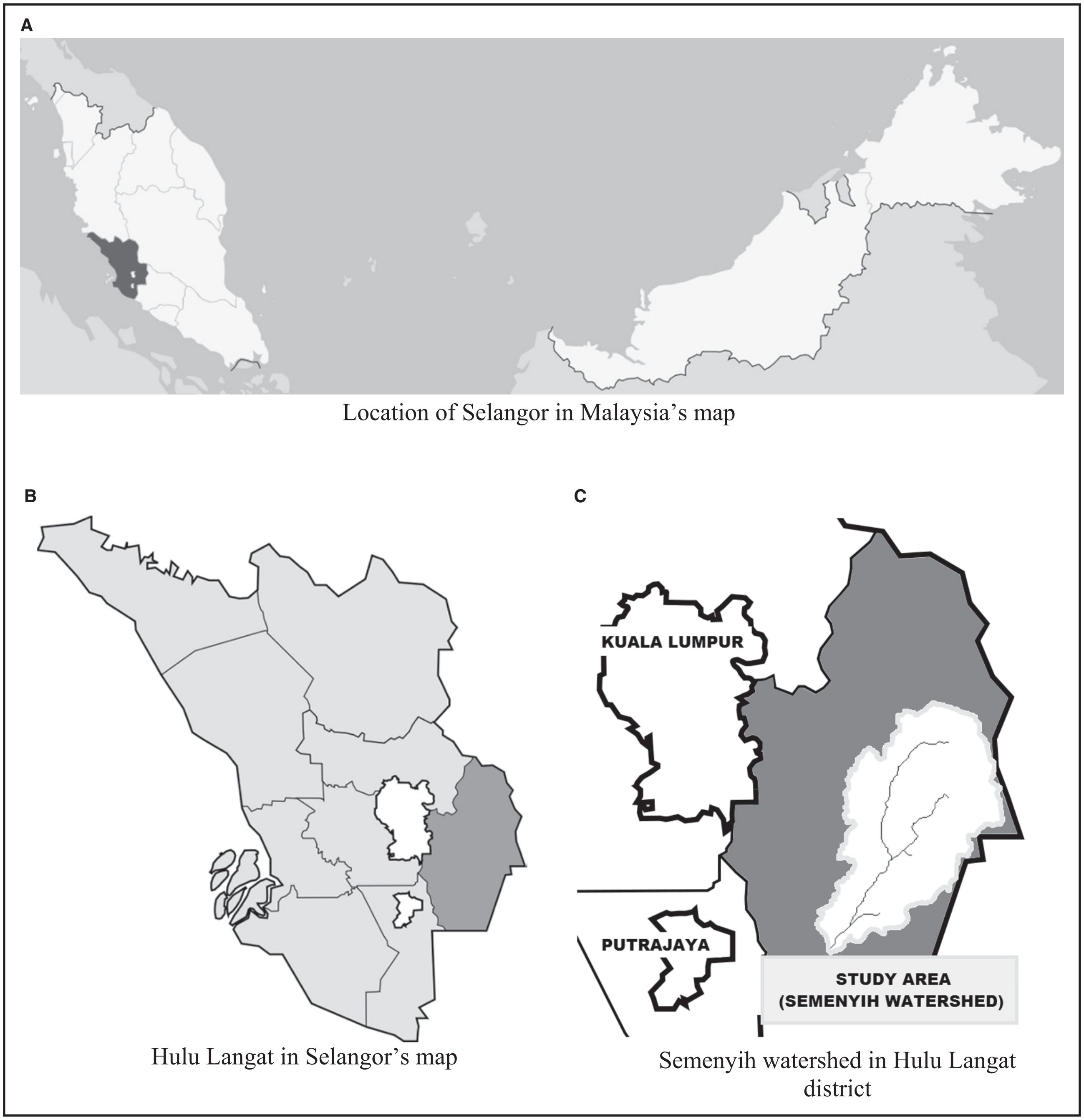


Fig. 1 Semenyih study watershed location map.

of Molnar and Julien.[13] The Digital Elevation Model (DEM) data for the site (Fig. 2a) were obtained from the Department of Surveying and Mapping Malaysia (DSMM). The resulting rectangular raster grid has 265 rows and 197 columns. Within this raster grid, the watershed area is defined by 29,139 cells. The DEM also allowed a delineation of the channel network with the watershed. The channel network includes seven links (reaches) and 399 nodes for a total stream length of approximately 36 km. Four soil types (Fig. 2b) and six land uses (Fig. 2c) were incorporated into the raster-based GIS representation of the watershed for the determination of hydraulic conductivity and surface roughness.

Calibration and Validation

The April 13, 2003, storm was used for calibration using the precipitation and flow records collected by Department of Irrigation and Drainage (DID). The calibration procedure focused on properly simulating peak flow, discharge volume, and time to peak at the outlet. Model parameters subject to calibration were simply the effective hydraulic conductivity (K_h), and roughness (Manning n). The values of the calibrated parameters are summarized in Table 1. The values of hydraulic conductivity K_h were adjusted during calibration to achieve good agreement between

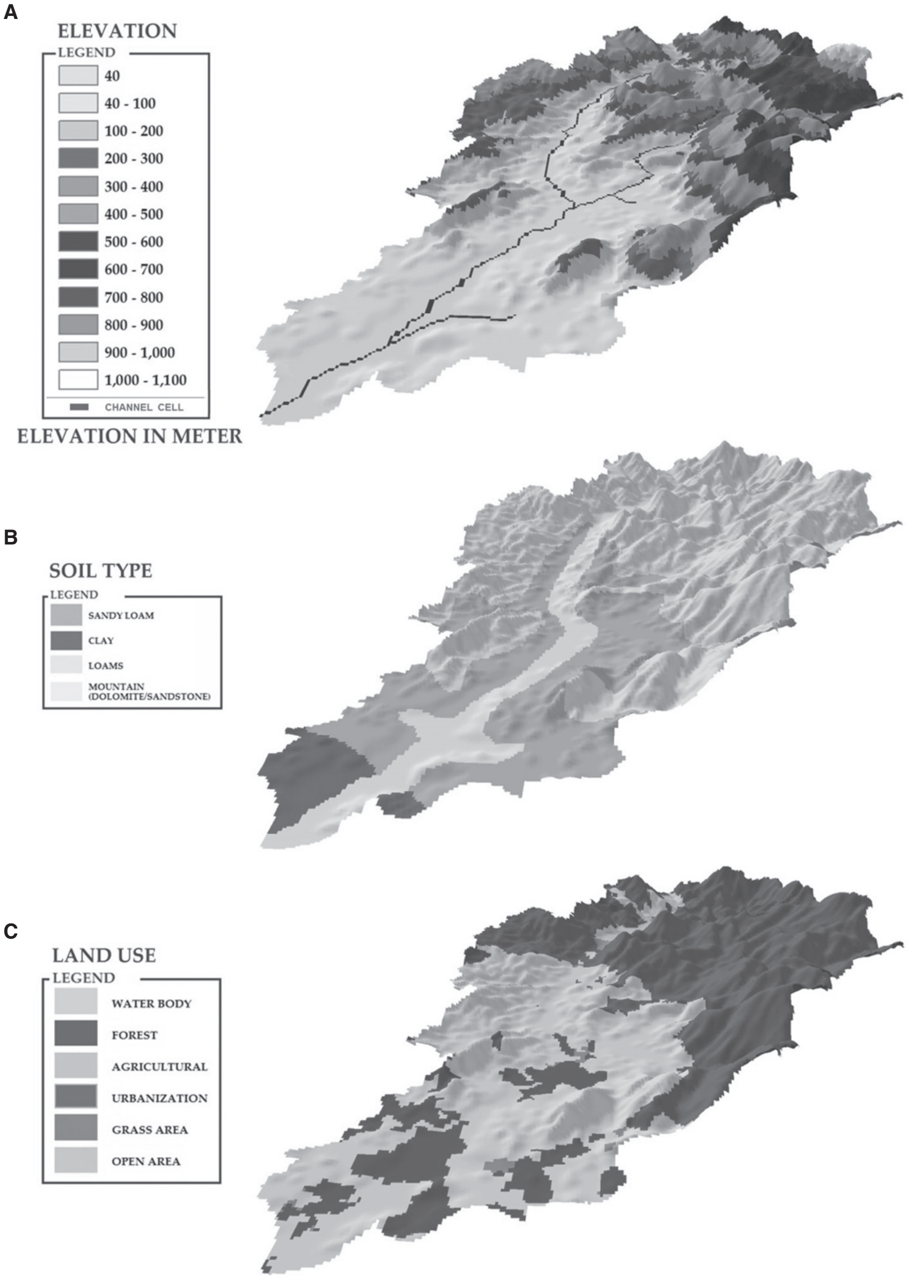


Fig. 2 Sungai Semenyih 90-m TREX GIS data layers: (**A**) elevation grid in meter and channels cells; (**B**) soil-type classes; (**C**) land use classes.

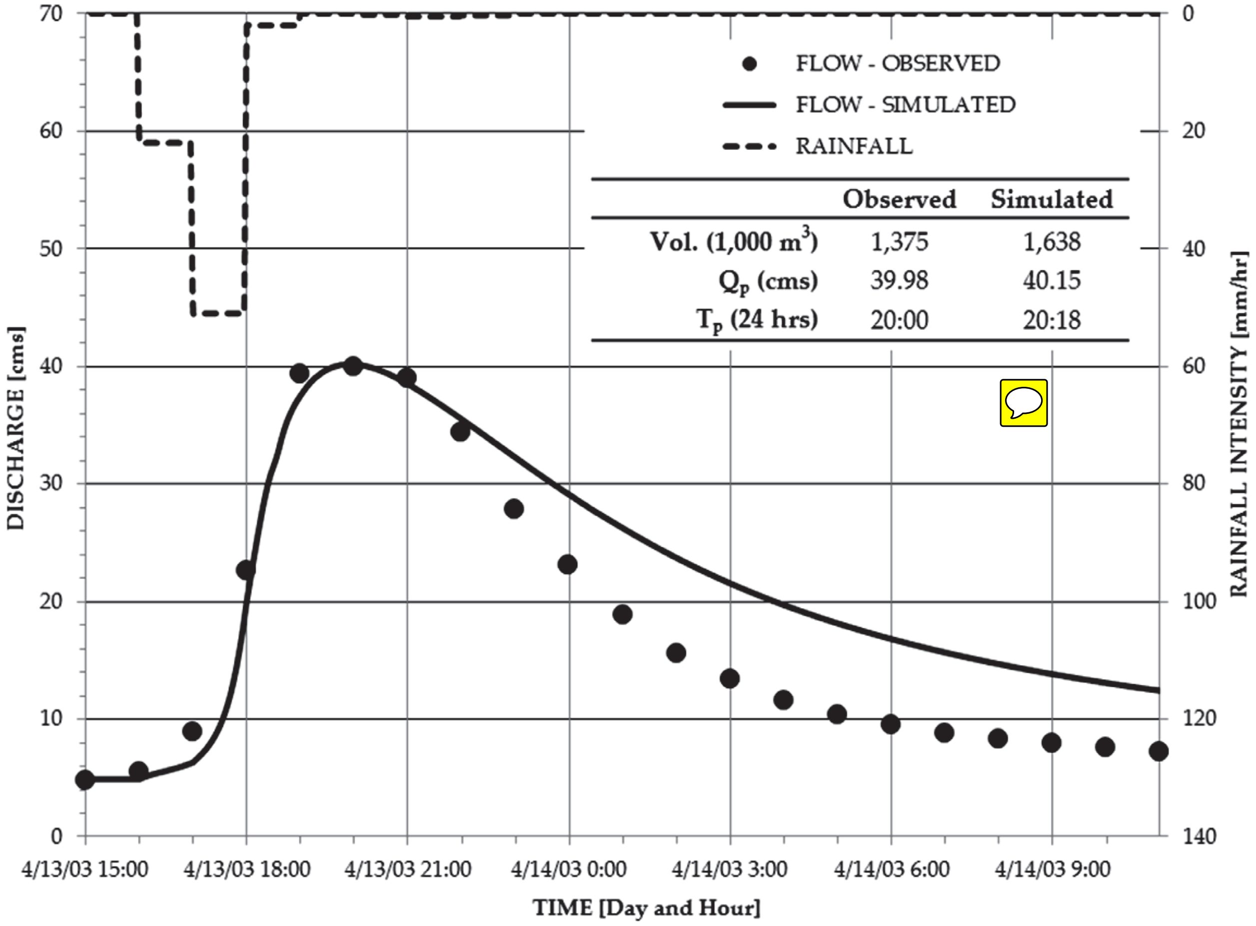
measured and simulated runoff. The antecedent moisture condition for the watershed was assumed to be fully dry.

The Nash–Sutcliffe Efficiency Coefficient (NSEC) and Percent BIAS (PBIAS) were used to evaluate model performance. The value of discharges and volumes from the simulated result were evaluated using these methods, respectively. The value of NSEC can be between $-\infty$ and 1.0, with NSEC = 1.0 being the optimal value. Generally, NSEC values between 0.0 and 1.0 are acceptable levels of performance, whereas values less than 0.0 indicate unacceptable performance. PBIAS measures the tendency of the simulated data to be larger or smaller than the observed data.[14] Positive and negative values indicate a model underestimated and overestimated, respectively. The optimal value of PBIAS is 0.0. In this study, the classifications for NSEC and PBIAS defined by Moriasi et al.[15] were used to determine whether the simulation results were good or very good.

The TREX model parameterization for the calibration on April 13, 2003, shows that peak flow, flow volume, and time to peak were all accurately simulated at the outlet (Fig. 3). A calibrated channel Manning n (0.04) was within the range proposed by Zakaria et al.[16] The Relative Percent

Table 1 Summary of model parameter values for Semenyih watershed

Parameter	Range	Application
Hydraulic Conductivity K_h (m/s)	1.5×10^{-8}–6.1×10^{-7}	Sandy Loam
	3.7×10^{-8}–6.9×10^{-8}	Loam
	1.7×10^{-9}–1.3×10^{-8}	Clay
	3.2×10^{-8}–3.2×10^{-10}	Mountain–Limestone
Manning's n ($s/m^{1/3}$)	0.05–0.18	Agricultural
	0.05–0.15	Urbanization
	0.20–0.40	Forest
	0.05–0.20	Grass area
	0.05–0.15	Open area
	0.02–0.04	Channel bed



	Observed	Simulated
Vol. (1,000 m^3)	1,375	1,638
Q_p (cms)	39.98	40.15
T_p (24 hrs)	20:00	20:18

Fig. 3 April 13, 2003, hydrograph and TREX calibration

Difference (RPD) for peak flow, total volume, and time to peak was 0.4, 19.1, and 1.5, respectively. The NSEC and PBIAS value peak discharge and total volume were 0.8% and −19.3%, respectively, and indicate a very high simulation performance. For the validation events, the peak discharge found to be near-perfectly simulated with an average RPD value as low as 0.28%. The simulated hydrographs generally had the same shape as the observed hydrographs with an average total flow volume RPD of 32%. The peak discharge from measured and simulated for calibrated and validated model are presented in Fig. 4. The model is numerically very stable and matches the peak discharge and time to peak. Performance evaluations for these simulations are presented in Table 2.

EXTREME EVENT SIMULATION

The importance of Probabe Maximum Precipitation (PMP) is always highlighted and emphasized in terms of public safety and hazard downstream of any major river regulating structures, especially if it is located upstream of populated areas. In the case presented in this analysis, the

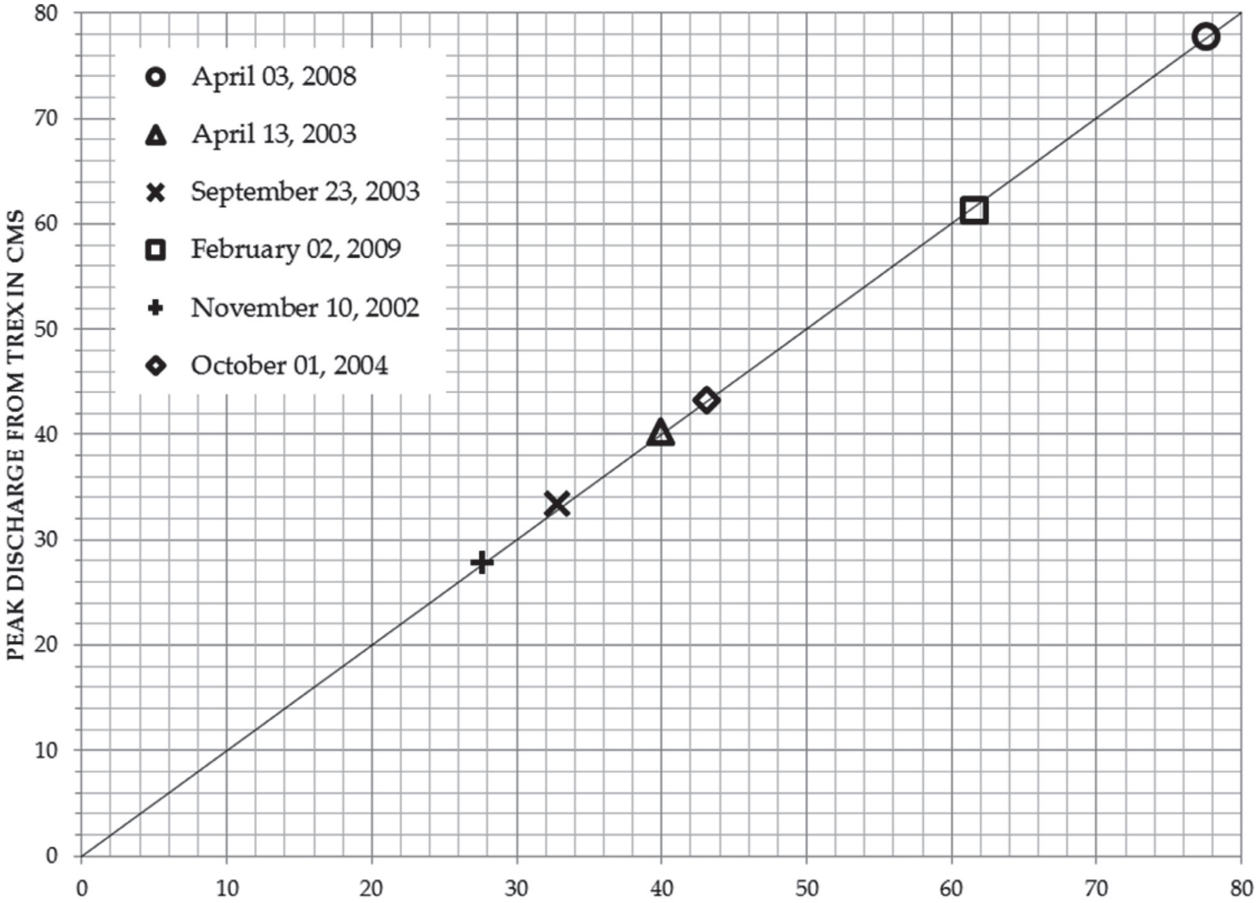


Fig. 4 Simulated and measured water discharge for the model calibration and validation events

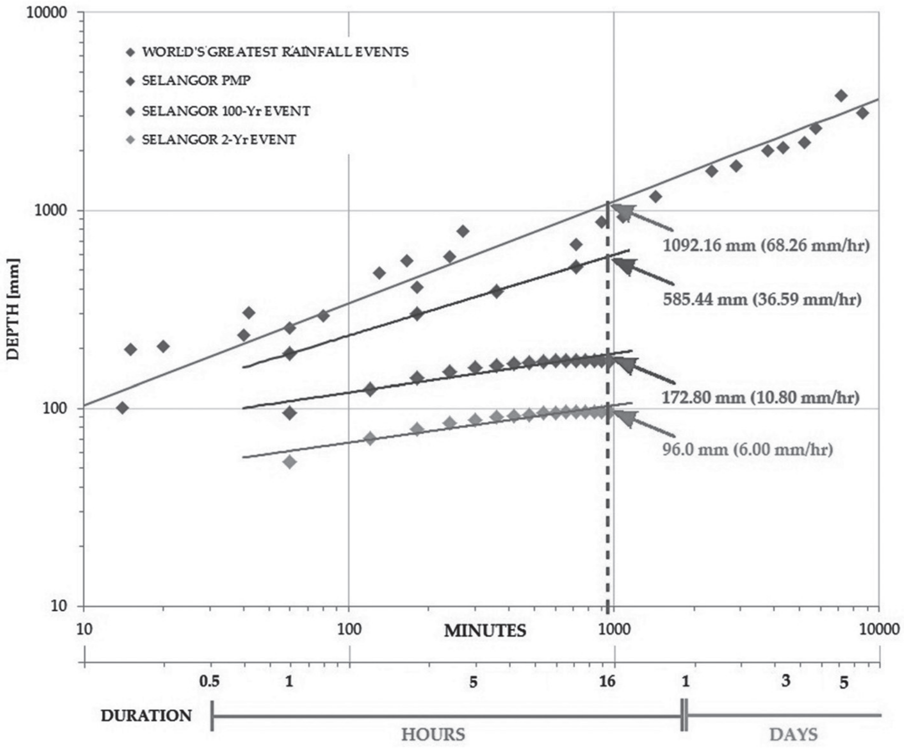


Fig. 5 Comparison between world's greatest rainfall events and Selangor extreme events.

Table 2 Hydrologic model performance evaluation summary

Calibration

	Peak flow (m³/sec)			Total volume (× 1000 m³)			Time to peak (hr)			Performance evaluation	
Event	**Observation**	**Simulated**	**RPD (%)**	**Observation**	**Simulated**	**RPD (%)**	**Observation**	**Simulated**	**RPD (%)**	**NSEC**	**PBIAS (%)**
April 13, 2003	39.98	40.15	0.4	1375	1638	19.1	20:00	20:18	1.5	0.8	−19.3

Validation

	Peak flow (m³/sec)			Total volume (× 1000 m³)			Time to peak (hr)			Performance evaluation	
Event	**Observation**	**Simulated**	**RPD (%)**	**Observation**	**Simulated**	**RPD (%)**	**Observation**	**Simulated**	**RPD (%)**	**NSEC**	**PBIAS (%)**
April 3, 2008	77.58	77.77	0.2	2939	3052	3.9	23:00	23:54	3.9	1.0	−7.6
September 23, 2003	32.83	33.37	1.6	590	950	61.2	7:00	7:42	10.0	0.1	−57.7
February 23, 2003	61.59	61.23	−0.6	1924	2530	31.5	22:00	22:45	3.4	0.4	−31.7
November 10, 2002	27.71	27.74	0.1	947	1277	34.9	0:00	0:42	2.9	0.8	−25.9
October 1, 2004	43.12	43.18	0.1	1236	1590	28.7	19:00	19:21	1.8	0.8	−28.9

Abbreviations: RPD, relative percent different; NEEC, Nash Sutcliffe Efficiency Coefficient; PBIAS, percent BIAS.

Table 3 Summary of intensity and peak discharge at Semenyih using 2-yr, 100-yr, PMP, and world's greatest precipitation

		Input		Results		
Events		**Depth (mm)**	**Intensity (mm/hr)**	**Peak discharge (cm)**	**Time to peak (24-hr)**	**Runoff coefficient**
Semenyih	2-Yr	96	6	136	18:12	0.3
	100-Yr	173	11	223	23:36	0.3
	PMP	585	37	1484	19:06	0.6
World's Precipitation		1092	68	3686	17:30	0.8

world's greatest precipitation (WGP) events are used as input to the calibrated TREX model to determine the magnitude of extreme floods. A 16-hr precipitation duration obtained from Jennings[17] with an intensity of 68.24 mm/hr has been applied (Fig. 5). The precipitation duration was selected at 16-hr because precipitation records for shorter duration can be determined with a sufficient level of certainty in this monsoon climate according to MSMA[18] (Urban Stormwater Management Manual). Table 3 shows the summary of the input for TREX. The 2-yr, the 100-yr[18] and also the PMP[19] conditions for Malaysia have also been applied in the model for a comparison of the peak discharge between the four simulated storms. The watershed runoff coefficient, $C = Q/iA$ (where Q = peak discharge [L^3T^{-1}]; i = rainfall intensity [LT^{-1}]; and A = watershed area [L^2]), increases in magnitude as intensity and peak discharge increased. The C values for the 2-yr and 100-yr storm events were lower because the infiltration and flow characteristics in the flat areas were dominant compared with steep areas. The C values for the PMP and WGP storm events were closer to unity because the flat areas became fully saturated and almost impervious.

Figure 6 shows the results from the WGP event. Figure 6a represents the watershed starting to receive precipitation at time 01:39 hours. The WGP simulation result indicates that the lowlands would be flooded with a water depth as high a 6 m (Fig. 6b). The DID website defines three water levels in relation to floods in Malaysia: 1) the "normal" water level corresponds to water depths less than 4.49 m; 2) the "alert" level corresponds to water depths between 4.49 m and 6.09 m; and 3) the "danger" level is reached when the flow depth exceeds 6.09 m. This "danger" condition is reached during our simulation as indicated in red color on Figure 6c. Flooding is expected to be widespread in the low valley

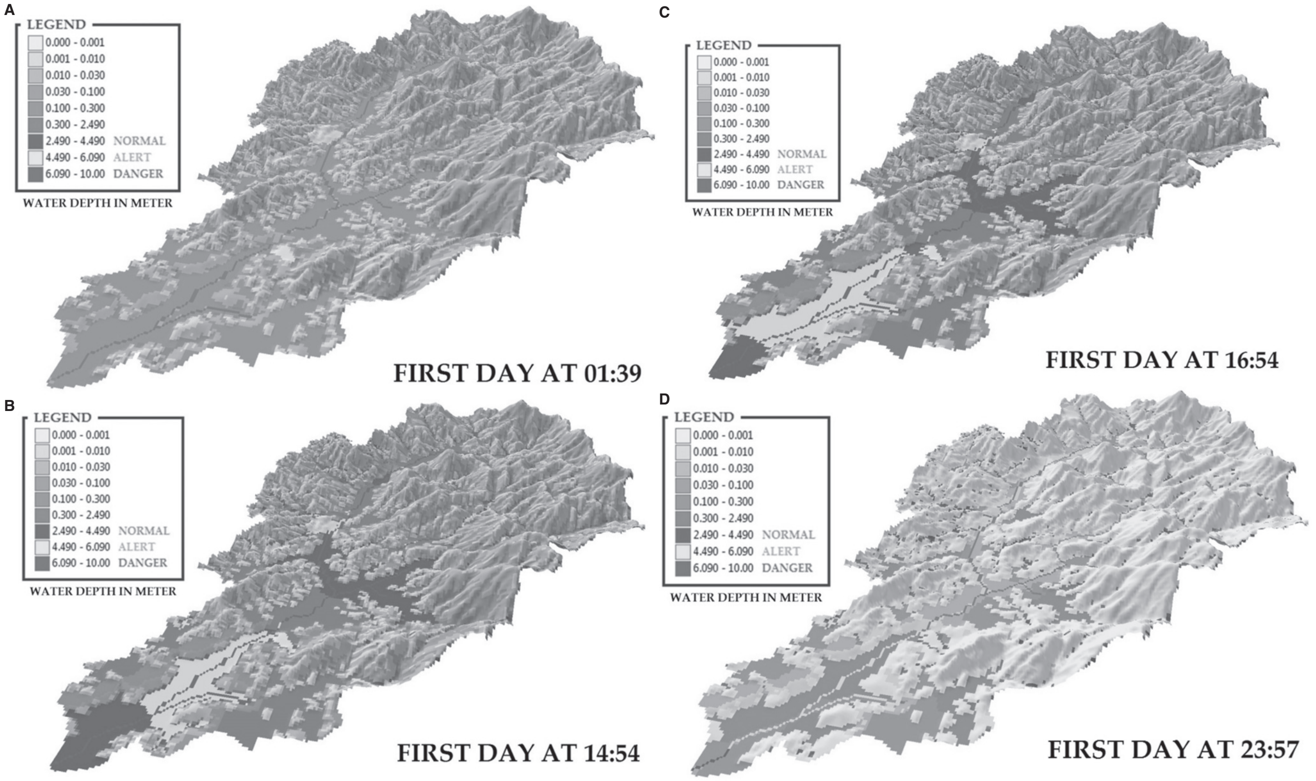


Fig. 6 Spatial distribution of water depth (m) with world's greatest precipitation event (68.24 mm/hr at 16-hr duration).

area. In this simulation, the "alert" condition (yellow in color) started around 11:00 hours and submerged about 50% of lowest area and lasted approximately 4 hr until 14:54 hours during the first day of the storm event. The flood took about 6 hr to recede and drain most of the surface water as shown in Fig. 6d.

The hydrograph (Fig. 7) for Semenyih watershed demonstrates that the TREX model can be effectively used to simulate and estimate the magnitude of flooding during extreme storms. The TREX result based on WGP input data are compared with floods of lesser magnitude, including the 2-yr, the 100-yr flood, as well as the PMP condition for Malaysia. A summary of the conditions and simulation results for these floods is presented in Table 3.

CONCLUSION

The model TREX has been successfully applied for the simulation of extreme floods on the 236 km^2 of Semenyih watershed in Malaysia. The April 13, 2003, storm was used to calibrate the model, whereas several other storm events served for the model validation. The calibrated TREX model can then simulate the hydrograph using the world's greatest precipitation (68.24 mm/hr for 16-hr duration). TREX successfully simulates extreme hydrographs for comparison with 2-yr and 100-yr flood events. TREX also provides visual flood hazard maps for this site.

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REFERENCES

1. England, J.F. Jr.; Velleux, M.L; Julien, P.Y. Two-dimensional simulations of extreme floods on a large watershed. J. Hydrol. **2007**, *347* (12), 229241.
2. England, J.F. Jr.; Godaire, J.E.; Klinger, R.E; Bauer, T.R.; Julien, P.Y. Paleohydrologic bounds and extreme flood frequency of the upper Arkansas river, J. Geomorphol. **2010**, *124*, 1–16.

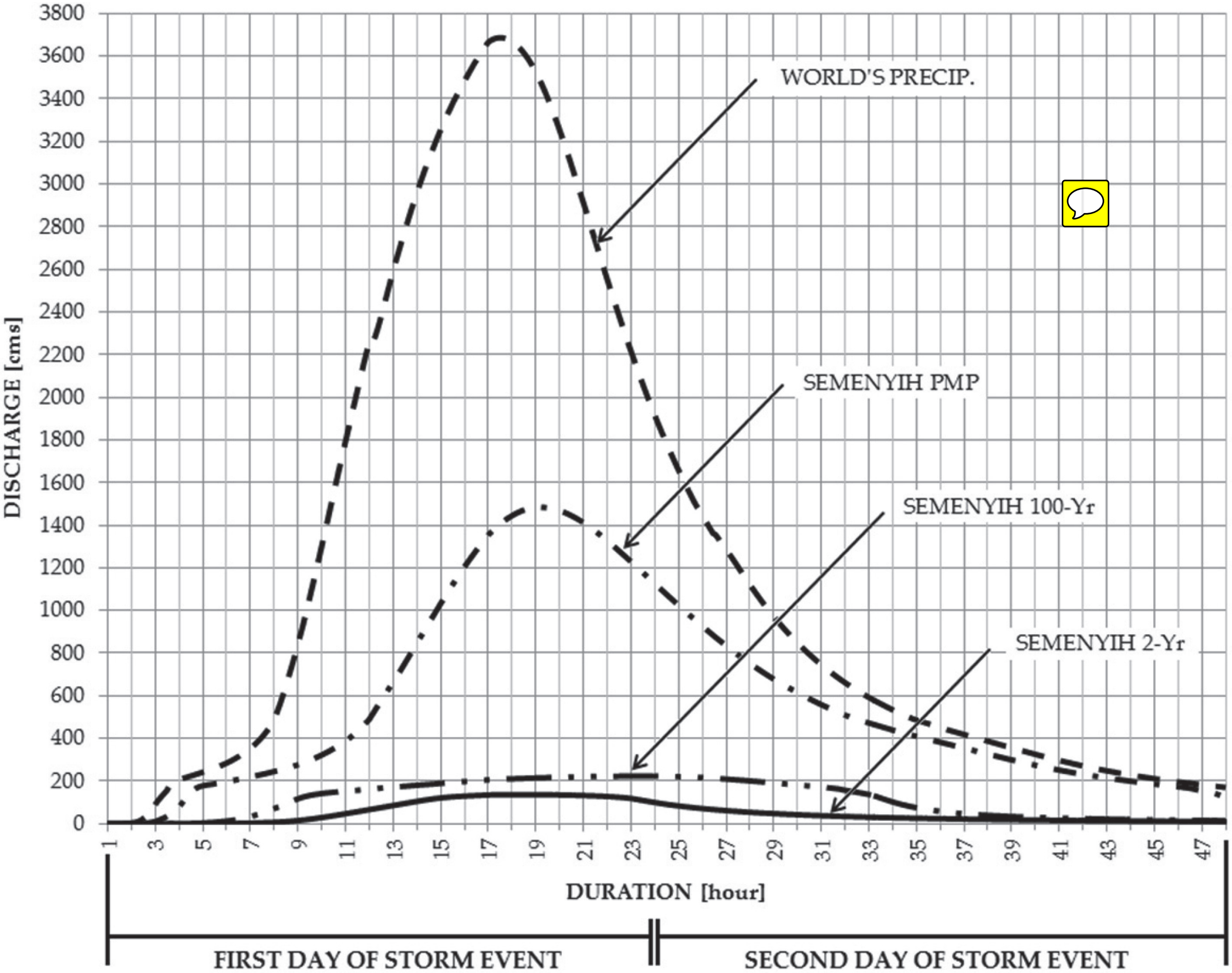

Fig. 7 TREX hydrograph with world's greatest precipitation event (68.24 mm/hr at 16-hr duration)

3. Velleux, M.L.; England, J.F. Jr.; Julien, P.Y. *TREX Watershed Modeling Framework User's Manual: Model Theory and Description*; Department of Civil Engineering; Colorado State University, Fort Collins, Colorado, 2006a; 83.
4. Julien, P.Y.; Saghafian, B.; Ogden, F.L. Raster-Based hydrologic modeling of spatially-varied surface runoff. Water Resour. Bull. AWRA **1995**, *31* (3), 523–536.
5. Johnson, B.E.; Julien, P.Y.; Molnar, D.K.; Watson, C.C. The two-dimensional upland erosion model CASC2D-SED. J. Am. Water Resour. Assoc. AWRA **2000**, *36* (1), 31–42.
6. Ogden, F.L.; Julien, P.Y. CASC2D: A two-dimensional, physically-based, Hortonian hydrologic model. In *Mathematical Models of Small Watershed Hydrology and Applications*; Singh, V.P.; Frevert, D. Eds.; Water Resources Publications: Littleton, CO, 2002; 69–112.
7. Julien, P.Y.; Rojas, R. Upland erosion modeling with CASC2D-SED. Int. J. Sediment Res. **2002**, *17* (4), 265–274.
8. Velleux, M.L.; Julien, P.Y.; Rojas-Sanchez, R.; Clements, W.H.; England J.F. Simulation of metals transport and toxicity at a mine-impacted watershed: California Gulch, Colorado. Environ. Sci. Technol. **2006b**, *40* (22), 6996–7004.
9. Jorgeson, J.; Julien, P.Y. Peak Flow Forecasting with CASC2D and Radar Data, Water International. IWRA, **2005**, *30* (1), 40–49.
10. Julien, P.Y. *River Mechanics*; Cambridge University Press: Cambridge, 2002; 434.
11. Julien, P.Y. *Erosion and Sedimentation*; Cambridge University Press: Cambridge, 2nd Ed., 2010; 371.
12. Velleux, M.L.; England, J.F. Jr.; Julien, P.Y. TREX: Spatially distributed model to assess watershed contaminant transport and fate. J. Sci. Total Envir. **2008**, *404*, 113–128.
13. Molnar, D.K.; Julien, P.Y. Grid size effects on surface runoff modeling. J. Hydrol. Eng., ASCE, **2000**, *5* (1), 8–16.
14. Gupta, H.V.; Sorooshian, S.; Yapo, P.O. Status of automatic calibration for hydrologic models: comparison with multilevel expert calibration. J. Hydrol. Eng., ASCE, **1999**, *4* (2), 135–143.
15. Moriasi, D.N.; Arnold, J.G.; Van-Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Am. Soc. Agric. Biol. Eng. **2007**, *50* (3), 885–900

16. Zakaria, N.A.; Azamathulla, H.M.; Chang, C.K.; Ab. Ghani, A. Gene expression programming for total bed material load estimation–a case study, Sci. Total Env. **2010**, *408*, 5078–5085.
17. Jennings, A. H. *World's Greatest Observed Point Rainfalls*. Hydrometeorological Section, U. S. Weather Bureau: Washington D.C., 1950; 4–5.
18. DID. Urban Stormwater Management Manual (MSMA Manual), 2000, 13 (3).
19. Hii, C.P.; Heng, H.H. Probable maximum precipitation derivation in Malaysia: Review and Comparison. Int. J. Hydro-Clim. Eng. **2010**, 37–72.