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Flood flow simulations and return period calculation for the Kota Tinggi watershed, Malaysia

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Extreme events; hydrological modelling; joint probability; monsoon.

Abstract

The City of Kota Tinggi in Malaysia was under more than 5 m of water during the floods in December 2006 and January 2007. The watershed received between 280 and 530 mm of rain in 4 days. These extreme events occurred 3 weeks apart and caused extensive damages. The application of the fully distributed two-dimensional model two-dimensional runoff, erosion and export (TREX) to simulate these events and the estimation of the return period of such extreme events are the main objectives of this study. The model performance was very good based on the relative percentage different (3.7%), percent BIAS (overestimated the volume by 1.5%) and Nash–Sutcliffe efficiency coefficient (0.8). The TREX model is successful in simulating extreme flood events. The December 2006 rainstorm event at Kota Tinggi is extremely rare, and this multiday rainstorm had an estimated return period greater than 2000 years. The analysis of the return period shows that multiday rainstorms occur more frequently than single-day events. In addition, we produce a flood threshold graph by integrating both the hydrological modelling process using TREX and the theoretical formulation of return period. The proposed flood threshold graph is useful in the estimation of the amount of accumulated rainfall from multiday rainfall that can cause flooding on a large watershed like Kota Tinggi.

Introduction

One of the most devastating floods that occur in Malaysian history is the Kota Tinggi floods in December 2006 and January 2007. Both events are multidays, and the observed accumulated rainfall of both events exceeded 350 mm. An economic loss of RM1.5 billion (equivalent to about half a billion US dollars) was estimated, and more than 100 000 local residents had to be evacuated during both events (Abu Bakar *et al*., 2007). Significant economic and social impacts of the floods motivated the authors to carry out this study. Kota Tinggi is classified as large watershed, with a drainage area larger than 1000 km^2. Such extreme floods on large watersheds under monsoon climates are poorly understood, and further research is required to better understand the climatic conditions of multiday rainstorms and the hydrological routing of extreme floods in tropical areas under rapid deforestation and urban development.

Malaysia is located near the equator and experiences two major monsoon seasons, that is, Northeast (November to March) and Southwest (May to September). As a result, the country receives significant amount of rainfall, ranging between 2000 and 4000 mm annually (Suhaila and Jemain, 2007). Most of the rainfall events are multidays (Muhammad, 2013), and this factor has been identified as the main cause of flooding. Statistical approaches (Suhaila and Jemain, 2007, 2008; Wan-Zin *et al*., 2009a, 2009b) and artificial neural networks (Nor *et al*., 2007; Wardah *et al*., 2008; Sulaiman *et al*., 2011) are the preferred methods used by most of the local researchers to predict flood frequency. The nature of rainfall in Malaysia is different from other regions as it is influenced by northeast and southwest monsoons. Muhammad (2013) found that most of the rainfall events in Malaysia are multidays, and these events are time-dependent. Therefore, the return period needs to be defined as the interarrival time or recurrence interval, following the analyses performed by Woodyer *et al*. (1972); Kite (1978); Lloyd (1970); Loaiciga and Mariňo (1991) and Şen (1999).

Ghani *et al*. (2009) found that deterministic models are still relatively new in Malaysia, although they have been widely used in many other countries. The few studies that use deterministic models to simulate floods in Malaysia, include Mah *et al.* (2007, 2010, 2011); Said *et al.* (2009); Ali and Ariffin (2011); Siang *et al.* (2007); Yusop *et al.* (2007); Razi *et al.* (2010); Mohammed *et al.* (2011); Izham *et al.* (2010); Billa *et al.* (2004, 2006); Lim and Cheok (2009); Ghazali and Kamsin (2008); Teo *et al.* (2009) and Toriman *et al.* (2009). However, most of the studies listed here were carried out using a one-dimensional approach (except Lim and Cheok, 2009; Teo *et al.*, 2009, which are two-dimensional approaches). Two-dimensional models offer more extensive results that cannot be achieved using one-dimensional simulations, such as the direction and rate of flood propagation, the flood inundation extent and flood stages and flood durations. Recent advances in hydrological modelling and increased data availability enable the use of two-dimensional models.

This study develops a new methodology for the analysis of multiday monsoon floods on large watersheds. The example of Kota Tinggi will be used as a case study to demonstrate the applicability of the proposed method. This study first examines the capability of a two-dimensional hydrological model in simulating multiday rainfall events. The hydrological model needs to have the capability to predict not only the discharge but also the aerial extent of flooding as well as the flood stages. Second, we propose a method for quantifying the return period of multiday rainfall events for monsoon climates. We introduce a new method known as the discrete auto-regressive and moving average (DARMA)/gamma model in order to estimate the return period of multiday monsoon rainfall. This method takes into account important factors of multiday rainfall, such as the sequence, amount and also the duration. We ensure that the time-dependent sequence of daily rainfall is preserved through the DARMA(1,1) model. In addition, the final objective of this study is to produce a flood threshold graph that can be used as a guideline in determining the flood threshold for the Kota Tinggi watershed.

Kota Tinggi Floods

Kota Tinggi is located at the southern part of Peninsular Malaysia, specifically in the state of Johor, and the watershed has an area of 1600 km^2, as shown in Figure 1. Mountains cover about 20% of the watershed at an elevation greater than 600 m. The lowest elevation is 4 m at the downstream-end of the watershed.

Kota Tinggi receives a significant amount of rainfall, and the total annual average is 2470 mm. There were historical floods recorded in 1926, 1967, 1968 and 1971 (Badrul Hisham *et al.*, 2010). However, the worst floods were reported in December 2006 and January 2007, which occurred 3 weeks apart.

The floods in December 2006 and January 2007 were the results of 5 and 4 consecutive rainy days, respectively. Table 1 gives the measured daily rainfall at several gauging stations for these events. For the December 2006 event,

Figure 1 Location of Kota Tinggi watershed on Malaysia's map.

Table 1 Total amount of daily rainfall in mm recorded at several gauging stations around Kota Tinggi during the December 2006 and January 2007 floods (after Shafie, 2009)

Date	Layang-Layang	Ulu Sebol	Bukit Besar	Kota Tinggi
December 2006				
17 December	66	33	29	48
18 December	52	23	47	43
19 December	156	189	200	161
20 December	73	78	69	39
4 days total	367	353	345	287
January 2007				
11 January	145	124	147	167
12 January	135	290	234	122
13 January	84	76	42	49
14 January	20	44	35	–
4 days total	384	534	458	338

most of the stations recorded an accumulated amount close to 100 mm in 2 consecutive days. A significant amount of rain was recorded on the third day, that is, December 19, 2010. The highest rainfall was recorded at Bukit Besar station, with a measurement of 200 mm, and this value is the same as the average monthly rainfall. The Ulu Sebol station located in the northeastern part of the Kota Tinggi watershed recorded 189 mm of rainfall on December 19, 2006. Total rainfall amounts recorded after 4 consecutive days exceeded 300 mm at most gauging stations.

The January 2007 flood was more severe than the December 2006 event. Figure 2 shows the satellite images of a band of clouds from 11th to 14th January 2007. The Kota Tinggi watershed received a significant amount of rainfall for 4 consecutive days from these clouds. The maximum magnitude of rainfall was recorded for the first 2 days, that is, 12–13 January 2007. For example, the accumulated rainfall for 2 days at Ulu Sebol station was 366 mm, which is almost twice the average monthly rainfall. This station also recorded the highest total rainfall for the 4 consecutive rainy days, with 534 mm. In general, most of the gauging stations in Kota Tinggi recorded an average total rainfall of more than 300 mm.

Methodology

This study focused on three main components in order to simulate and quantify the return periods of these extreme events: (1) hydrological modelling, (2) simulation of daily rainfall sequences and (3) return period estimation. These components are discussed in the following sections.

Hydrological modelling

This study performs hydrological modelling using the two-dimensional runoff, erosion and export (TREX) model to further understand the watershed response based on the Kota Tinggi floods. This model was selected because it is a two-dimensional distributed model, compatible with ArcGIS and able to model continuous rainfall. Moreover, this model has been extensively tested and applied to different sizes of watersheds, ranging from small to large (Ogden and Julien, 2002; Velleux, 2005; England, 2006). In addition, England *et al.* (2007); Velleux (2005) and Velleux *et al.* (2006, 2008) have simulated rainfall. Model state variables are the water depth in the overland plane and stream channels. Precipitation can be uniform or distributed in both time and space (Jorgeson, 1999; Ogden, 1992; Ogden and Julien, 1993, 1994, 2002; Ogden *et al.*, 2000) and can also be specified using several grid-based formats to facilitate radar precipitation data use.

The fully distributed two-dimensional TREX model was used for the simulation of infiltration, overland runoff and channel flow during extreme rainfall events. Overland and channel flows are simulated using the diffusive wave approximation in two and one dimensions, respectively. 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 3.

Precipitation and interception

The precipitation volume reaching the near surface can be described in mathematical form as

$$\frac{dV_g}{dt} = i_g A_s \tag{1}$$

where V_g is the precipitation volume [L^3]; t is time [T]; i_g is the net rainfall intensity after interception [LT^{-1}]; and A_s is the drainage area. The presence of forests or any other vegetation cover over an area of land influences the distribution pattern of precipitation. Some of the precipitation is intercepted and retained by the leaves and other parts of

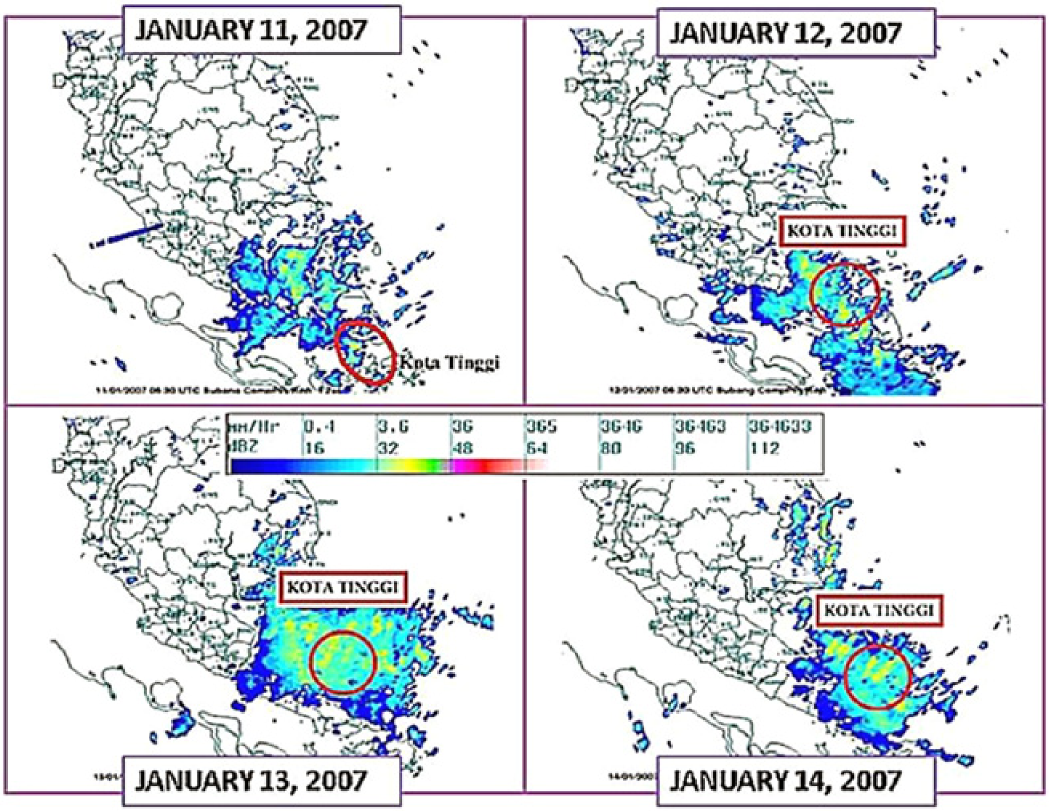

Figure 2 Satellite images rainfall distribution (modified from Shafie, 2009).

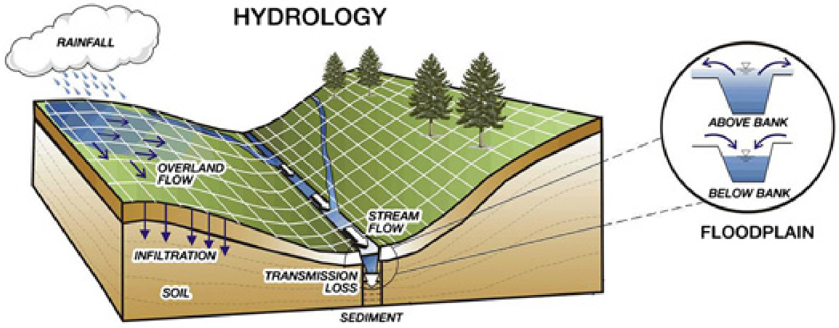

Figure 3 Overview of hydrological processes in TREX model.

the tree and then eventually lost to the atmosphere in the form of evaporation. The TREX model factors interception in volume. The interception volume could be calculated using Eqn (2).

$$V_{\mathrm{i}} = (S_{\mathrm{i}} + Et_{\mathrm{R}})A_{\mathrm{s}} \tag{2}$$

where V_{i} is the interception volume [L^3]; S_{i} is the interception capacity of the projected canopy per unit area [$\mathrm{L}^3\mathrm{L}^{-2}$]; E is the evaporation rate [LT^{-1}]; and t_{R} is the rainfall duration [T].

Infiltration and transmission losses

Green and Ampt (1911) first analysed the process of infiltration. In the TREX model, infiltration rate is calculated using Eqn (3).

$$f = K_{\mathrm{h}}\left[1 + \frac{H_{\mathrm{C}}(1 - S_{\mathrm{e}})\theta_{\mathrm{e}}}{F}\right] \tag{3}$$

where f is the infiltration rate [LT^{-1}]; K_{h} is the effective hydraulic conductivity [LT^{-1}]; H_{C} is the capillary pressure (suction) head at the wetting front [L]; S_e is effective soil saturation [−]; θ_e is effective soil porosity ($\varphi - \theta_r$) [−]; φ is total soil porosity [−]; θ_r is residual soil moisture content [−]; and F is the cumulative infiltrated water depth [L].

Transmission losses describe the water lost from seepage to groundwater and overbank flow onto floodplains, wetlands and isolated ponds and returns very slowly to the river. The rate of transmission may be affected by several factors, particularly the hydraulic conductivity. The Green and Ampt (1911) method has been applied to calculate transmission losses (Eqn (4)).

$$t_l = K_h\left[1 + \frac{(H_w + H_C)(1 - S_e)\theta_e}{T}\right] \tag{4}$$

where t_l is the transmission loss rate [LT^{-1}]; H_w is the hydrostatic pressure head (depth of water in channel) [L]; and T is the cumulative depth of water transported by transmission loss [L].

Depression storage

Precipitation retained in small surface depressions is called the depression storage. Water in depression storage may be conceptualised as a volume, or a depth, when normalised by the surface area. When the water depth is below the depression storage threshold, overland flow is zero. Note that water in depression storage is still subject to infiltration and evaporation. Similar to depression storage in overland areas, water in channels may be stored in depressions in the stream bed, which are caused when the channel water depth falls below some critical level; flow is zero; and the water surface has discontinuities, but individual pools of water remain. This mechanism is termed dead storage. Note that the water in dead storage is still subjected to transmission losses and evaporation. For single-storm events, the recovery of depression storage volume by evaporation can be neglected. Similarly, the recovery of a dead storage volume by evaporation can also be neglected for single-storm events.

Overland and channel flow

Overland flow occurs when the water depth of the overland plane exceeds the depression storage threshold. Overland flow is governed by the conservation of mass (continuity) and conservation of momentum. The two-dimensional (vertically integrated) continuity equation for gradually varied flow over a plane in rectangular (x, y) co-ordinates is shown in Eqn (5).

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = i_n - f + \dot{W} = i_e \tag{5}$$

where h is the surface water depth [L]; q_x, q_y is the unit discharge in the x- or y-direction (Q_x/B_x , Q_y/B_y) [L^2T^{-1}]; Q_x, Q_y is the flow in x- or y-direction [L^3T^{-1}]; B_x, B_y is the flow width in x- or y-direction [L]; .W· is the flow discharge from/to a point source/sink [LT^{-1}]; i_n is the precipitation [LT^{-1}]; f is the infiltration rate [LT^{-1}]; and i_e is the excess precipitation [LT^{-1}].

The application of momentum equations (Saint-Venant equations) for the x- and y-directions may be derived by relating the net forces per unit mass to flow acceleration. The small terms, local and convective acceleration components, of the full Saint-Venant equations may be neglected (Cunge *et al.*, 1980), resulting in the diffusive wave approximation for x- and y-directions (Eqn (6)).

$$S_{fx} = S_{ox} - \frac{\partial h}{\partial x} \quad \text{and} \quad S_{fy} = S_{oy} - \frac{\partial h}{\partial y} \tag{6}$$

where S_{fx}, S_{fy} are the friction slope components (energy grade line) in the x- or y-direction [−], and S_{ox}, S_{oy} is ground surface slope in the x- or y-direction [−].

Five hydraulics variables must be defined in terms of the depth–discharge relationship (Eqn (7)) to describe flow resistance before the overland flow equations can be solved. Turbulent flow is assumed, and resistance is described using Eqn (8).

$$q_x = \alpha_x h^{\beta} \text{ and } q_y = \alpha_y h^{\beta} \tag{7}$$

$$\alpha_x = \frac{{S_{fx}}^{1/2}}{n} \quad \text{and} \quad \alpha_y = \frac{{S_{fy}}^{1/2}}{n} \tag{8}$$

where α_x, α_y is the resistance coefficient for flow in the x- or y-direction [$L^{1/3}\ T^{-1}$]; β is the resistance exponent (=5/3) [−]; and n is Manning's roughness coefficient [$TL^{-1/3}$].

One-dimensional channel flow (along the channel in the downgradient direction, which laterally and vertically integrated) is also governed by conservation of mass (continuity) and momentum. The method suggested by Julien *et al.* (1995); Johnson *et al.* (2000) and Julien and Rojas (2002) is applied for gradually varied flow, as given in Eqn (9).

$$\frac{\partial A_c}{\partial t} + \frac{\partial Q}{\partial x} = q_l + \hat{W} \tag{9}$$

where A_c is the flow cross section area [L^2]; Q is the total discharge [L^3T^{-1}]; q_1 is the lateral flow into or out of the channel [L^2T^{-1}]; and $\hat{W}$ is the unit discharge from/to a point sink/source [L^2T^{-1}].

To solve the channel flow equations, from the momentum equation (by neglecting the local and convective terms), the diffusive wave approximation may be used for the friction slope (Eqn (8), only in x-direction). The

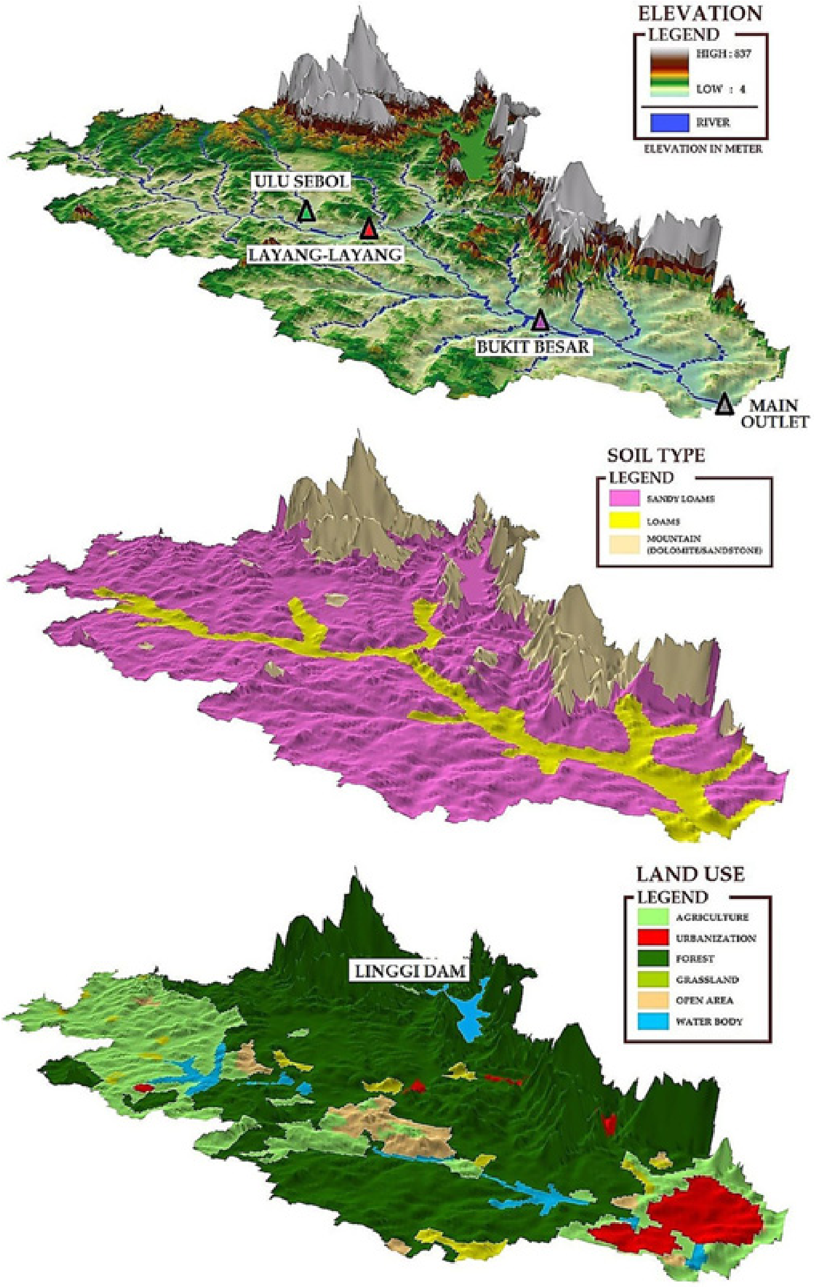

Figure 4 (a) DEM, (b) soil type and (c) land use.

Manning relationship is used to solve the channel flow equations for mass and momentum.

Model parameterisation

The TREX model simulates infiltration, overland runoff and channel flow during extreme rainfall events. Input data were prepared using ArcGIS 9.3 and converted into a text file. The surface topography of the watershed was discretised at a 230 by 230-m scale. The grid size was used to delineate these watersheds. The digital elevation model (DEM), as shown in Figure 4(a), was downloaded at a 90-m resolution from the ASTER GDEM website (www.gdem.aster.ersdac.or.jp/search.jsp). The watershed was described with a total of 31 000 active grid cells within a matrix of 292 rows and 292 columns. The total of river length at the large watershed is 250 km (1081 nodes and 42 links). The

Table 2 Summary of model parameters

Parameter	Value	Application
Interception depth (mm)	2.0	Agriculture
	0.05	Urban/commercial
	5.0	Forest
Soil moisture deficit	0.29	Sandy loams
		Loams
		Mountain – limestone
Capillary suction head (m)	0.14	Sandy loams
	0.22	Loams
	0.17	Mountain – limestone
Hydraulic conductivity [K_h (m/s)]	3.5×10^{-10}–3.5×10^{-7}	Sandy loams
	3.7×10^{-10}–3.7×10^{-7}	Loams
	7.7×10^{-10}–1.3×10^{-8}	Clay
	3.5×10^{-11}–3.2×10^{-6}	Mountain – limestone
Manning's n (m/s$^{1/3}$)	0.05–0.35	Agriculture
	0.01–0.10	Urban/commercial
	0.18–0.65	Forest
	0.05–0.35	Grass area
	0.05–0.35	Open area

input data for soil types and land use for this watershed are shown in Figure 4(b) and (c), respectively.

Calibrated model parameters are listed in Table 2. A sensitivity analysis showed that the hydraulic conductivity, K_h and Manning n are the most sensitive parameters during calibration (Abdullah, 2013). The range of values for K_h and n are also shown in Table 2. These values were adjusted during calibration to achieve very good agreement between observed and simulated discharges. The antecedent moisture condition for the watershed was assumed to be fully dry at the beginning of simulation. Rainfall was so abundant during this event that hydrological losses to interception and detention storage were negligible. The evaporation rate was assumed to be negligible as the simulations were done during high rainfall intensity; thus, the evaporation process does not affect the results.

Simulation of daily rainfall sequences

In hydrology, there are two definitions used, that is, first arrival time and interarrival time or recurrence interval. The first arrival time is more suitable for applications such as for reservoir operation because knowing the first time that the reservoir is at risk of failure is of greater interest than the average time between failures (Vogel, 1987; Douglas *et al.*, 2002). Previous studies reported that for single and independent events, the first arrival time and recurrence interval gives the same value (Fernández and Salas, 1999a). However, Fernández and Salas (1999a, 1999b) show that these definitions give different values when the events are dependent on time.

In this paper, a new approach is investigated. The DARMA(1,1) model was used to simulate the occurrence of daily rainfall. This model was chosen because it has longer persistence and memory (Chang *et al.*, 1982, 1984a, 1984b; Delleur *et al.*, 1989; Cindrić, 2006), which enables it to simulate multiday rainfalls effectively.

The mathematical formulation of DARMA(1,1) is (Jacobs and Lewis, 1978a)

$$X_t = U_t Y_t + (1 - U_t) A_{t-1} \tag{10}$$

with

$$X_t = \begin{cases} Y_t \text{ with probability } \beta \\ A_{t-1} \text{ with probability } (1-\beta) \end{cases}$$

where U_t is an independent random variable taking values of 0 or 1 only, such that

$$P(U_t = 1) = \beta = 1 - P(U_t = 0) \tag{11}$$

Y_t is another i.i.d. (independent and identically distributed) random variable having a common probability $\pi_k = P(Y_t = k)$, and $k = 0$, 1, and A_t is an autoregressive component given by

$$A_t = \begin{cases} A_{t-1} \text{ with probability } \lambda \\ Y_t \text{ with probability } (1-\lambda) \end{cases}$$

The variable A_t has the same probability distribution as Y_t but is independent of Y_t. It should be noted that X_t is not Markovian, but (X_t, A_t) forms a first-order bivariate Markov Chain.

The parameters π_0 and π_1 are based on the dry and wet run lengths that are obtained from the observed daily rainfall dataset. They are estimated using the equations given below (Buishand, 1978):

$$\pi_0 = \frac{\overline{T}_0}{\overline{T}_0 + \overline{T}_1} \tag{12}$$

$$\pi_1 = 1 - \pi_0 \tag{13}$$

where $\overline{T}_0$ is the mean run length for dry days, and $\overline{T}_1$ is the mean run length for wet days.

The autocorrelation function of the DARMA(1,1) is (Buishand, 1978)

$$corr(X_t, X_{t-k}) = r_k(X) = c\lambda^{k-1}, \; k \geq 1 \tag{14}$$

where

$$c = (1-\beta)(\beta+\lambda-2\lambda\beta) \tag{15}$$

The DARMA(1,1) model has three parameters, that is, π_0 or π_1, λ, and β. The parameters π_0 or π_1 may be estimated from Eqns (12) and (13). The estimation of λ may be determined by minimising Eqn (16) using the Newton–Raphson iteration techniques, and Buishand (1978) suggested using the ratio of the second to the first autocorrelation coefficients as an initial estimate for λ, as shown in Eqn (17).

$$\phi(\lambda) = \sum_{k=1}^{M} \left[r_k - c\lambda^{k-1}\right]^2; \quad k \geq 1 \tag{16}$$

$$\hat{\lambda} = \frac{r_2}{r_1} \tag{17}$$

in which M is the total number of lags considered; c can be determined from the lag-1 autocorrelation coefficient of the DARMA(1,1) model; and β can be estimated from Eqn (18).

$$\hat{\beta} = \frac{(3\hat{\lambda}-1) \pm \sqrt{(3\hat{\lambda}-1)^2 - 4(2\hat{\lambda}-1)(\hat{\lambda}-\hat{c})}}{2(2\hat{\lambda}-1)} \tag{18}$$

In this study, 100 samples of daily rainfall sequences, with the duration of 2000 years, were generated in order to examine the return period of multiday rainfall events. The estimation for the return period is given in the next section.

Return period of multiday rainfall events

In hydrology, the severity on an event is usually described in terms of the return period. The estimation of return period for multiday rainfall events has not been the interest of many Malaysian researchers, although these events occur quite frequently during monsoons. Muhammad (2013) suggested the method to estimate the return period for multiday rainstorms. The definition of return period in this study is 'recurrence interval', that is, average time (in days) between the occurrences of specific events. The formula to estimate multiday rainfall events is given in Eqn (19).

$$T = \frac{\overline{T}_1 + \overline{T}_0}{P(E|t)} \tag{19}$$

where $\overline{T}_1$ is the mean run length for wet days; $\overline{T}_0$ is the mean run length for dry days; and $P(E|t)$ is the probability of a single or multiday rainfall event occurring.

There are two important parameters in estimating the return period, that is, duration and the amount of cumulative rainfall. Following this, the probability of a rainfall event occurring was estimated integrating the univariate probability distribution functions of rainfall amount and duration to describe the conditional distribution of both properties. The relationship is presented in Eqn (20).

$$P(E|t) = \int_{x_0}^{\infty} f(x)\,dx \tag{20}$$

where t is number of consecutive rainy days; x is the total amount of rainfall (mm); and $f(x)$ is the univariate probability distribution function of rainfall amount and duration.

Results and discussions

Simulation of the Kota Tinggi floods

The simulated peak discharge, total runoff volume and time to peak at the main outlet were estimated by the TREX model. A very short time step (less than 20s) was used for the flow calculations, and more details on the numerical model simulations can be found in Abdullah (2013). The calibration and validation procedure focused on the accuracy of simulated peak discharge, the total runoff volume and time to peak at the main outlet (refer to Figure 4(a)). The hydrological parameters of the model were calibrated to fit the observed daily flow data from DID flow gauging stations (Figure 4(a)) for this large watershed in 2010. Three different gauging stations were selected for calibration and validation, that is, one upstream (Figure 4(a), green triangle) and two in the middle (Figure 4(a), red and blue triangles) of the Kota Tinggi watershed. The storm event between 23 November and 4 December 2010 was used to calibrate the model (Figure 5). It is important to notice that the calculated magnitude and timing of the flood discharge over this period matched the field measurements very well. The calibrated model was then applied to several other rainfall events for validation purposes without any change to the calibrated parameters (K_h and n). The storm event of 7–17 May 2010 was used for the model validation. The comparison between observed and simulated discharge hydrographs for this event is presented in Figure 6.

To evaluate the overall model performance, the Nash–Sutcliffe efficiency coefficient (NSEC) and percent BIAS (PBIAS) parameters were used. The ability of the NSEC parameter to evaluate the difference between observed and simulated hourly discharge predictions gives a detailed evaluation of the model performance in replicating the selected storm events.

The value of NSEC can be between ∞ and 1.0, with NSEC = 1.0 being the optimal value. Generally, NSEC

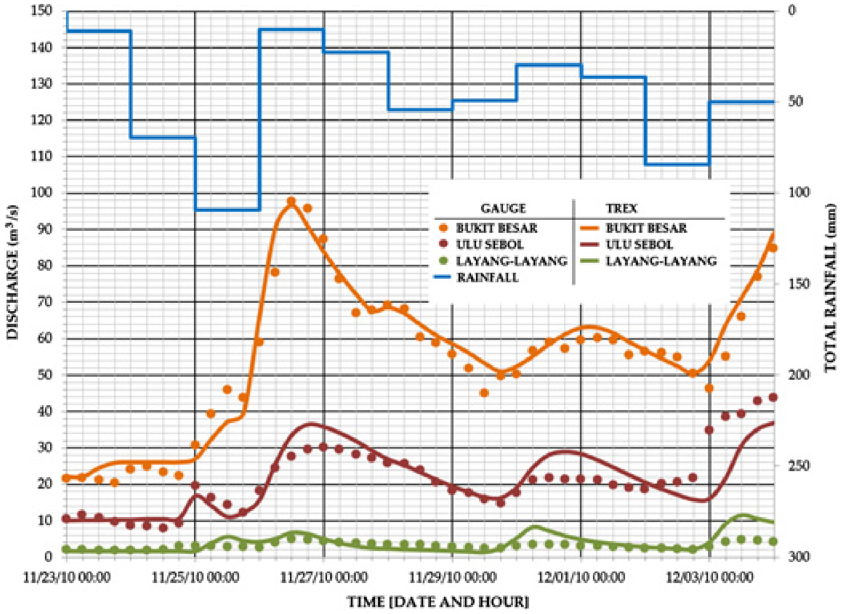

Figure 5 Hydrologic calibrations parameters at Kota Tinggi watershed on 23 November to 3 December 2010.

values ranging between 0.0 and 1.0 are acceptable levels of performance, while values less than 0.0 indicate unacceptable performance. PBIAS measures the tendency of the simulated data (i.e. volume in cubic metre) to be larger or smaller than the observed data (Gupta *et al.*, 1999). Positive and negative values indicate a model underestimated and overestimated, respectively. The optimal value of PBIAS is 0.0. The relative percent different (RPD) method was also used to evaluate the total volume, peak discharge and time to peak by comparing observed and simulated results.

Table 3 shows the TREX model performance using RPD, NSEC and PBIAS methods. The classification of the model

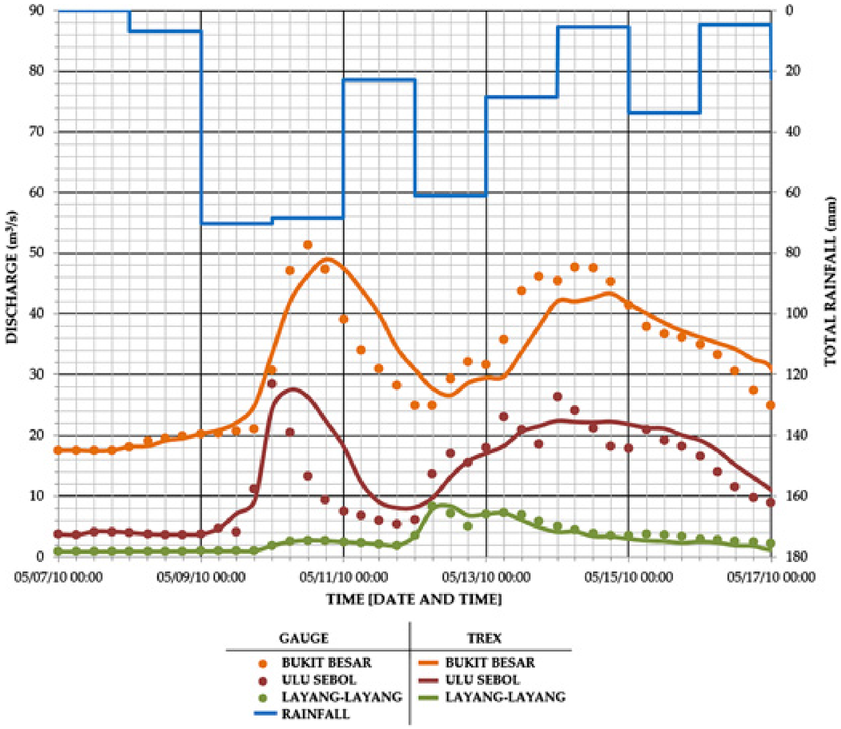

Figure 6 Hydrologic validations parameters at Kota Tinggi watershed on 7–17 May 2010.

Table 3 Summary of the evaluation of hydrological model performance at the Kota Tinggi watershed

Calibration

		Total volume ($\times$1000 m^3)			Peak flow (m^3/s)			Time to peak (24 h)			Performance	
Streamflow gauge	Event	Obs.	Sim.	RPD (%)	Obs.	Sim.	RPD (%)	Obs.	Sim.	RPD (%)	NSEC	PBIAS (%)
Layang-Layang	23 November to 4 December 2010	2948	2945	−0.1	5.14	5.73	11.5	12:00	12:00	0.0	0.80	0.09
Ulu Sebol		20 179	19 954	−1.1	30.18	35.82	18.7	00:00	18:00	25.0	0.60	1.11
Bukit Besar		51 411	52 900	2.9	97.68	96.67	−1.0	12:00	12:00	0.0	0.95	−2.89
Validation												
Layang-Layang	7 May to 17 May 2010	2798	2634	−5.9	8.34	7.94	−4.8	06:00	06:00	0.0	0.90	5.87
Ulu Sebol		11 602	13 010	12.1	28.56	27.56	−3.5	00:00	06:00	25.0	0.88	−12.14
Bukit Besar		29 473	298 806	1.2	51.36	48.96	−4.7	12:00	18:00	25.0	0.97	−1.16

Obs., observed; Sim., simulated; RPD, relative percentage different; NSEC, Nash–Sutcliffe efficiency coefficient; PBIAS, percent BIAS.

performance described by Moriasi *et al.* (2007) was used. The agreement between observed and simulated total volume and peak flow was 'very good'. This was supported by the calculated RPD values for the total volume and peak discharge where these values were underestimated by about 1.5% and overestimated by about 2.7%, respectively. The model was classified as 'good' in estimating the time to peak, with an average RPD value of about 9.3% (about 3 h delay on average). From the calibration/validation procedures, we concluded that TREX is able to simulate the flood flow in Kota Tinggi watershed.

The explicit Euler method (Chapra and Canale, 1985) was used to compute the mass balances for each time step by counting all materials that enter, accumulate within or leave a grid cell through precipitation excess, interception, infiltration, transmission losses and storage. The finite difference approach, when employed in the TREX model, will remain stable when the suitable time step used in the simulation. Hourly rainfall data at Ulu Sebol, Layang-layang and Bukit Besar were used in these simulations. One of the advantages of the model is that it has the ability to reduce time steps automatically when the simulation is unstable. Simulation started with the recorded time step. The time step used in this study is between 0.5 and 20 s. The lowest time step was used when there was high-wave celerity (i.e. during flood simulations in 2006 and 2007), as suggested by the Courant–Friedrichs–Lewy condition.

Figure 7 shows a detailed water depth distribution on the Kota Tinggi watershed from the TREX model at the time when the water reached the alert level. The stage continued to increase and easily passed the alert and danger levels as a result of the continuous rainfall. Figure 8 shows the TREX model results in terms of the flooding areas on the Kota Tinggi watershed on 21 December 2006. This location was totally inundated with water (as shown in the red circle) after it passed the alert level (Figure 6). The maximum

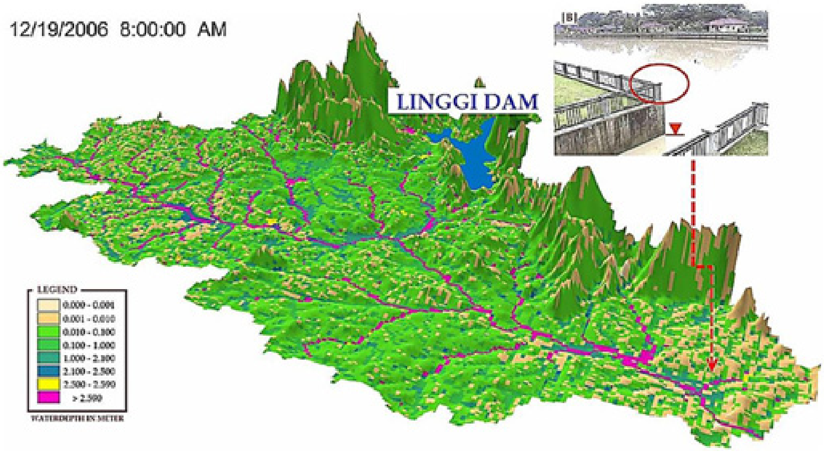

Figure 7 Three-dimensional representation of the water depths at Kota Tinggi watershed on 19 December 2006 (adapted from Abdullah, 2013).

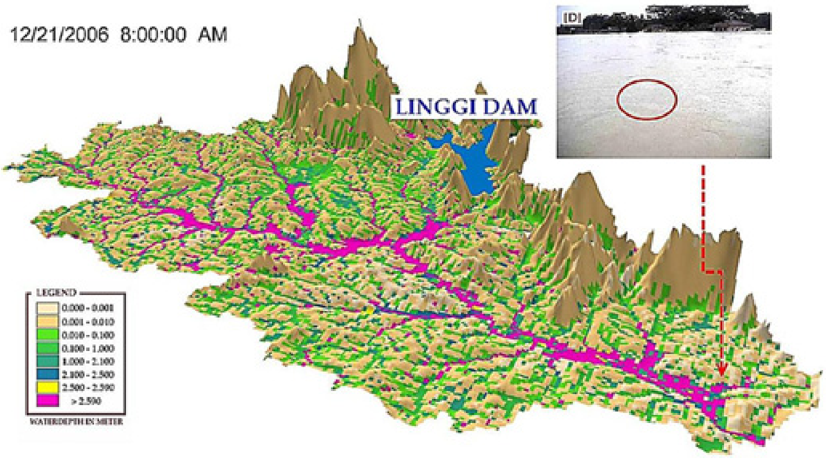

Figure 8 Three-dimensional representation of the water depths at Kota Tinggi watershed on 21 December 2006 (adapted from Abdullah, 2013).

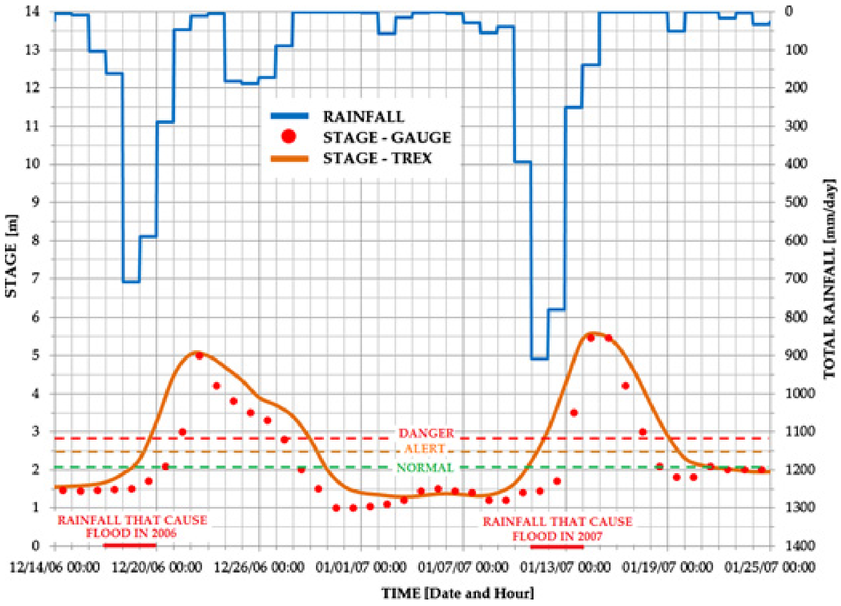

Figure 9 Comparison of stage between gauge and TREX model for flood in 2006 and 2007.

stage was reached on 22 December 2006, that is, 2 days after the rainfall stopped.

The TREX model was able to simulate the hydrological conditions of the study area with reasonable accuracy, as shown in Figure 9.

The validation process was performed using stage data from 14 December 2006 to 25 January 2007. The comparison between observed and simulated stage for these events is presented in Figure 9. The validated model shows that the multiday rainfall event in December 2006 passed the normal level after 2 days.

The stage increased more rapidly during the second event in January 2007. The increase to the alert and danger level was after 1 day of rainfall. This condition is driven by the high intensity of rainfall for 2 consecutive days. The maximum stage was reached on the fourth day of the multiday rainfall event. It took 6 days for the stage to return to the normal level.

The difference between the observed and simulated maximum stage was used for the two floods in 2006 and 2007 instead of discharge and volume in storm events of 23 November to 4 December 2010 and 7–17 May 2010 (Table 4). This is because the flow gauge has been washed out during the 2006–2007 flood events (Shafie, 2009). The RPD value indicated that the model performance is 'very good' in estimating the maximum stage and time to peak.

Table 4 Summary of the simulated results for Kota Tinggi flood in December 2006 and January 2007

	Maximum stage (m)			Time to become maximum stage (24 h)			Model's performance	
	Observed	Simulated	RPD	Observed	Simulated	RPD	NSEC	PBIAS
Flood in December 2006	5.0	5.0	0.0	12:00	12:00	0.0	0.5	–
Flood in January 2007	5.45	5.57	2.2	12:00	12:00	0.0	0.7	–

RPD, relative percentage different; NSEC, Nash–Sutcliffe efficiency coefficient; PBIAS, percent BIAS.

The NSEC and PBIAS methods were also used to define the performance of the TREX model for both peak discharge and total volume, respectively. Both methods indicated that the model gave very good estimates of the peak discharge and total volume, with an average overestimation of about 0.8% and 1.5%, respectively. The hydrological modelling results presented here give physical representation of the flooding at Kota Tinggi. The results further prove that the multiday rainfall events are the main cause of severe flooding in the area.

Simulation of daily rainfall sequences

The DARMA(1,1) model performs well in modelling the sequences of multiday rainfall events (Muhammad, 2013). There are three parameters that need to be estimated, namely λ, β and π_1(or π_0). The estimated values are 0.8445, 0.5446 and 0.5314 (0.4686) for λ, β and $\hat{\pi}_1(\hat{\pi}_0)$, respectively.

As discussed earlier, multiday rainfall events are the main cause of flooding in the area. Therefore, rainfall data from four rainfall gauging stations were analysed, namely Layang-Layang, Ulu Sebol, Bukit Besar and Kota Tinggi. We found that the rainfall distributions at these stations are best represented using two-parameter gamma distribution. In order to simplify the analysis, a general two-parameter gamma distribution function with scale parameter α = 24 and shape parameter β = 0.6 t was proposed to represent the rainfall at this study area. The mean, scale and shape parameters for all stations and the general equation are summarised in Table 5. Figure 10 gives the plot of cumulative density function (CDF) of the rainfall at these stations and the general equation.

Therefore, the univariate probability distribution function of rainfall amount and duration, $f(x|t)$ is represented as

$$f(x|t) = \frac{1}{24.0\Gamma(0.6t)}\left(\frac{x}{24.0}\right)^{0.6t-1}\exp\left(-\frac{x}{24.0}\right) \tag{21}$$

The probability distribution function of wet run lengths $f(t)$ is estimated using the formulations from DARMA(1,1), as shown in Eqn (22). More details can be seen in Jacobs and Lewis (1977, 1978a, 1978b, 1983)

Table 5 Mean, scale and shape parameters of gamma distribution for all stations

Location	Mean (mm)	Scale parameter, α	Shape parameter, β
KotaTinggi	14	0.5	29
Layang-Layang	17	0.5	34
Bukit Besar	12	0.5	27
Ulu Sebol	16	0.7	25
General equation	13	0.6	24

$$\begin{aligned} f(t) = P(T_1 = t) = P(&X_0 = 0, X_1 = 1, \ldots, \\ &X_t = 1, X_{t+1} = 0 | X_0 = 0, X_1 = 1);\quad t = 1, 2, \ldots \end{aligned}$$

$$P(T_1 = n) = \frac{P(X_0 = 0, X_1 = 1, \ldots, X_t = 1, X_{t+1} = 0)}{P(X_0 = 0, X_1 = 1)} \tag{22}$$

The combination of DARMA/gamma model was used in simulating long sequences of daily rainfall at Kota Tinggi. A hundred samples, with the duration of 2000 years, were generated in order to examine and estimate the return period of extreme events in Kota Tinggi. The analyses and results for return period estimation are given in the following section.

Return period estimation

The hydrological simulations using TREX clearly demonstrate that the multiday rainfall events caused extreme floods in the Kota Tinggi watershed. To describe the severity of these events, this section detailed the estimation of the return period.

The theoretical formulations by Muhammad (2013) were used to estimate the return periods for the cumulative rainfall that occured in December 2006 and January 2007, as shown in Eqns (19)–(22). However, we show the estimated return periods for the December 2006 rainstorm only (refer to Table 6). The estimated return periods for the January 2007 rainstorms are available in Muhammad (2013).

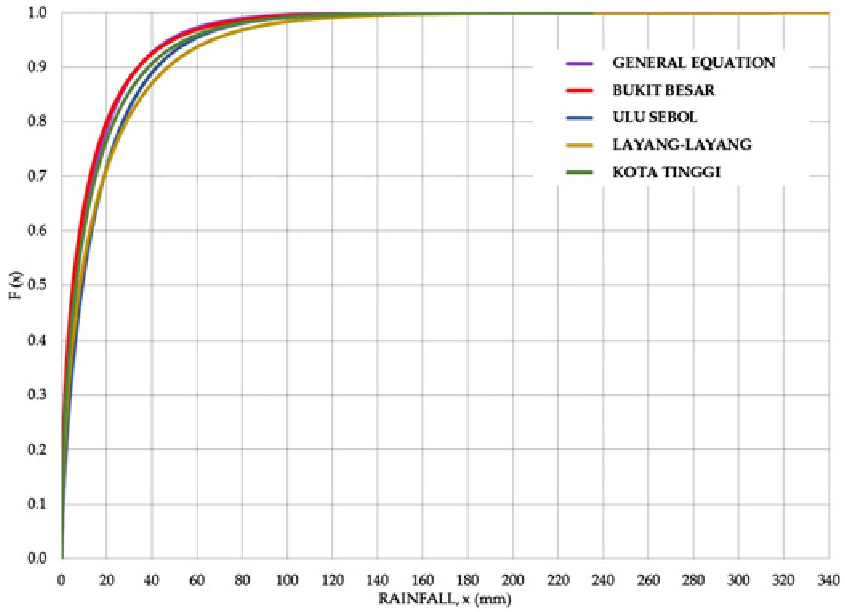

Figure 10 CDF of rainfall amount at the study area.

The highest rainfall on the first day was measured at the Layang-Layang station, with 66 mm. This rainfall amount corresponds to the return period of 2 years. Other stations recorded lesser rainfall amounts, and the return periods estimated for these measurements are less than 1 year. Successively, the observed rainfall amounts for the second (18 December), third (19 December) and fourth (20 December) of the multiday rainstorm events are much more significant as compared to the first day. Layang-Layang recorded the most rainfall with the estimated return period of 8 years, followed by Kota Tinggi (3 years), Bukit Besar (1.5 years) and Ulu Sebol (0.7 years). These values continue to increase on the third and fourth day. Most of the stations recorded the rainfall amount with return period of more than 1000 years. Bukit Besar station received 276 mm on the third day, which corresponds to 2750 years of return period. On 20th December, 2006, the Kota Tinggi watershed received between 291 and 347 mm of cumulative rainfall. The return periods measured from these stations are greater than 2000 years.

Return period estimations for flood threshold

In this section, we demonstrate the potential application of the results obtained from flood flow simulations using TREX and the return period estimation of multiday rainfall events using the simple algorithm proposed by Muhammad (2013). This method is proposed in order to determine the flood thresholds with the duration of up to four consecutive-day rainstorm events and also to give an idea of

Table 6 Estimation of return periods for the December 2006 rainstorm event

December 2006				
Date	17 December	18 December	19 December	20 December
Station: Layang-Layang				
Cumulative rainfall (mm)	66	118	274	347
Return period (years)	2	8	2534	20 575
Station: Ulu Sebol				
Cumulative rainfall (mm)	33	56	245	323
Return period (years)	0.3	0.7	778	7910
Station: Bukit Besar				
Cumulative rainfall (mm)	29	76	276	345
Return period (years)	0.3	1.5	2750	19 013
Station: Kota Tinggi				
Cumulative rainfall (mm)	48	91	252	291
Return period (years)	0.7	3	1036	2247

Table 7 Rainfall duration, flood threshold and the respective return period

Rainfall duration (t-consecutive days)	Flood threshold (mm)	Return period (years)	
		Upper values	Lower values
1	Between 140 and 170	220	54
2		83	23
3		42	13
4		24	7

the severity of the event. Also, these simulations were conducted in order to determine the total rainfall amount that would overtop the levee at Kota Tinggi. We hope that the flood threshold and return period may give some idea to the authorities and civil engineers in deciding the best flood protection method at a large watershed like Kota Tinggi.

A range of values for flood threshold was given, taking into account the hydrological model uncertainty. Eqns (19)–(22) were used to estimate the return periods corresponding to the flood thresholds. Table 7 provides the summary of the return periods of each rainfall duration, while Figure 11 illustrates the relationship between the estimated flood thresholds, return periods and flood thresholds.

For a 1-day rainfall event, the return period was estimated to be 220 years in order to achieve the flood threshold. However, the return period decreased to 83 years for 2 consecutive days of rainfall. It is interesting to note that

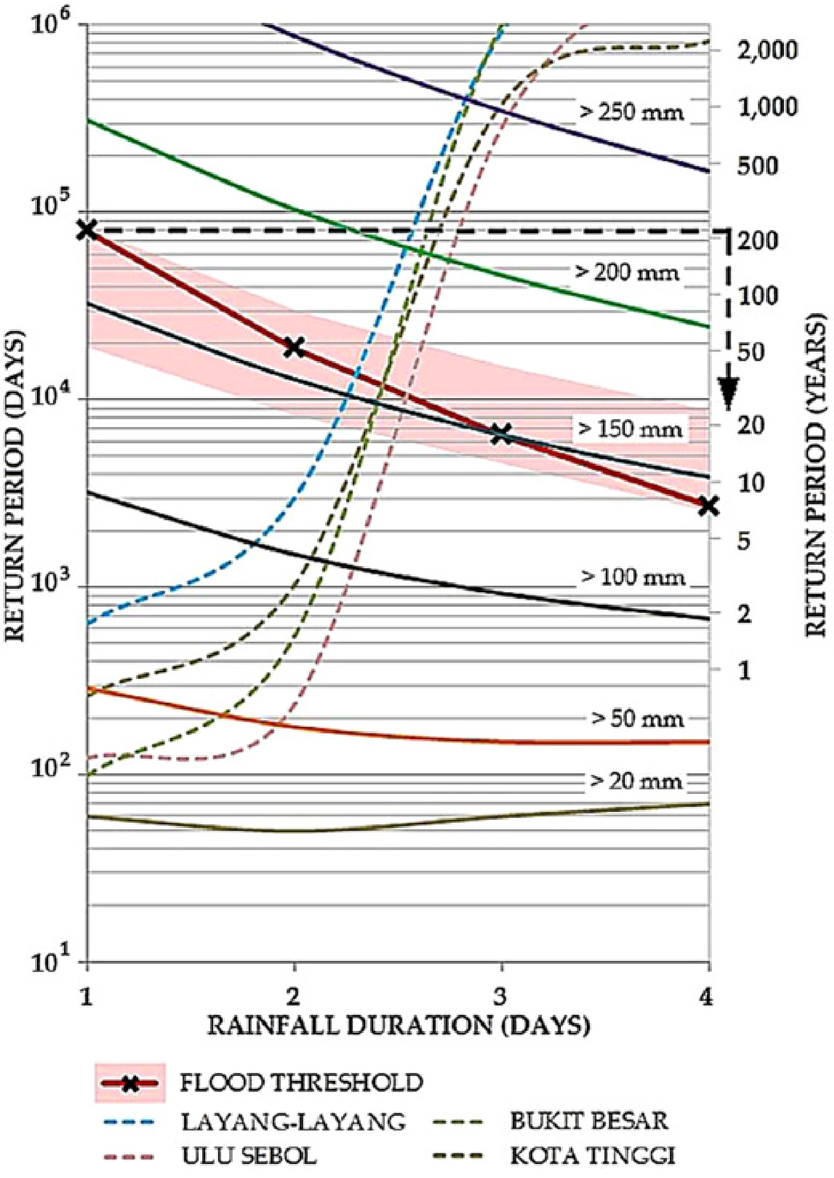

Figure 11 Rainfall durations versus return periods for the December 2006 rainstorms.

the return period for 2 consecutive days is significantly lower than the 1-day event because the probability of receiving 170 mm of rainfall in 2 days is much higher than a single day. For the same reason, it can be observed from Table 6 that the return periods for 3 and 4 consecutive rainy days are lower than the 2-day event at 42 and 24 years, respectively. Overall, the return period estimated for the multiday rainfall is significantly lower than a single-day event. For example, the return period to reach the flood threshold in 1 day is 220 years, while the return period for 4 consecutive rainy days is only 24 years. These results also concluded that flooding as a result of the multiday rainfall events are most likely to occur more frequently than a single rainy day.

Conclusion

The TREX model has successfully simulated the Kota Tinggi flood events that occurred in December 2006 and January 2007. The simulated flood stages were within 10 cm of the field measurement. Multiday rainfall, resulting in a significant amount of accumulative rainfall is identified as the main cause of flooding for both events. The method proposed by Muhammad (2013) is useful in determining the return period for multiday monsoon rainstorms. The estimated return period for the December 2006 rainstorm is greater than 2000 years and considered extremely rare. Multiday rainstorms can cause tremendous damage on large watersheds. This paper also produced a flood threshold graph by integrating both the hydrological modelling process using TREX and the theoretical formulation of the return period. The proposed flood threshold graph is useful in the estimation of the amount of accumulated rainfall from multiday rainfall that can cause flooding on a large watershed like Kota Tinggi. More specifically, floods on the Kota Tinggi watershed are found to occur when the amount of rainfall precipitation is approximately 150 mm. As shown in Table 7, this precipitation amount corresponds to periods of return around 50–225 years when the rain falls in 1 day. However, one of the most important findings of this article is that flooding at the same level will occur at a period of return between 7 and 25 years when this rainfall amount occurs in 4 days. This study of the Kota Tinggi flood highlights one of the peculiar features of monsoon precipitation on large watersheds.

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