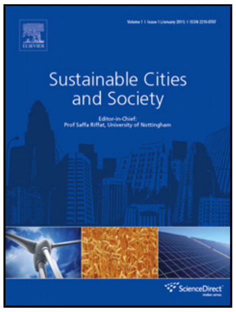

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Urban flash flood index based on historical rainfall events

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Highlights

- Calculation of urban flash flood index using readily available historical data
- Determination of flood susceptibility, vulnerability, impact on socio-economy
- Based on total rainfall depth, rainfall duration, flood depth and land use
- Developed procedure is validated by the flood numerical modelling
- Colour coded GIS-based mapping to identify the flood critical areas within a catchment

Abstract

Urban flash flood poses significant hazards on urbanised area, in particular to buildings and infrastructure due to its fast occurrence and high magnitude in financial loss. Risk assessment of the flash flood identify the critically flood-prone areas and provide assistance in improving the resiliency of mitigation plans. In this study, we developed an assessment of flood susceptibility, vulnerability, the impact of socio-economic, and integrated flash flood index based on the historical data of flood events recorded in Kuala Lumpur. Data of rainfall characteristics, inundated location, and areas are extracted from the reports of flood events from the year 2005-2015. Each event is then segregated according to the place of incidence, providing point-based recurrence of flood at each identified location. Indicators of assessment include frequency and month of occurrence, rainfall characteristics (of intensity, duration, and depth), and land use categories. A total of 137 (point) locations have been identified, where each location is colour-coded based on a 5-point rating scale. The point-based flood-prone locations are validated with the watershed based of 50-ARI rainfall modelling, providing comprehensive hotspot maps. Developed interactive colour-coded flood prone maps facilitate relevant agencies for improved coordination in flash flood mitigation, response and early warning.

Keywords: urban flash flood; flood vulnerability; flood susceptibility; integrated index; hydrological modelling.

1. Introduction

Urban flooding occurs when the capacity of both natural and drainage systems could not cater to the volume of precipitation and runoff discharge within an urbanised area. High surface runoff discharge from heavy rainfall due to impervious surfaces and high building densities escalate the urban flooding (Gaitan et al., 2016; Yao et al., 2016). Although urban flooding is commonly associated with the short duration-high intensity precipitation, such flooding also has been recorded due to prolonged moderate rainfall (Coulthard et al., 2007; Abdullah and Julien, 2014a; Abdullah et al., 2018).

Flash flood is defined as the flood events resulted from high precipitation in short duration, usually less than 6 hours (Suparta et al., 2014). Localised convective storms in a small catchment within short time results in fast-rising of water level, usually with no advance or little time of warning. As such, the flood occurrence in the urbanised area due to insufficient drainage capacity from short duration-high intensity rainfall-induced the urban flash flooding (UFF). Considering the short duration of rainfall, the limb of the hydrograph rose fast to the peak flow whereby the UFF can even be visible just only after 30 minutes of rainfall. The non-alerted and unpredicted flood events caused devastating impacts to the road infrastructures, particularly at the low-lying areas (Doocy et al., 2013). Risk assessment of UFF on the intra-urban transportation network by evaluating the impact of flood depth (obtained through the 2D hydrodynamic modelling) and traffic or probability analysis provide a quantitative impact of UFF (Yin et al., 2016; Li et al., 2018).

Due to the increasing occurrence, the unpredictability of climate and associated devastating impacts, risk assessment identification and urban flood management have received attention (Ogden et al., 2011; Wu et al., 2012). Urban flood prediction is technically possible based on the integrated methods of forecasting the extreme rainfall and its associated susceptible areas, of which able to provide longer warning time to solicit appropriate coordination by the responding organisations (Falconer et al., 2009). Challenges in estimating the flash flood lie in the availability of prediction modelling in providing an accurate estimation of the short time scale of rainfall and limited gauged watershed whereby scarce or no information of measured discharge is available.

The severity of flash flood-induced impacts is assessed based on the indicators and indices. Exhaustive research has looked into the development of flash flood index based on the hydrological characteristics, including flashiness, peak flow, and land use types (Kim et al., 2008). Incorporating with the existing framework of flash flood index, impacts of UFF are assessed based on a detailed, microscale urbanised area. Recent work determined the flash flood index based on the spatial characteristics through the implementation of GIS (Li et al., 2018). Hydrodynamic models (with varying return periods) provide the spatiotemporal flood depth and area, whereby the impact assessment is made based on the simulated inundation level. Important modelling parameters are commonly the hydrological (rainfall-runoff hydrograph), and spatial land use and geological characteristics. However, exhaustive data mining is anticipated for a bigger scale of assessment, in particular for larger metropolitan cities whereby access to the data might be restricted. Identification of urban flooding thresholds (as the bases to set up an early warning system) was successful even without hydrodynamic models (Bouwens et al., 2018).

The assessment of flood prone areas is crucial and one of the major aspects in creating flash flood resilient cities. Impacts of flash flood varied and can be devastating either through direct (infrastructure repair), indirect (traffic delays), secondary (adverse impacts on people who depend on output produced by damaged property or services) and intangible effects (environmental quality) (Petersen, 2001). An accurate evaluation of both extent and severity of each flood event and associated impacts is crucial to provide an objectified consequences analysis based on the economic, society and environment, whereby the identification of exact critical areas is even more important. Besides engineering approach, community participation is of paramount importance, where population residing in the flood prone areas is the key elements in creating flash flood resilient society. The cooperative and concerted efforts within the community and the integration with appropriate structural measures is the way forward in an efficient flood management (Loggia et al., 2012).

District and urban scale based risk assessment on Kuala Lumpur showed that the city centre has the highest probability of flash flood (Nasiri et al., 2019). Here, we attempt to develop a methodology to assess the susceptibility and vulnerability of urban flash floods based on the historical data of flood events. Additionally, we verify the results using a two-dimensional physically-based distributed model. The simulation results and the detailed historical-based locations are presented in the form of maps, to indicate the problematic areas, which are most susceptible to urban flash floods.

2 Methodology

2.1 Study Area

Kuala Lumpur is situated at the middle western stretch of Peninsular Malaysia, as shown in Figure 1. The Malaysian climate is influenced by two dominant monsoon seasons, i.e., the North-East Monsoon (NEM) during November to February and South-West Monsoon (SWM) between May and August. NEM brings more substantial rainfall and is commonly responsible for the flood events at the eastern and southern regions. The SWM and inter-monsoon seasons of March-April and September-October have intense convective precipitation in the West Coast of Peninsular Malaysia (Syafrina et al., 2015). The heavily urbanised capital of Malaysia covers an area of 243 km2 and is bordered by the Titiwangsa Mountains in the east, ranges on both north and south parts with the Strait of Malacca in the west. The wider flat land was allowing a much booming economic development and population growth with an estimated population density of 6,696 inhabitants per square kilometer. The city lies in the middle of the Klang River basin, one of the major river basins in Malaysia with a watershed of 1,288 km^2. Kuala Lumpur experienced a tropical rainforest climate with the temperature between 32 to 35^{o}C. The city received an average annual rainfall of 2,600 mm and is prone to flood, particularly flash flood. Kuala Lumpur has witnessed changes of land use and land cover since the 1980s as a result of globalising phase, not only within the capital city but also extended to the Greater Kuala Lumpur (Bunnell and Nah, 2004).

Batu, Gombak, Ampang, and the upper Klang Rivers are the tributaries to the main stem of Klang River in the upper catchment of Kuala Lumpur. The confluence of Batu and Gombak (at the North-West) flows and meet the upper Klang River (from North-East) at the famous Jamek Mosque whereby the downstream of this point is known as Klang River. The contribution of flow from the Gombak River catchment is higher than the upper Klang River catchment (DID, 2019b). Being close to or on the floodplain, Kuala Lumpur is no stranger to flooding events, with the earliest recorded event, occurred in the year 1926 (Abdullah et. al., 2019), although it cannot be ascertained with confidence (due to limitation of data) whether this flood event is a pluvial or fluvial induced. The worst flood in KL was in the year 1971, whereby the monsoonal flood lasted for five days and caused massive damages to the infrastructure, properties, agricultural land. The flood level increased up to 2 meters, causing estimated damage worth RM36 million within the region. Annual flash floods were recorded since the big 1971 flood, with recorded events can go up to 58 episodes in a year (Jamaluddin, 1985). Although numerous Flood Mitigation Plan has been proposed, designed and constructed to minimise flood impact on the city area, the Plan mostly prioritized the fluvial based flood and yet to give focus on the pluvial type of flood. The mega project of 9.7 km long Stormwater Management and Road Tunnel (SMART), built in the year 2007 diverted the flow from the upper segment of River Klang through River Kerayong and significantly reduced fluvial-induced flash flood events (Samsuri et al., 2018).

The increasing hazard due to the flash flood in Kuala Lumpur is not only due to the urbanised-area induced high surface runoff but also caused by the poorly maintained and designed drainages

(Mohd Nasir and Othman, 2015; Samsuri et al., 2018). Despite continuous efforts from the authority to minimise the probability of flash flood occurrence, regular frequency of flood events are still observed. The increasing incidence of flash flood occurrences is due to the increasing numbers in very wet and extremely wet hours within the western stretch of Peninsular Malaysia, including Kuala Lumpur (Syafrina et al., 2015). Recent flash flood events occurred on 11 November 2018 where two hours of heavy precipitation crippled most of the main roads and inundated the commercial areas in Kuala Lumpur. Despite booming development and advanced design of the drainage system, due to the frequent short duration and high intensity of precipitation, Kuala Lumpur is nonetheless vulnerable to flash flooding.

2.2 Extraction of data from the flood reports

An inventory of the regional flash flood reports is available at the Department of Irrigation and Drainage (DID). The department is responsible to record relevant data including flood area, rainfall characteristics and publish the report including pictures of the affected area, whenever available. The details of each event depend on the recording procedure and data availability, whereby the format and data presentation of available reports may differ from one to another. We acknowledge that there could be flood events, which are either not recorded (due to insufficient data) or the reports were not available.

Flood reports prepared by the DID from the year 2003 to 2015 were intensively scrutinised to identify essential parameters including rainfall intensity, the month of occurrence, duration, flood depth and area (if available) and causes of the flood. A total of 76 flash flood events were identified. The reports not only recorded the flood characteristics of the event but also listed the specific multi flood locations or areas. Thus, the report was then further audited to list the associated flooded areas (for that particular event) along with its flood characteristics. The compiled data is then segregated based on the name of the flooded area/location to assist on further analysis. We noticed that the flooded locations do not necessarily report as an area, district, or famous landmark, but also can be as a road specific. Rigorous and repetitive procedures were conducted, producing a total of 137 locations with flash flood records.

2.2 Flood Susceptibility

The categorical area-based event allowed for the frequency of flash flood occurrence for each area/location to be obtained. The frequency of flood events was then calculated as the total number of flood recurrence in the same area/location. Flood susceptibility is determined as the frequency of occurrence within the ten years period, whereby each area/location is then categorised as presented in Table 1. The colour-coded susceptibility for each area/location provides a comprehensive overview of the flood-prone zones or points within the Kuala Lumpur City Centre.

2.3 Flood Vulnerability Index (FVI)

Available data on the flood reports permit parameters of the month of occurrence, rainfall intensity, and rainfall duration as indicators to be incorporated in the FVI. Based on the 12-year data, the frequency of FF occurrence is shown in Figure 3. Out of the 76 identified events, the month with the highest events was April, followed closely by May with 12 and 11 events, respectively. Short temporal rainfall during inter-monsoon season, where convective rain brings higher intensity rains contributing to the high frequency of flash flood events, particularly in April (Syafrina et al., 2015).

The months with the lowest frequency of UFF are January and July, both are at the end of NEM and SWM monsoons, respectively. Data shows an interesting trend where notable high frequency of flash flood events during NEM, in particular during November and December.

Based on the frequency, each month is given a Likert Scale score based on the month-specific weight w, calculated as

$$w_j = f_j / F, \qquad \text{and } j = \text{Jan, Feb, Mar, Apr, ……, Dec.}$$

where f_j denotes the frequency and $F$is the total frequency of flood events, which is 76. Based on the calculated w, the 5-point Likert scale, as tabulated in Table 2 is based on the systematic interval at $0.2w$.

The score based on month M is determined for each UFF event. As an example, if the month is April, M= 5. Next is the determination of score based on rainfall duration R using the definition described in Table 3. The classification of 5-point Likert scale associated with rainfall duration is established at an interval of one hour. The determination of the interval is based on the averaged daily rainfall, whereby in Malaysia is 13 mm (Muhammad et al., 2015). Considering this, we opted twice of the average value as the interval of the total rainfall depth (which is rounded up) as 25. As such, in this study, the total rainfall depth score D is defined based on the interval of 25 mm. Furthermore, the values are well within the rainfall intensity (mm/hr) based classification of storm, described as light, moderate, heavy and very heavy with values of 1-10, 11-30, 31-60, and > 60 mm/hr, respectively (DID, 2019a).

The FVI index is calculated based on the rainfall characteristics, as additive function of three components presented as

$$\frac{FV\mathrm{I} = M + R + D}{3},$$

giving a similar 5-point score. The FVI score was calculated and colour coded based on the definition described in Table 4 for each recorded FF event.

2.4 Socio-economic impact (SI)

One of the well-established and commonly used approach in estimating the flood-induced loss in an urban area is based on flood-depth damage relationship (Appelbaum 1985; Penning-Rowsell and Fordham 1994). Important parameters in the assessment of damage include the topography, economic characteristics, land use, and stormwater design, whereby the evaluation varied between one city to another (Oliveri and Santoro, 2000; Pistrika et al., 2014). In this study, the score was assigned according to the procedures and guideline stipulated in DID (2003).

The impact on socio-economic is determined based on the five categories of flood depth. The low flood depth is defined as less than 0.3 m, where the following categories are a systematically increased of 0.3 m, here shown in Table 3. Considering Kuala Lumpur is an urban area, the land use is then classified as residential, commercial, transportation, and tourist place. The definition of land use is as per described in Table 4. Areas with a high turnaround of tourist were also included as the total tourist arrival hit up to 25.9 million in the year 2017 (MoTAC, 2018). Kuala Lumpur boasts several tourist hotspots and as such, warrants inclusion in the analysis.

Although a complete SI should include both tangible and intangible impacts, the linkages to indefinite consequences such as mental health, diseases, and cascading effect of one system to another are difficult to be quantified (Hammond et al., 2013). Utilising abundant literature on direct tangible flood impacts on residential, commercial and industrial properties, the SI score is only based on the monetary readily quantifiable.

The categorical hazard for residential property is modified from the definition given in FHRC, 2010 (as cited in Alexander, 2011). The categorical hazard based on the water level-velocity is well established, particularly for extreme events such as fluvial, coastal, storm, typhoons and tsunami-induced flood events (Jonkman et al., 2008; Priest et al., 2007). Although the water rapidly rises during UFF, the generally shallow water levels and considerably low flow velocity significant reduces the risk of losing a life. Furthermore, as most of the entrance to the house is built 10 cm above the porch level, the water inundation is possible to be impeded and is expected to cause minimum financial loss. For commercialised area, the score is slightly higher for low flood depth (< 0.3 m) considering potential basement flood, which increases both building damages and loss in supplies (Rozer et al., 2016). High possibility of business interruption due to flood additionally contributes to the loss of damage.

Where flood event occurs on road infrastructure, a starting score of 3 is given to the low flood depth. At this level, a car still can move at slow speed. However, slow-moving traffic is expected at urban area due to high car volume, whereby the massive traffic is highly likely should the UFF occurred during peak hours. A score of 5 is given for an increased flood depth to 0.3 m due to not only motorcycles, but cars are also no longer able to move at such water height, causing a complete standstill. At low-lying areas, in particular, submergence of a car caused a total loss to the owner. Not restricted to physical losses, the delay in urban traffic consequential caused to intra-urban road congestion, increasing the time of travelling.

Buildings with tourist hotspot label are prioritised, in particular for historical monuments. Not only had it caused tangible impacts due to repair and rehabilitation costs, the intangible implications of loss in value naturally increased the SI score (compared to residential areas).

The hazard level is given as 5 for all land use types when the water level reaches more than 0.9 m. At this height, it is considered as dangerous for people and would immediately prompted significant socio-economic impacts. The level of impact is presented into five categories as very low, low, moderate, high and very high.

2.5 Flash Flood Index (FFI)

The total FFI is determined based on additive multi-attribute function as

$$\mathrm{FFI} = (FS + FV\mathrm{I} + \mathrm{SI})/3.$$

where FS, FVI and SI denote the susceptibility, vulnerability and associated socio-economic impacts, respectively. The level of hazard based on the developed FFI is described according to five categories as very low, low, moderate, high and very high.

2.6 TREX modelling

This study includes verification of the proposed flood index method with 2-dimensional hydrological-hydraulic modelling using a numerical model known as TREX (Two-Dimensional Runoff Erosion and Export), developed by researchers at Colorado State University, USA. 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). TREX has three main components, which are hydrology, sediment transport, and chemical transport and fate. The hydrological processes simulated are rainfall (e.g. Abdullah et al., 2014; Abdullah and Julien, 2014; Abdullah et al., 2018; Abdullah et al., 2019) and snowfall, interception, snowmelt (Kang, 2005), and surface storage, infiltration and transmission loss and overland and channel flow. Rainfall data were set as uniform in both time and space (e.g., Jorgeson 1999) for the whole basin. Infiltration and transmission loss rates are simulated using the Green and Ampt (1911). 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 4.

Model parametrisation

The input data for TREX model were prepared using ArcGIS10.4 and converted into a text file. The topography of the basin area is divided into a grid size of 230 x 230 m. Digital Elevation Model (DEM) provided by the Department of Survey and Mapping Malaysia (JUPEM) was used in this study. The latest type and land use information for the Sungai Klang basin area is also required and this data can be obtained from the Department of Agriculture (DOA) Malaysia.

The models used need to go through the calibration process and all perimeter are listed in Table 6. Sensitivity analysis shows that hydraulic conductivity, K_h and Manning roughness n are the most sensitive parameters during calibration proces (Abdullah and Julien, 2014). In this process, these values were adjusted to achieve at leat satisfactory value when comparisons were made between observed and simulated data. Due to the simulation being carried out for extreme rain events, interception and evaporation rate are neglected. This will not affect the results (Abdullah et al., 2018; Abdullah et al., 2019).

2.7 GIS Mapping

The coordinate (latitude and longitude) for each area/location with their associated categorical flood susceptibility, FVI, socio-economic impact, and FFI were organised for GIS mapping. Mapping of flood area is completed using ArcGIS 10.5 software. A total of 137 locations of flood events was mapped to identify the rainfall distribution by referring to the WGS 84 coordinate system. Each location is mapped and confirmed by reference to several other sources such as google earth and annual flood reports issued by DID and local governments. Identified flood locations are mapped on the 2016 land use data (as background), which includes various land use classes i.e., Commercial, Industry, Infrastructure & Utilities, Institution & Facilities, Open Space & Recreation, Residential, School, Transportation and Water Bodies. All flood data has been overlaid with river and land use data using the technique of multi overlay features.

3 Results and Discussion

3.1 Observed Storm Events

The minimum and maximum cumulative rainfall depths were 36 and 171 mm, respectively obtained for 2-hour rainfall events. Based on the data, Kuala Lumpur experienced multiple episodes of short duration and high rainfall intensities induced flash floods. Out of the identified events, half of the incidents (about 51%) recorded the cumulative rainfall depth between 50 to 100 mm. About 33% of the episodes were due to between 100 to 150 mm rainfall, and 2% falls during extreme precipitation with more than 150 mm of cumulative rainfall depth.

The flood depth varied between 0.1 to 2 m, and the flood subsided within to 2-6 hours. Majority of the flooded areas are localised, spanning about 0.01 to 0.5km^2, with one event reported an inundation area of 1.5km^2. Commonly reported socio-economic impacts to include car submergence and inundation of water into commercial areas. Considering the level of the socio-economic effects on affected areas along with the micro-spatial characteristics of flooded areas, we believed that a micro level analysis would provide a more robust assessment in providing a detailed UFF risk mapping.

3.2 TREX modelling

Calibration and validation process

Two storm events in April 2008 were selected to carry out the model's ability to estimate the discharge and time to peak at three different locations. These locations are Sungai Klang (upper), Sungai Klang (center) and Sungai Kerayong. These three rivers are selected based on the quality of rainfall data and the flow rates recorded by the Department of Irrigation and Drainage (DID) and SMART. An analytical approach, namely Relative Percentage Different (RPD) was used to evaluate the TREX model performance. The classification of the model performance is; 1) less than 10% is very good, 2) between 10% and 15% is good, and between 15% and 25% is acceptable for the difference between observed and simulated of peak discharge and time to peak. If RPD value of more than 25%, the results are rejected and the calibration and validation process has to be repeated. Negative values indicate that the estimated time and maximum flow rate are more than the record value. Table 7 shows the RPD values for peak discharge and time to peak for the three (3) locations. From Table 7, the RPD for all estimated peak discharge and time to the peak are less than 25%. The ability of this software to estimate time to peak is very good, and the difference is less than 10%. The TREX model simulated time to peak earlier or later by 1 to 2 hours from the observed data. The RPD values in the calibration and validation process are between 4.2% and 8.4%. Simulated peak discharge found to be between 4% and 25%. In conclusion, TREX software has the ability to estimate peak discharge and time to peak at Klang River basin.

Estimated distribution of water depths for 50- and 100-year of ARI

Intensity and duration of rainfall for 50- and 100-year ARI were developed using MSMA (2012) (see Figure 5). Simulations were conducted for duration of rainfall between 2 and 24 hours. From the simulation, short duration of rainfall with high rainfall intensity produced high discharge in the river (Table 8) and this has been identified as the main cause of flooding. In addition to rainfall, the dominant urbanised land use also contributed to the occurrence of UFF. The ability of soil to absorb water has been reduced by the replacement of impervious layer (hard surface) (refer to Figure 1 - settlement). Figures 5-9 shows the water depth distribution on overland in study area for 50-year return period event. Historically, the flood occurrence in the study area is at minimum two events in each month (see Figure 3).

3.3 Risk mapping

In this section, we integrate the calculated vulnerability, susceptibility and socio-economic impact of the study area based on the historical data and performed mapping using ArcGIS with the 50-year ARI simulation results from TREX model.

3.3.1 Flood Susceptibility

Figure 5 shows that most of the locations within the Klang River watershed are visibly fall under the category of green, that is less susceptible for UFF. The concentration of green areas can be found at the confluence of Klang River and Batu River, where the old commercialisation districts (i.e. Pudu and Putra) are. These areas are saturated with buildings, narrow roads and drainage systems designed based on at least 10-year ARI rainfall events. Increased surface coefficient due to urbanisation contributes to the increasing surface runoff whereby the discharge capacity of existing drainage was exceeded. The city centre is prone to flash floods where 39% of the recorded flood events between the year 2011 to 2016 was reportedly occurred here (Bhuiyan et al., 2018). For the 10-year data analysed here, two locations were classified as red, i.e., Jalan Kolam Air and Kampung Baru where both are long-established housing areas, particularly the latter since 1900. The points obtained from the historical data coincide well with the inundated area based on the TREX simulation, in particular at the confluence of Klang-Batu Rivers. The flood depth can be more than 0.5 m, providing high risk in economic loss.

3.3.2 Flood Vulnerability Index

The vulnerability of flash flood occurrence in Kuala Lumpur is mapped in Figure 6. A total of 38 locations are categorised as extremely vulnerable to flood, with the concentration of red zones is found at the confluence of Batu-Gombak Rivers and further downstream at the Batu-Klang Rivers. Multiple locations are vulnerable (classified as orange) within the 1 km radius of both confluences.

Interestingly, there are areas with the high vulnerability of flood, situated further away from the fluvial system. These are the places prone to flash flood, where during an extreme rainfall event, the runoff discharge exceeds the existing drainage capacity causing an immediate overflow.

Locations with high and extremely vulnerable flood made up to 65.9% of the total identified locations. As flash flood occurs in a short time period with high rainfall intensity and sudden, the time taken for initial flood could be only 30 minutes. Flood management of discharge diversions such as SMART Tunnel and Batu Jinjang Ponds delayed or even eliminated the occurrence of a flood. Both flood mitigations diverted the flow from the upper catchment of Gombak and Batu Rivers, and upper Klang River (including Ampang River), respectively, minimising overflow discharge into the city centre from both North-West and North-East. The construction of these hard structure approach did not necessarily reduced the flooding events, where high frequency of flood episodes; 8, 11, 7 and 6 were reported for years 2015, 2014, 2013 and 2012, respectively, compared to the 5 and 4 flood events recorded in the year 2003 and 2004 (pre-SMART), respectively. The increasing flood events did not indicate the inefficiency of the constructed mitigation structure, but more of due to higher frequency of extreme rainfall events with shorter period and higher intensity (Muhammad et al., 2016). Most of the recorded flash flood in the red and orange spots are pluvial based, where either due to poorly maintained or under designed drainage systems.

3.3.3 Socio-economic impact

As Kuala Lumpur is an urbanised, well developed, and the capital city of Malaysia, the impacts on socio-economic are immense. Recall that there are four categories i.e., residential, commercialisation, road infrastructure, and tourist spots. Figure 7 illustrates the risk level of socio-economic impact due to an urban flash flood in Kuala Lumpur. Red and orange spots are well distributed at the upper and lower middle of Kuala Lumpur. An inundation of even 0.3 m ultimately affects the commercial areas and definitely disrupt the traffic as can be seen in Figure 2. Four lanes of the carriageway were reduced to two lanes as the water rises on the lower lying lanes. Runoff flow along the lanes during the rising stage of rainfall causing an insignificant impact on the road users. As rain continues, the stormwater accumulates in the low-lying road sections during the falling limb of the rainfall, where the maximum inundation level is reached after the rainfall peak (Yin et al., 2016). Flash flood usually took about 1-2 hours to subside through the drainage network, infiltration, and evapotranspiration.

3.3.4 Flash Flood Index

The calculated FFI for all 137 locations is shown in Figure 8. As shown in the map, most of the spots are categorised as (yellow), and only eight and three locations are classified as orange and red, respectively. The three red areas are two crucial roads (i.e., Duta and Chan Sow Lin) and a commercial area (Segambut Bahagia), located just outskirt of the heart of Kuala Lumpur.

Duta Road is the main road connecting Kuala Lumpur to northern Malaysia, while Chan Sow Lin Road is the old road connecting Kuala Lumpur towards the south. Segambut Bahagia is majority of the residential with a significant fraction of commercialisation buildings. Zooming into the orange classified locations, 75% of the areas are road infrastructures. This is a rather interesting finding as a transportation network is an essential element in the city centre, whereby measure to prevent the risk of frequent closure due to flooding is crucial.

4 Conclusions

Identified flash flood prone locations/areas based on historical data coincide well with the watershed simulations. Although it can be said that the risk of the flash flood can be accurately assessed using past records, the limitation of point-based location (through this approach) is validated by the spatial distribution of flood from the simulation. As such, the evaluation of critical flood areas is feasible through the developed index procedure with readily available information. The classification of susceptibility, vulnerability and associated impacts of flash flood events based on a catchment area provides a full overview of the critical areas and assist on the identification of undetected locations. Colour-coded risk mapping furnishes a holistic view not only on the specific target areas, but also assisting the local authority for a more comprehensive, integrated and cost-effective flood mitigation plan.

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Figure captions

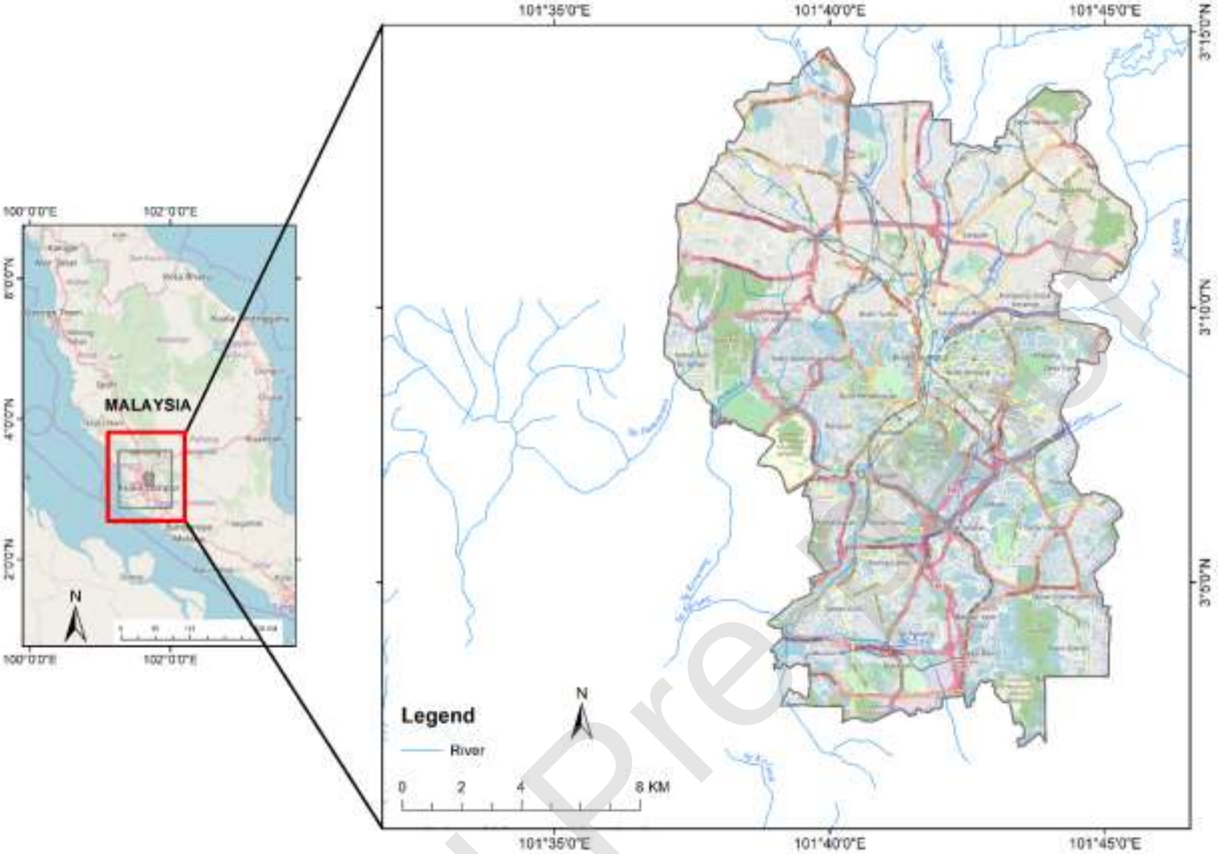

Figure 1. The location of Kuala Lumpur within the Klang River basin. Transportation network including highways and main roads, and strategic districts of Kuala Lumpur are presented.

Figure 2 Only one lane is allowable for motorists and inundation of water at the sidewalk of commercial areas during and after the heavy downpour on 6th April 2018. Reprinted with permission from New Straits Times.

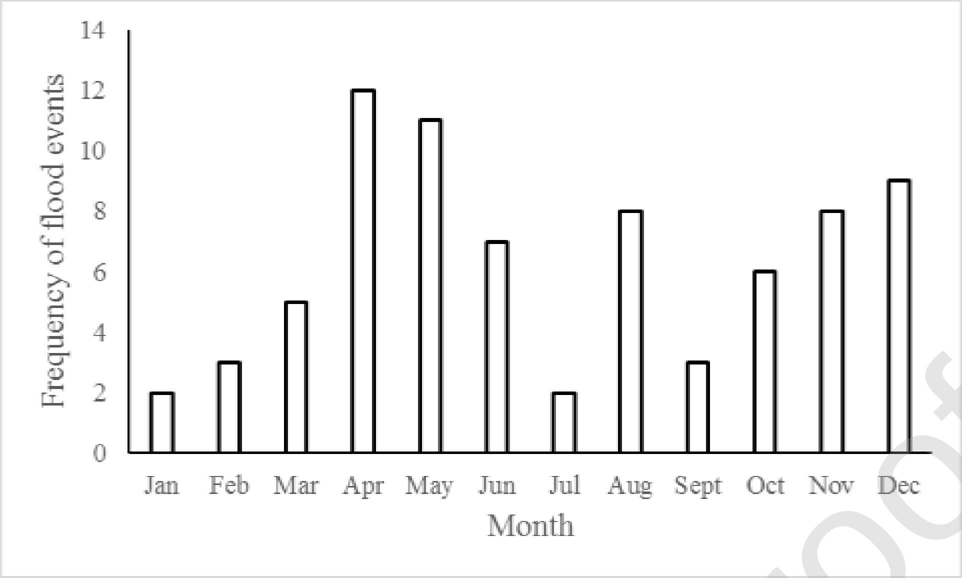

Figure 3 Frequency of UFF events in Kuala Lumpur from the year 2005 to 2015.

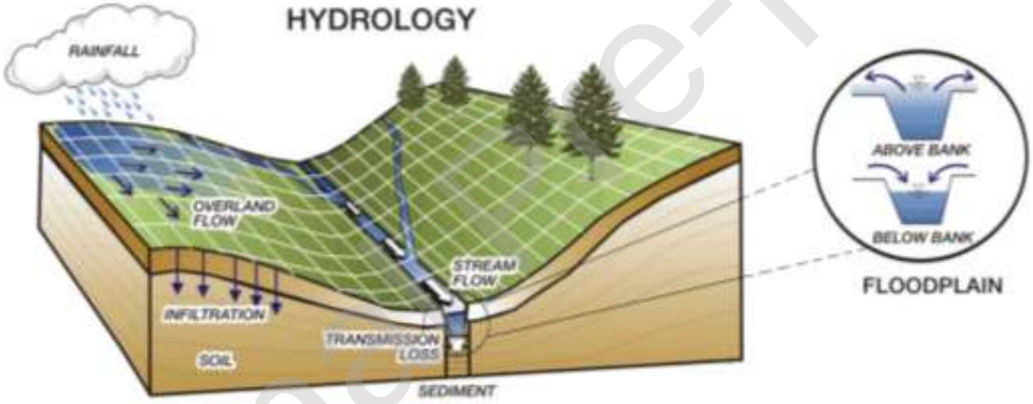

Figure 4 Overview of hydrological processes in TREX model

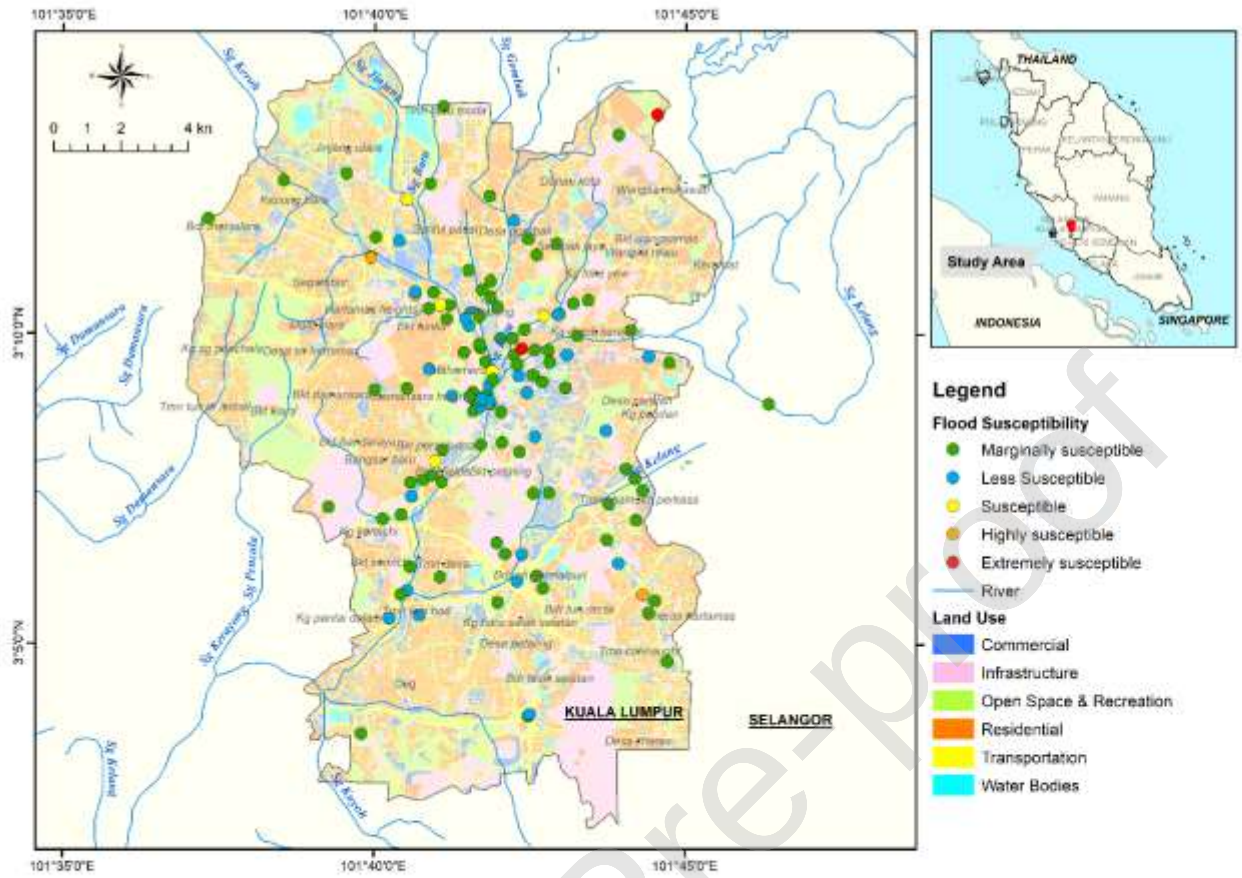

Figure 5 Flash flood susceptibility map of Kuala Lumpur

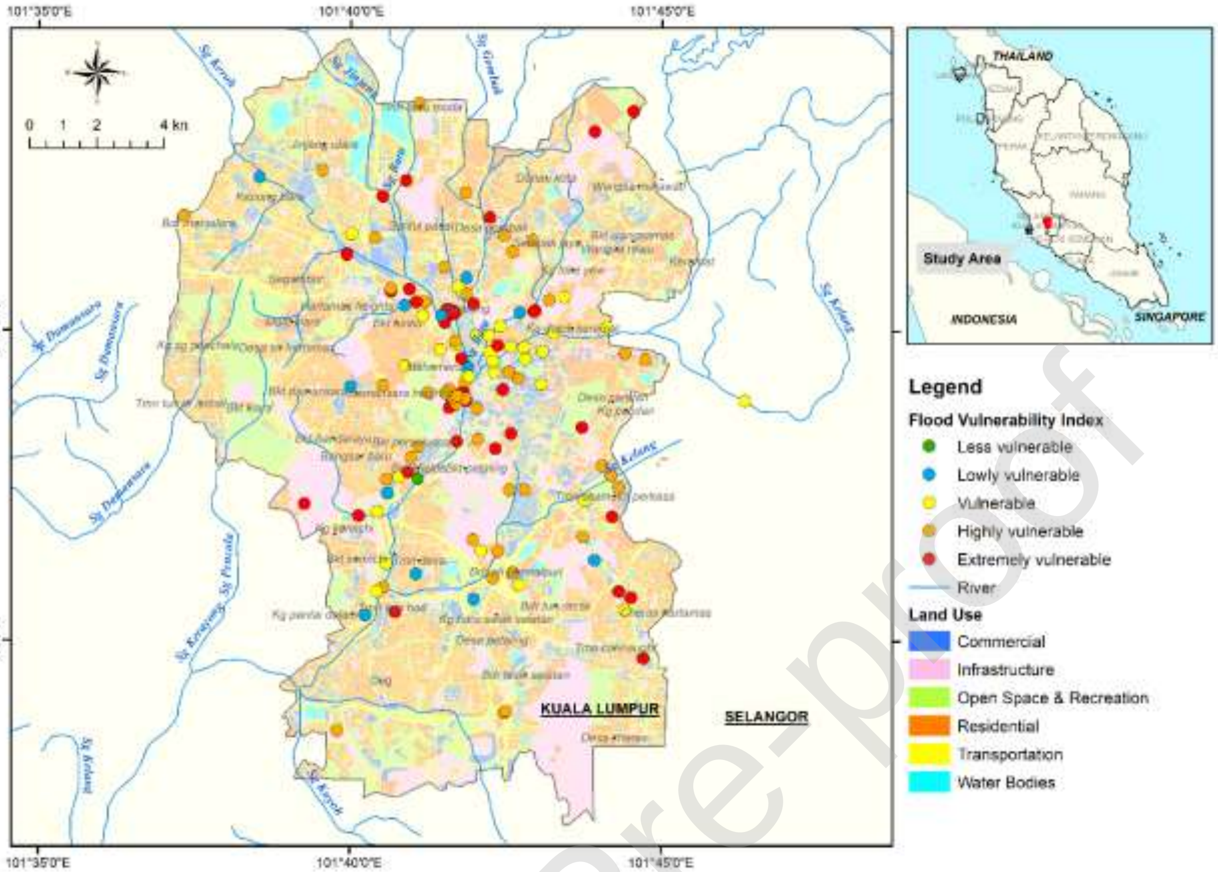

Figure 6 Flash flood vulnerability map of Kuala Lumpur

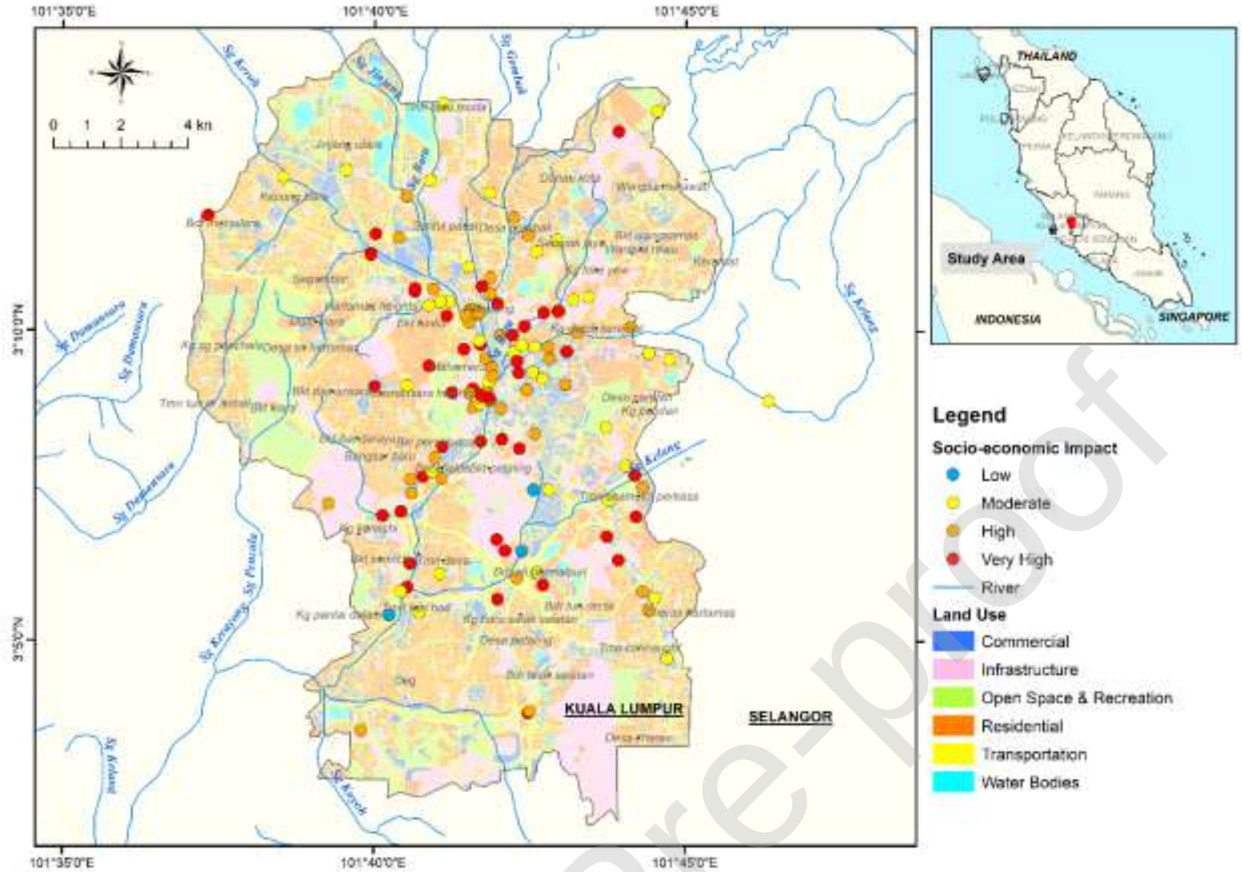

Figure 7 Map of flash flood induced socio-economic impact at Kuala Lumpur

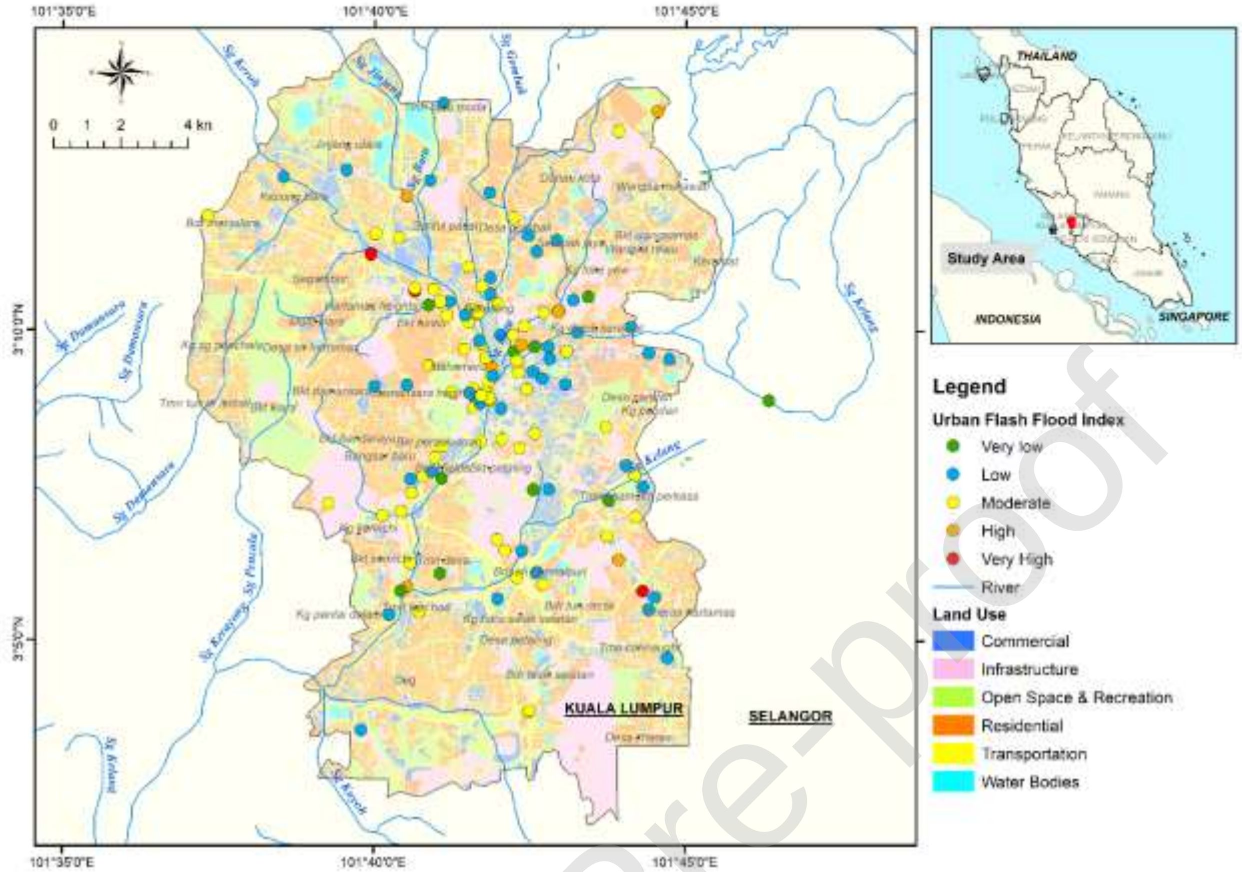

Figure 8 Map of integrated flash flood index in Kuala Lumpur

Table

Table 1 Determination of flood susceptibility based on the historical frequency of flash flood occurrence

Frequency of occurrence	Category	Susceptibility level	Colour
<2	1	Marginally susceptible	Green
2-3	2	Less susceptible	Teal
4-5	3	Susceptible	Yellow
5-6	4	Highly susceptible	Orange
>6	5	Extremely susceptible	Red

Table 2 Given monthly Likert-scale based score for the frequency of flash flood episodes in Kuala Lumpur

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Score of M	1	2	3	5	5	4	1	5	2	4	5	5

Table 3 Likert-scale based rainfall duration and total rainfall depth

Score for R and D	Duration (hr)	Total rainfall depth (mm)
1	>4	≤25
2	3.1-4	25
3	2.01-3	50
4	1.01-2	75
5	0-1	≥100

Table 4 Definition and associated colour coded for FVI

FVI	Definition	Colour
≤1	Lowly vulnerable	Green
≤2	Less vulnerable	Teal
≤3	Vulnerable	Yellow

≤4	Highly vulnerable	Orange
≤5	Extremely vulnerable	Red

Table 4 Definition of categorical land use used

Land use	Definition
Residential (R)	An area when the majority (>70% of the area) is residential, including landed and apartment houses.
Commercial (C)	An area when the majority (>70% of the area) is commercial including shopping districts, offices, and factories
Transportation (T)	Highway/road with a minimum of four lanes
Tourist place (TP)	Distinguished historical buildings and tourist places in Kuala Lumpur

Table 5 The flood depth-land use matrix based SI score on Residential (R), Commercial (C), Road Infrastructure (I) and Tourist Place (P).

	SI score			
Flood depth (m)	R	C	I	P
0-0.29	2	3	3	3
0.3-0.59	3	4	5	4
0.6-0.89	4	5	5	5
0.9-1.11	5	5	5	5
>1.2	5	5	5	5

Table 6 Model Parameterisation

Parameters	Value	Application
Interception (mm)	2.0	Agriculture
	0.05	Urban/Commercial
	5.0	Forest
Soil moisture deficit (-)	0.29	Sandy loam
		Loam
		Mountain - limestone
Infiltration (m)	0.14	Sandy loam
	0.22	Loam
	0.17	Mountain - limestone

Hydraulic conductivity, K_h (m/s)	3.5×10^{-10} – 3.5×10^{-7} 3.7×10^{-10} – 3.7×10^{-7} 7.7×10^{-10} – 1.3×10^{-8} 3.5×10^{-11} – 3.2×10^{-6}	Sandy loam Loam Clay Mountain - limestone
Manning roughness n $(\mathrm{m/s^{1/3}})$	0.05 – 0.35 0.01 – 0.10 0.18 – 0.65 0.05 – 0.35 0.05 – 0.35	Agriculture Urban/Commercial Forest Grass area Open area

Table 7 The RPD values of peak discharge and time to peak between observed and simulated

Event date	Station name	Maximum discharge (m^3/s)			Time to peak (hour)		
		Observed	Simulated	RPD (%)	Observed	Simulated	RPD (%)
CALIBRATION							
25 – 29 April 2008	Sg. Klang (upper)	45.51	55.45	-21.84	---	---	---
	Sg. Kerayong	184.00	161.81	12.27	19:00	20:00	- 4.2
	Sg. Klang (middle)	688.00	762.22	-10.76	20:00	18:00	8.4
VALIDATION							
1 – 5 April 2008	Sg. Klang (upper)	15.45	19.45	-25.49	---	---	---
	Sg. Kerayong	54.44	51.80	4.84	19:00	20:00	- 4.2
	Sg. Klang (middle)	446.81	480.22	-7.48	17:00	18:00	- 4.2

Table 8 Estimated maximum flow rate and rainfall duration from TREX simulations

ARI (Year)	Estimated peak discharge (m^3/s)							
	Sg. Klang (u/s*)	Rainfall duration (hr)	Sg. Kerayong	Rainfall duration (hr)	Sg. Klang (mid.*)	Rainfall duration (hr)	Sg. Klang (d/s*)	Rainfall duration (hr)
50	139	2	137	2	1,002	4	1,670	14
100	140	2	166	4	1,232	4	1,944	18

*Note: u/s = upstream; mid. = middle-stream; d/s = downstream