Keynote: Analysis of Extreme Floods in Malaysia

Pierre Y. Julien, Jazuri Abdullah, and Nur Shazwani Muhammad

Abstract This article reviews some of the recent advances in the analysis of extreme flood events in Malaysia. First, a detailed analysis of daily rainfall precipitation measurements leads to new understanding regarding Malaysian monsoons: the conditional probability of rainfall steadily increases as a function of the number of successive rainy days. The probability of multiday rainfall events has also been analyzed using stochastic models like DARMA(1,1) to demonstrate lower periods of returns of large precipitation amounts for rainfall events between 4 and 12 days. Advances in numerical modeling of surface runoff using the TREX model allowed improved simulations of large floods when considering rainfall amounts between the 2- and 100-year events and the PMP for extreme floods on both small to large watersheds in Malaysia. Examples on Lui, Semenyih, and Kota Tinggi have also been possible with GIS data at 30–90 m resolution. The recent floods of the Kota Tinggi and Muda River are also briefly discussed. Finally, a brief overview of the DID River Management Manual is also presented.

Keywords Monsoon precipitation • Extreme floods • Flashflood modeling • River management

1 Introduction

Southeast Asia has long experienced a monsoon climate with dry and wet seasons. With a mean annual rainfall precipitation around 2,500 mm and locally in excess of 5,000 mm, the very intense rainstorms in the steep mountains of Malaysia have caused frequent and devastating flash floods. In the valleys, floodwaters spread over very wide flood plains developed for agriculture, predominantly rice paddies and oil

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palm. Urbanization and deforestation exacerbate flooding problems due to the increased runoff from impervious areas. The industrial developments fostered a new way of urban life, and flood control in Malaysia is undergoing significant changes.

The objective of this article is to provide a brief description of recent developments in the analysis of new engineering methods for the analysis of extreme floods. The first objective is to describe developments in the analysis of daily rainfall precipitation data under monsoon climates. The second objective is to share some of the developments in hydrologic modeling of extreme surface runoff from exceptional rainstorms on small to large watersheds. The third objective is to illustrate some of the implications in terms of direct applications to recent flood events in Malaysia and specifically on the Muda River and near Kota Tinggi. Finally, a brief overview of the DID manual of River Management will be presented.

2 Extreme Rainfall Precipitation

2.1 Analysis of Daily Rainfall Precipitation

Muhammad [1] recently reviewed the daily rainfall precipitation data at Subang Airport from 1960 to 2011. During this period of 18,993 days, there were 10,092 rainy days with more than 0.1 mm of precipitation. The average daily rainfall is 13 mm and standard deviation 17 mm. She demonstrated that the distribution of rainfall precipitation followed a gamma distribution. The equation of the probability density function can be approximated as

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

where x is the daily rainfall depth in mm, and t is the number of consecutive rainy days. The cumulative distribution function is the integral of Eq. (1). As shown in Fig. 1, there is a 37 % probability that the total precipitation from six consecutive rainy days will exceed 100 mm. It is interesting to note that the NE and SW monsoons produced fairly similar rainfall distributions at that location.

One of the main findings from her research was that the conditional probability of rainy days increased with the number of consecutive rainy days as shown in Fig. 2. Monsoon rainfall events cannot be considered to be independent.

Muhammad [1] then developed a detailed DARMA(1,1) model for the simulation of long sequences of wet and dry days including the amount of daily precipitation. The main results of this analysis have demonstrated that the periods of return of the amount of precipitation from multiple rainy days vary with the number of rainy days as shown in Fig. 3. The agreement between the DARMA(1,1) model

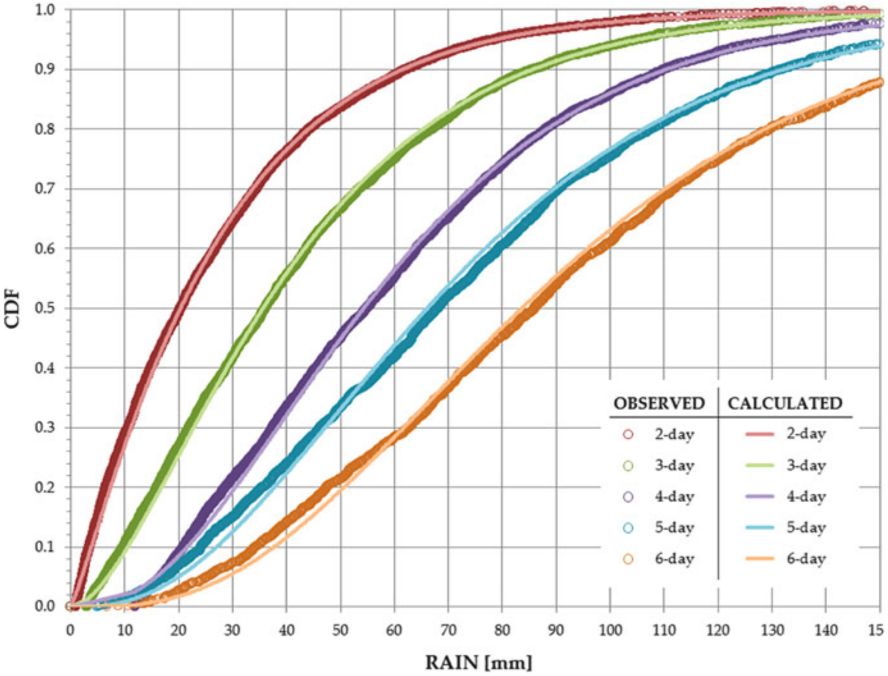


Fig. 1 Multiday cumulative distribution functions for the daily rainfall data at Subang Airport from 1960 to 2011, from Muhammad [1]

simulations and the field measurements was excellent. For instance, the accumulation of 120 mm of rainfall in a single day has a period of return of approximately 20 years; however, when accumulated over eight consecutive rainy days, the period of return is now reduced to approximately 2 years.

Daily rainfall simulation sequences up to 1,000,000 days (i.e., ~2,700 years) are readily possible as shown in Fig. 4. For instance, it now becomes possible to predict that a 250 mm rainfall in 4 days will have a period of return of about 500 years. The extension of daily precipitation analysis to rare and extreme events can now be better investigated using this methodology. The practical implications of this research are most important for the analysis of floods on large watersheds, i.e., larger than 1,000 km^2.

2.2 *Return Periods and Probable Maximum Precipitation*

Abdullah [2] recently examined the frequency distribution of rainfall precipitation as a function of storm duration for the State of Selangor. His analysis of data from several sources led to Fig. 5 where large events are comprised between the two lines with a period of return of 2–100 years. The world maximum precipitation (WMP)

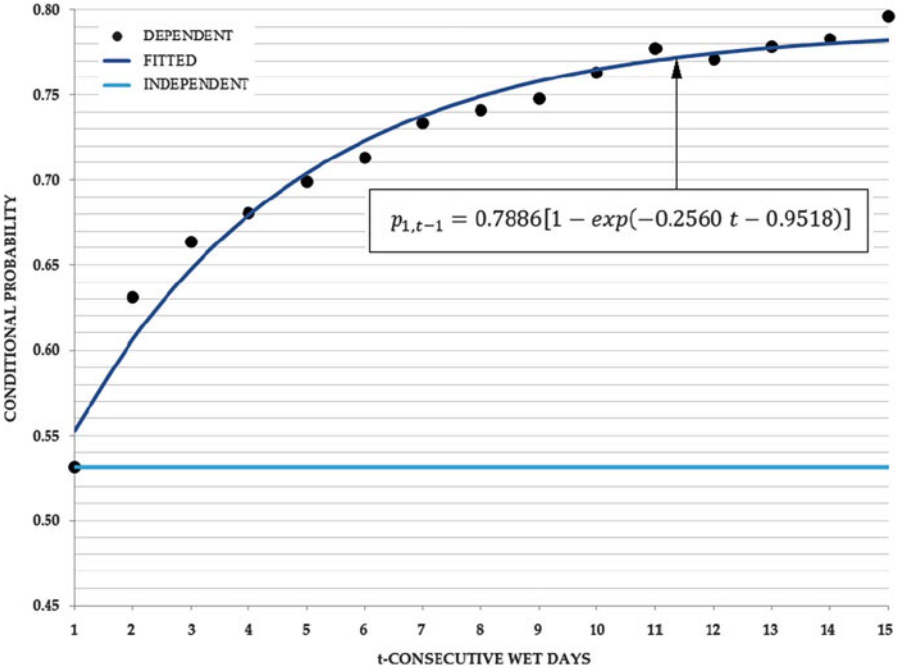


Fig. 2 Increase in conditional probability of rainfall at Subang Airport, from Muhammad [1]

events can be found on the top line with the probable maximum precipitation (PMP) for Selangor between the WMP and the 100 year rainfall precipitation. It is observed that the 100-year precipitation is approximately two times the 2-year rainfall precipitation event, and the rainfall depth increases approximately with the square root of rainfall duration. This means that the average rainfall intensity gradually decreases with rainfall duration. The PMP for the State of Selangor is approximately three times the 100-year rainfall depth and half the world maximum precipitation.

3 Large Flood Simulation with TREX

Abdullah [2] successfully applied the fully distributed two-dimensional TREX model to the simulation of infiltration, overland runoff, and channel flow during extreme rainfall events on small and large watersheds in Malaysia. There are four main processes in the TREX hydrological sub-model developed by Velleux et al. [3, 4]: (1) precipitation and interception; (2) infiltration and transmission loss; (3) depression storage; and (4) overland and channel flow.

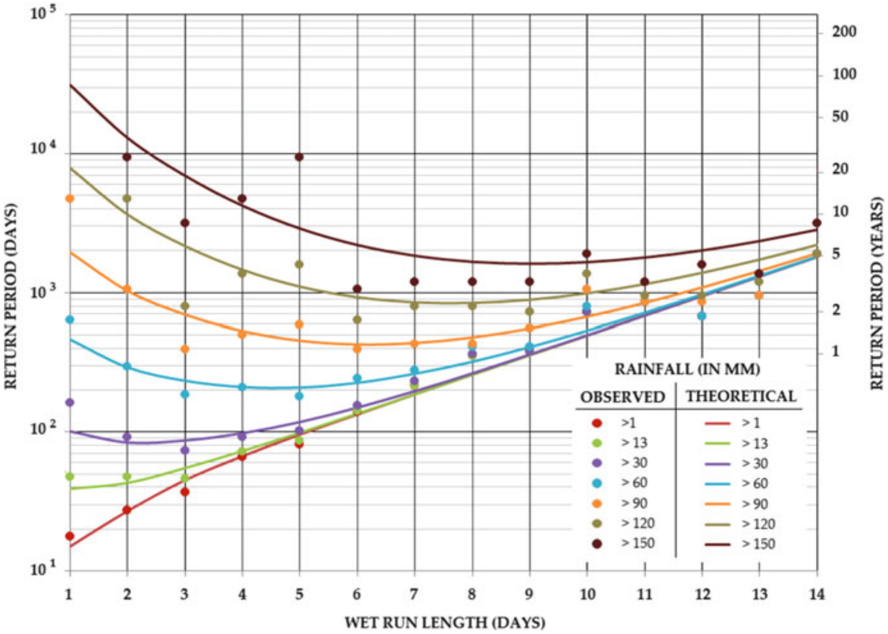


Fig. 3 Return period of multiple rainy days as a function of the cumulative rainfall precipitation, from Muhammad [1]

3.1 Precipitation and Interception

The precipitation volume reaching the near surface can be written as the product of rainfall intensity and surface area. The presence of forests or other vegetation influences the distribution pattern of the net rainfall precipitation. Some of the precipitation is intercepted and retained by the leaves and other parts of the canopy, and then eventually returned to the atmosphere in the form of evaporation.

3.2 Infiltration and Transmission Losses

In the TREX model, the infiltration rate is calculated using the well-known Green and Ampt equation. Transmission losses describe the water reaching the groundwater, overbank flow onto floodplains, wetlands and billabongs, and water never returning to the river. The rate of transmission may be affected by several factors, particularly the soil hydraulic conductivity.

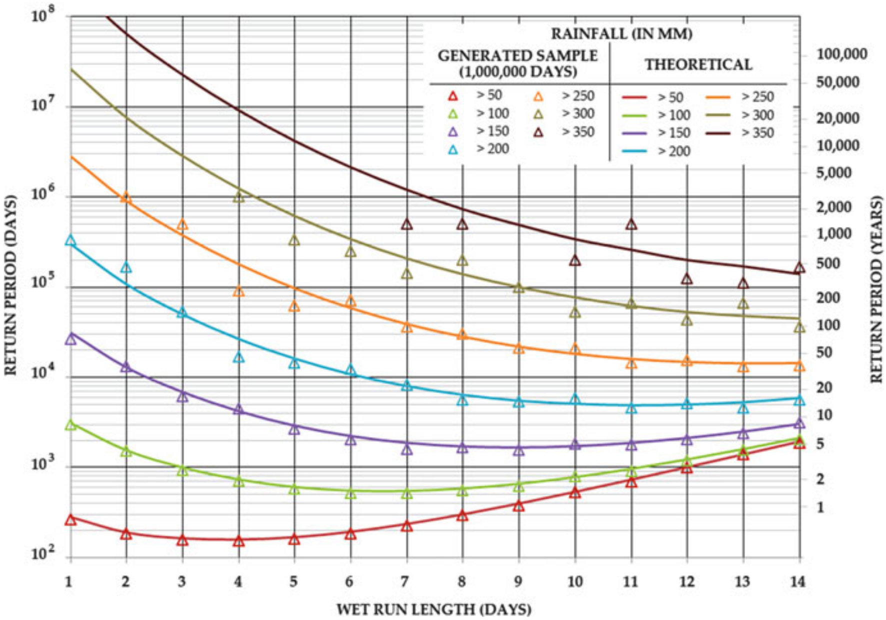


Fig. 4 Extension of the return period analysis of multiple rainy day precipitation by using the DARMA(1,1) model, from Muhammad [1]

3.3 Depression Storage

Precipitation retained in small surface depressions is called the depression storage, which may be conceptualized as a depth when normalized 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 dead storage volume by evaporation can also be neglected for single storm events.

3.4 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

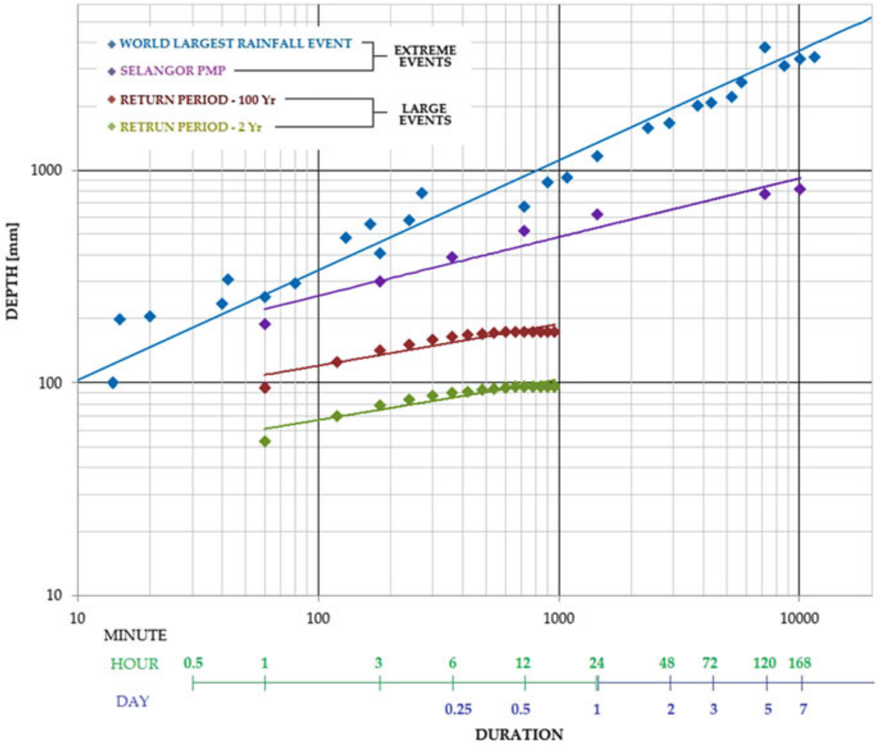


Fig. 5 Rainfall depth vs. duration for the 2-year, 100-year, the PMP-Malaysia and the world maximum precipitation for small and medium watersheds in Selangor, from Abdullah [2]

mass (continuity) and conservation of momentum. The two-dimensional vertically integrated continuity equation for gradually varied flow over a plane in rectangular coordinates is used in the TREX model.

The application of momentum equations (Saint-Venant equations) for two-dimensional runoff calculations are derived in terms of net forces per unit mass or acceleration. Five hydraulic variables must be defined in terms of depth-discharge relationship to describe flow resistance before the overland flow equations can be solved.

One-dimensional channel flow (along the channel in the down-gradient direction which laterally and vertically integrated) is also governed by conservation of mass (continuity) and momentum. The method suggested by Julien [5] is applied for gradually varied flow. 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. The Manning relationship is used to describe resistance to flow.

3.5 Model Parameters

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 discretized at a 230 by 230 m scale. The grid size was used to delineate these watersheds. The DEM was downloaded at a 90 m resolution from the ASTER GDEM website. The watershed was described with a total of 31,000 active grid cells within a matrix of 292 rows and 292 columns. The total river length of the large watershed was ~250 km (1,081 nodes and 42 links).

Calibrated model parameters and modeling details can be found in Abdullah [2]. A sensitivity analysis showed that the hydraulic conductivity, K_h, and Manning, n, are the most sensitive parameters during calibration. These values were adjusted to achieve very good agreement between observed and simulated discharges. The antecedent moisture condition for the watershed was assumed to be dry at the beginning of simulation. Rainfall was generally sufficiently abundant to neglect interception and detention storage.

The TREX model provides illustrations of the evolution of flow depth with time during a flood event. It can provide maps of the distribution of flow depth at different times. For instance, Fig. 6 illustrates the simulation of an extreme event on the Semenyih watershed by Abdullah [2].

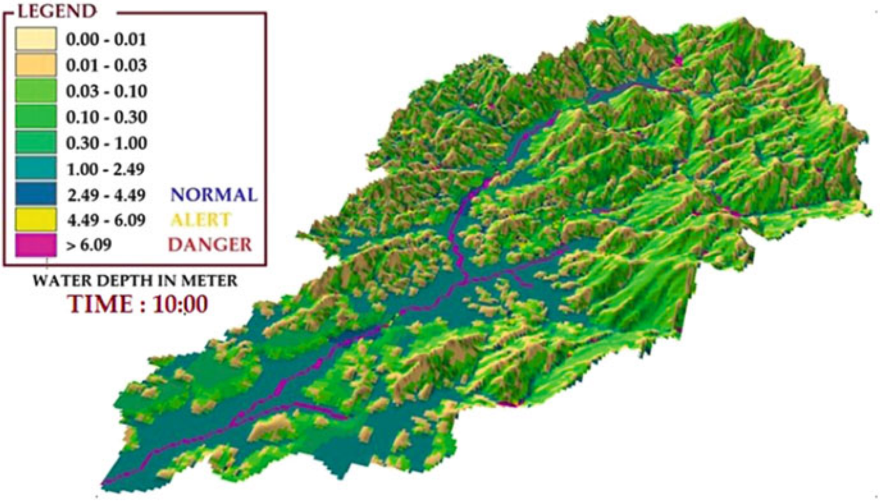


Fig. 6 Illustration of the distribution in flow depth on the Semenyih watershed, from Abdullah [2]

4 Kota Tinggi Flood

Shafie [6] compiled the information relevant to the extreme rainfall precipitation leading to the Kota Tinggi flood. During the calibration, in the TREX model, Abdullah [2] was able to simulate the hydrological conditions of the Kota Tinggi Flood with reasonable accuracy, as shown in Fig. 7.

The validation process was performed using stage data from December 14, 2006 to January 25, 2007 as shown in Figs. 8 and 9.

Figure 8 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 on December 19, 2006. The stage continued to increase and easily passed the alert and danger levels as a result of the continuous rainfall. Figure 9 shows the TREX model results in terms of the flooding areas on the Kota Tinggi watershed on December 21, 2006. The maximum stage was reached on December 22, 2006, i.e., 2 days after the rainfall stopped.

The model gave very good estimates of the peak discharge and total volume with average overestimation of about 0.8 % and 1.5 %, respectively. The hydrological modeling results presented here give a physical representation of the flooding at Kota Tinggi. The results further prove that the multiday rainfall events are the main causes of severe flooding on this large watershed.

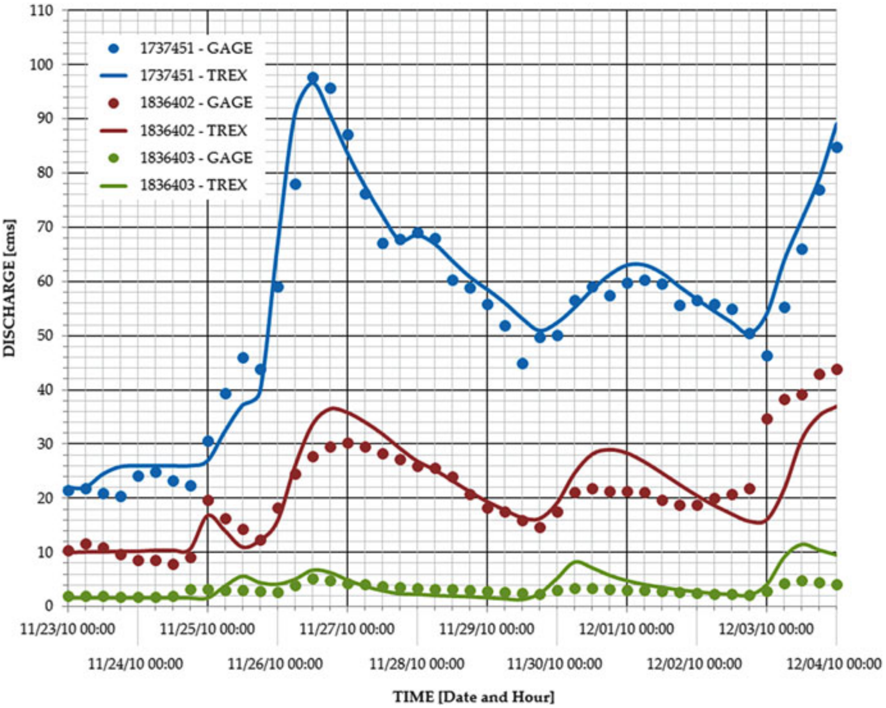


Fig. 7 Calibration results of the TREX model applied to the Kota Tinggi watershed, from Abdullah [2]

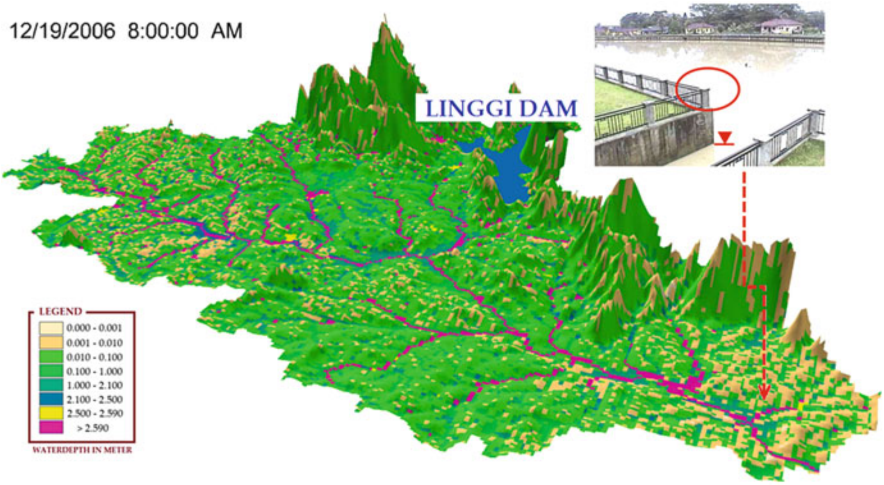


Fig. 8 TREX simulation of the Kota Tinggi Flood on December 19, 2006, from Abdullah [2]

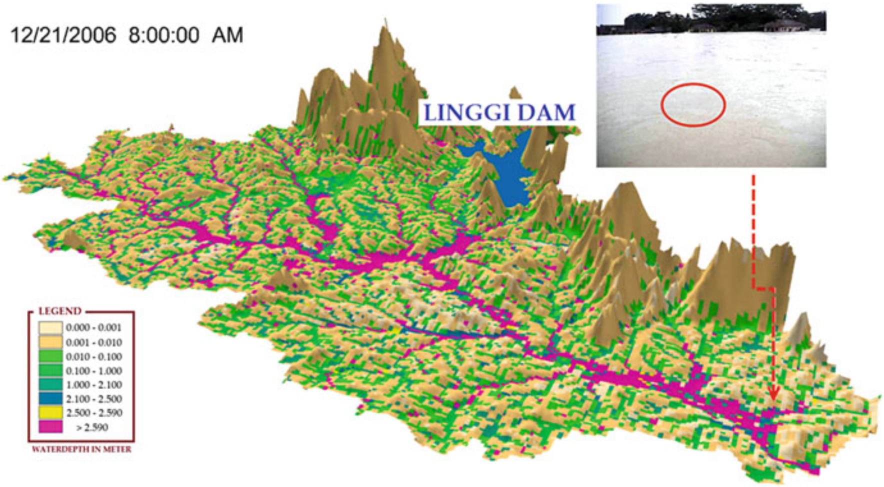


Fig. 9 TREX simulation of the Kota Tinggi Flood on December 21, 2006, from Abdullah [2]

Figure 10 illustrates the relationship between the estimated flood thresholds, return periods, and flood thresholds. A return period of 220 years (upper value) is the flood threshold for 1 day of rainfall. 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 four consecutive rainy days is only 24 years.

These results are useful in determining the design rainfall for a flood mitigation structure on a large watershed like the case of the Kota Tinggi flood.

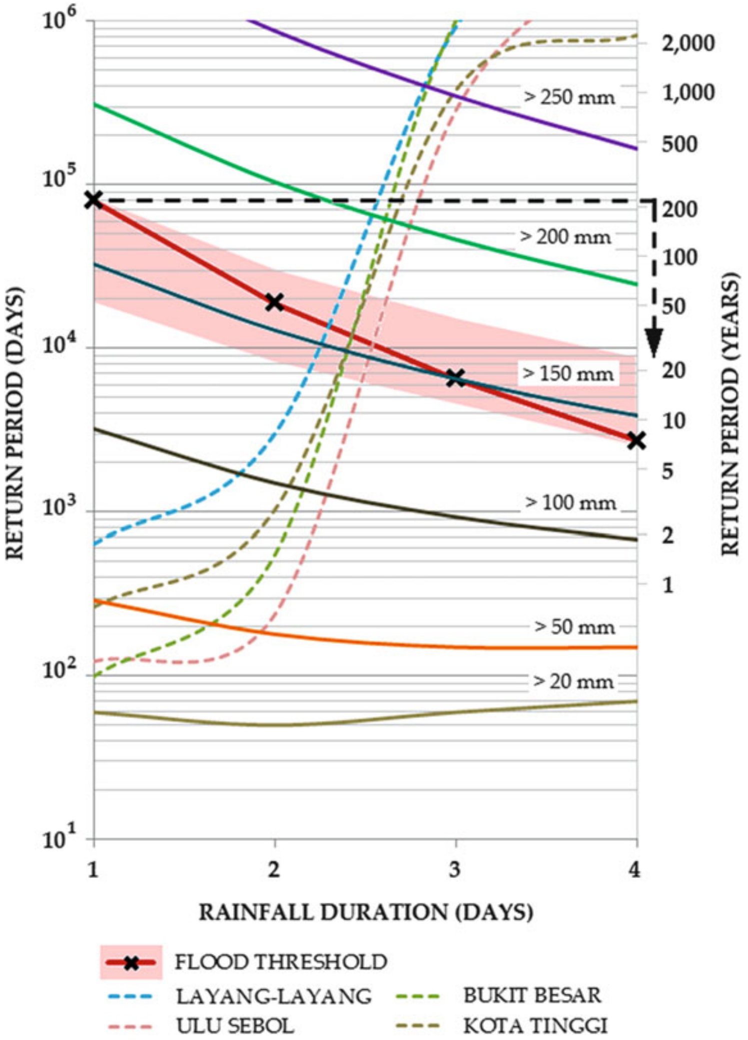


Fig. 10 Return period of multiple rainy days as a function of the cumulative rainfall precipitation and flooding threshold, from Muhammad [1]

5 Muda River Flood

The Muda River in Malaysia experiences floods every year, and the floods of 1996, 1998, and 1999 were particularly high. The Department of Irrigation and Drainage (DID) in Malaysia (Jabatan Pengairan dan Saliran Malaysia is also known as JPS) enacted a Flood Control Remediation Plan. Figure 11 illustrates the aerial extent of this flood, which adversely impacted 45,000 people in the State of Kedah.

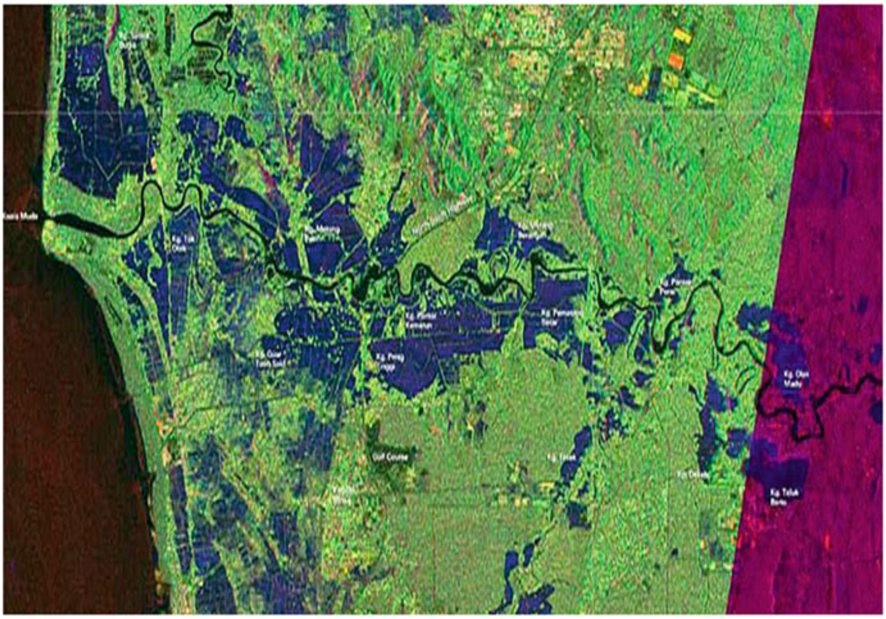


Fig. 11 Aerial extent of flooding of the Muda River, from Julien et al. [8]

Julien et al. [7, 8] reviewed the flood control remediation plan for the Muda River. This highlights several important points in the design of flood remediation countermeasures against the frequent and intense floods during the monsoons. For instance, the analysis of measured daily discharge records can produce a more reliable 50-year peak discharge than hydrologic models. There was a 25 % difference in flood frequency analysis between the field measurements (1,340 m^3/s) and hydrologic model results (1,815 m^3/s) as shown in Fig. 12.

Sand and gravel mining operations have caused major problems associated with riverbed degradation. The riverbed degradation has exposed the foundations of numerous bridges and caused additional stability problems to riverine structures like bridges and pumping stations as shown in Fig. 13. Also, the river longitudinal profile shown in Fig. 14 indicates that the bed elevation remained below the mean sea level up to some 25 km upstream of the river mouth. There is always a significant risk of having saltwater intrusion in the river for long distances, which requires the construction of estuary barrages besides pumping requirements at irrigation canal intakes.

It is thus recommended to replace in-stream sand and gravel mining operations with off-stream mining operations within the flood plain corridor at a minimum distance of 50 m from the river banks.

The concept of river corridor has been explored, as shown in Fig. 15, and the proposed levee height of the Muda River could have been based on the 2003 flood plus a 1-m freeboard.

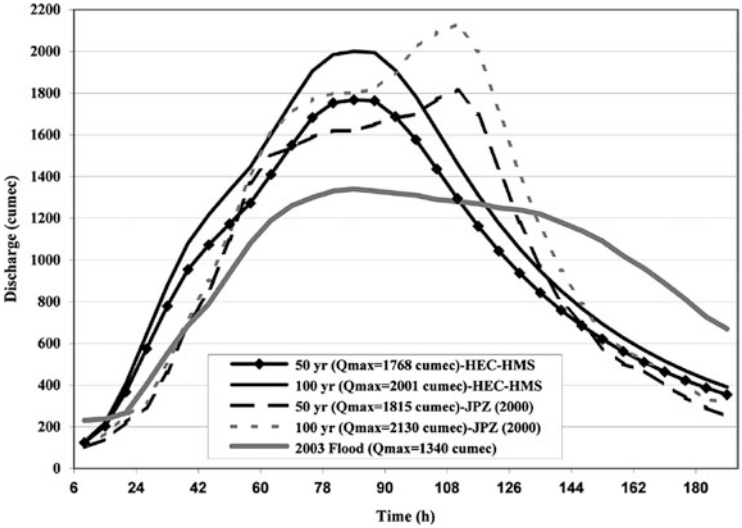


Fig. 12 Design hydrographs and measurements of the Muda River at Ladang Victoria, from Julien et al. [8]

Fig. 13 Impact of river bed degradation near bridge crossings, from Julien et al. [8]

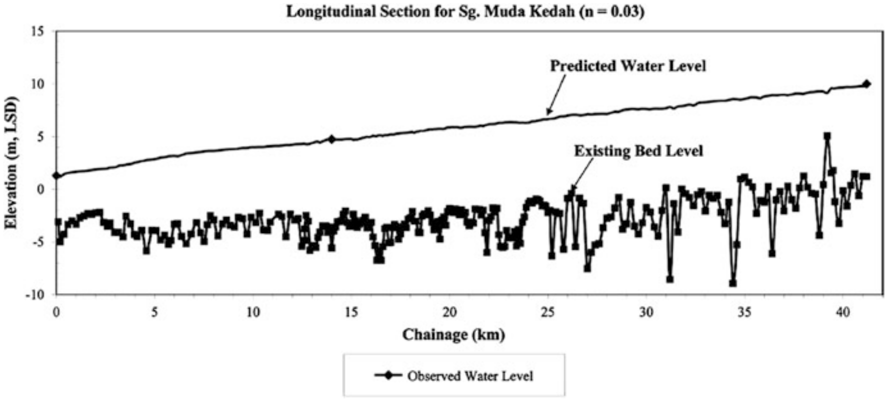


Fig. 14 Longitudinal profile of the Muda River, from Julien et al. [7]

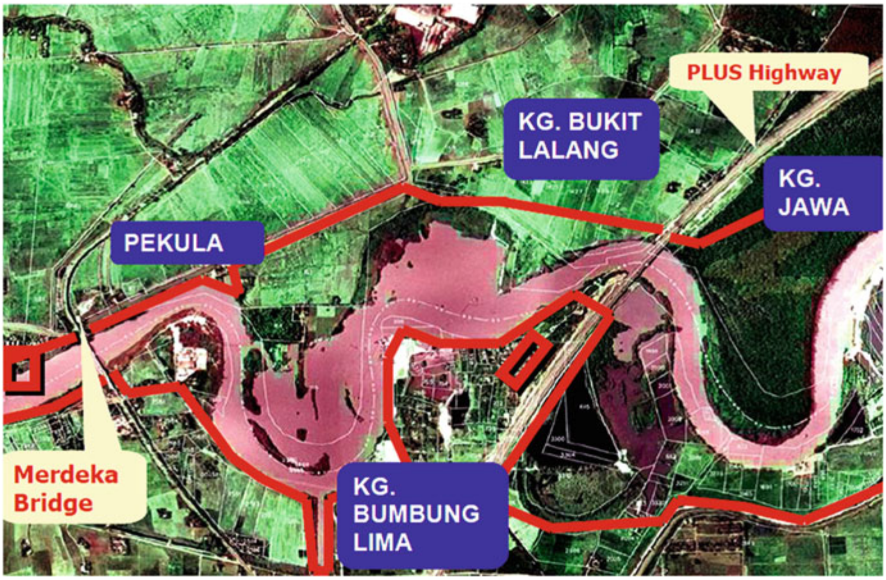
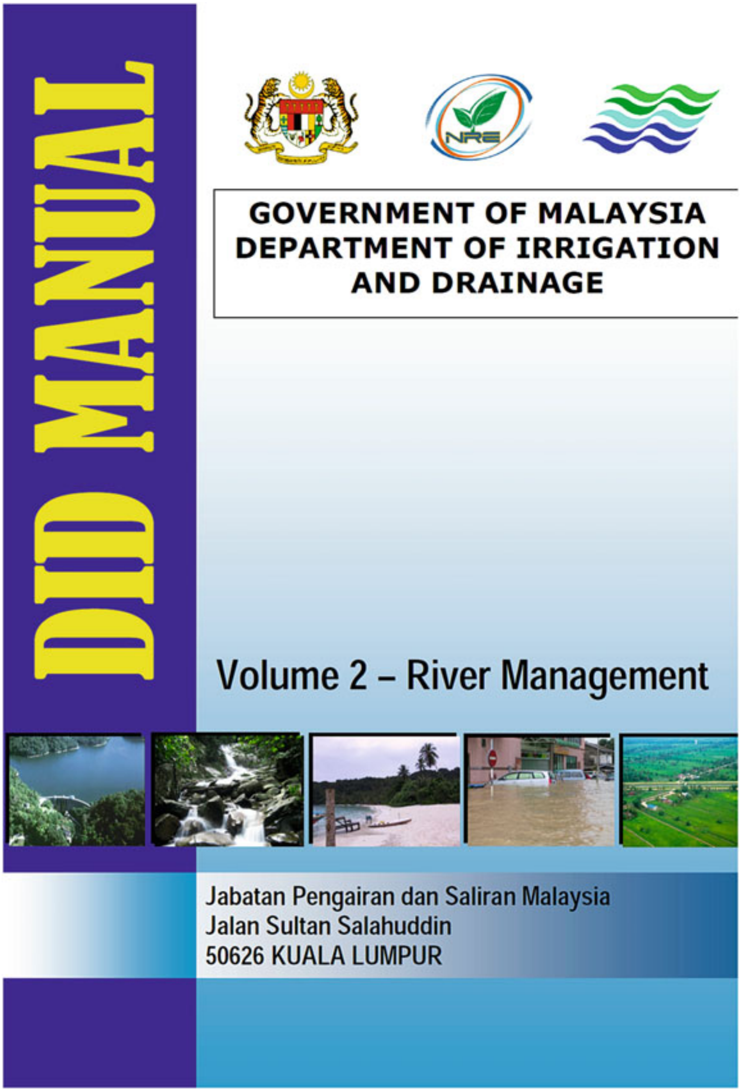


Fig. 15 Concept of river corridor on the Muda River near Merdeka Bridge, from Julien et al. [7]

6 River Management Manual

This new River Management Manual of the Malaysia Department of Irrigation and Drainage [9] has been a tremendous effort for the development of rivers in Malaysia. The manual contains more than 600 pages of technically sound river management practices; see Fig. 16.

The first chapter of the manual contains a statement of river management issues as well as a clear definition of the responsibilities of the Federal, State, and Local



DID MANUAL

GOVERNMENT OF MALAYSIA
DEPARTMENT OF IRRIGATION
AND DRAINAGE

Volume 2 – River Management

Jabatan Pengairan dan Saliran Malaysia
Jalan Sultan Salahuddin
50626 KUALA LUMPUR

Fig. 16 Cover page of the DID River Management Manual

authorities in Malaysia. Chapter 2 discusses the concepts of Integrated River Basin Management (IRBM) and describes the main river characteristics and fluvial geomorphology followed with a description of river ecology and river health. Chapter 3 provides an ample discussion on river restoration, river rehabilitation, and river engineering. There is also a discussion of the recovery of disturbed river systems and on rehabilitation monitoring and management. Chapter 4 focuses on the concept of river corridor. Issues relative to the management of river corridors, riparian land, and floodplains are covered in detail. Chapter 6 broaches other relevant topics like sand/gravel mining, water quality improvement, and solid waste management. There is also a brief description of climate change, research and development, as well as periodic reviews. Throughout the manual, there are numerous figures, illustrations, worksheets, and examples to assist the engineer and scientist with their river work. This is one of the most innovative contributions to river engineering management in Malaysia.

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