〈論文〉

Estimation of Design Flood Criteria toward Integrated Watershed Management in the Johor River Watershed, Malaysia

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Abstract

This research aims to investigate a necessary procedure for providing a design flood value using a hydrological frequency analysis in the Johor River Watershed, Malaysia, considering the relatively long duration of consecutive rainy days under the monsoon climate. Four investigations, including two rainfall characteristics surveys, rainfall-runoff simulations using the Hydrological Simulation Program-FORTRAN (HSPF), and the hydrological frequency analysis, were conducted to determine the critical rainfall duration. This will be the basic input for the hydrological frequency analysis and one of the most important factors in design flood estimation. The results showed that 5-day rainfall duration was the most rational to determine the most reasonable design flood value in the Johor River Watershed. As a result of runoff simulations using HSPF, this research revealed the flood design value of 851.0 m^3/s. The design flood value, which considers the characteristics of each watershed, can be used for more efficient and effective flood management.

Keywords : monsoon climate, rainfall duration, design flood criteria, hydrological frequency analysis, Johor River Watershed

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1. Introduction

Flooding is a serious disaster in Malaysia because of the continuous rainy days under the monsoon climate. Two major monsoon seasons, the Southwest (SW) monsoon (from May to September) and the Northeast (NE) monsoon (from November to March), trigger frequent seasonal floods almost every year[1,2]. Multiday rainfall events are very common during the NE monsoon season in the Johor River Watershed[3,4], the target watershed of this research, and it is well known that flooding is an unavoidable natural phenomenon given such a rainfall characteristic[1]. Furthermore, once flooding occurs, it lasts for a week or even longer[5]. Two big floods that occurred in the Johor River Watershed from December 2006 to January 2007, which is during the NE monsoon season, showed the representative characteristics of flooding in the watershed[6,7]. Considering these unusually long wet days, grasping the critical rainfall duration based on the aspect of a hydrologic design is one of the most important factors in terms of accurately measuring the design flood to avoid over- or underestimation[8]. It is a critical part of the design flood estimation in the Johor River Watershed. However, a deterministic method to define the rational rainfall duration has not yet been proposed. The Johor River Watershed plays an important role in water supply not only to the Johor district but also to Singapore. There is the Linggui Dam (**Fig. 1**), which supplies water to Singapore, in

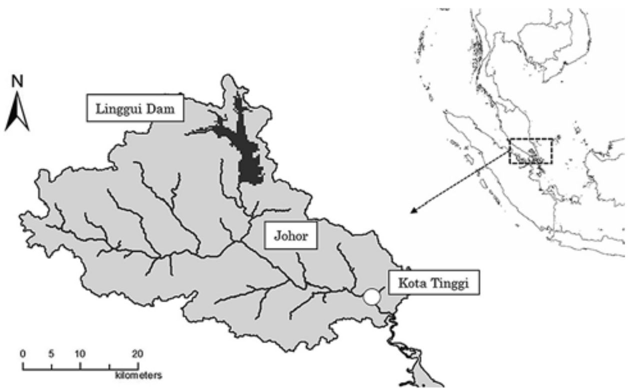

Fig. 1 Location of the Johor River Watershed, Malaysia[17]

the watershed. Because Singapore is contracted to operate the Linggui Dam for managing the country's main water source, the dam has been controlled by Singapore. The management of the watershed is not only a state matter but also a diplomatic matter between two countries, Malaysia and Singapore, through the water. Thus, the Malaysian government has been focusing on the management of the Johor River Watershed.

Up until now, 24 hours, or the time of concentration, has been considered as the critical rainfall duration that gives the maximum peak flow in a watershed. It is traditionally used for design flood estimation. For example, the U. S. Federal Emergency Management Agency's (FEMA) guidelines for flood-risk analysis and mapping[9] define the critical duration as a design storm that provides the maximum/highest peak flow. However, the guidelines have assumed that the 24-hour rainfall duration produces the highest peak flow in any watersheds. In Malaysia in the same manner, using the 24-hour rainfall duration is recommended for flood management[10]. According to the previous studies[11-13], the critical rainfall duration actually varies depending on the topography of the watershed, the slopes of the river, the storm sewer capacities, and the regional flood storage facilities. In addition, the duration equal to the time of concentration does not reflect a storm depth of rainfall excess and the critical rainfall duration exceeded 24 hours in some of the investigated watersheds. Thus, the hypothesis is that the current critical rainfall duration using 24-hour rainfall duration, or the time of concentration is not appropriate for design flood estimation. The application of the appropriate rainfall duration, considering watershed characteristics and conditions, is absolutely required for more accurate design flood estimation. Determining design floods accurately is difficult, particularly in areas that do not have enough hydrologic data, such as in Southeast Asian countries. Therefore, a way to rationalize the appropriate rainfall duration has to be established for more accurate design flood estimation in those regions by overcoming the limited data availability using a hydrologic model.

There still are some gaps between hydrologic research and its practical application. Research usually proposes the design flood based on the highest peak flow obtained from the intensity-duration-frequency (IDF) curve. However, the results of latest hydrologic research are rarely practically applied. In the practical application, if the estimated design flood value is over- or underestimated, it will cause problems such as the wasting of resources (e. g., money, time, manpower, and materials) and excessive disasters, respectively. Thus, a well-designed flood value can provide rational and valuable support for the decision-making processes initiated by practitioners, such as designing the hydraulic infrastructure[8,14]. In addition, a wise choice of rainfall duration reflecting the watershed conditions would lead to the rational flood design under the monsoon climate. Accordingly, this research aims to integrate these gaps for design flood estimation in a manner that is acceptable for stakeholders and practitioners. This research, thus, is dedicated to (1) determining the rational rainfall duration in the Johor River Watershed for a more reasonable design flood estimation and (2) estimating the design flood value using the hydrological frequency analysis and rainfall-runoff simulation that considers the rainfall duration under the monsoon climate. The design flood value for the Johor River Watershed is finally provided in the results and discussion section.

2. Methodology

2.1 Target watershed

The Johor River Watershed—the target watershed of this research—is located in the southern region of Peninsular Malaysia (**Fig. 1**). **Table 1** summarizes the characteristics of the watershed and its main stream, the Johor River[15,16]. The origin of the main stream is Mt. Gemuruh, and the highest point of the main stream is 46.0 m. The Johor River has a gentle slope with a long time of concentration, 2.9 days, based on the preliminary investigation[16] using the Bransby-Williams' Equation[10]. Kota Tinggi, which is located in the lower basin of the main stream, is the major city area in the watershed. Approximately 70% of the watershed is occupied by forest and farmlands consisting of oil palm and rubber plantations[17].

The Johor River Watershed was one of the most

Table 1 Characteristics of the Johor River Watershed and its main stream[15,16]

Length of mainstream (km)	122.7
The highest point of mainstream (m)	46.0
Time of concentration (days)	2.9
Catchment area (km^2)	1,655.0

severely damaged areas during two flood events that occurred in December 2006 and January 2007. In fact, the two flood events in the Johor River Watershed are representatives of the flooding in Peninsular Malaysia. They revealed one of the defining characteristics of Malaysian watersheds, that is, the continuous rainy days during monsoon season[3,4,18-20]. Thus, rational flood design criteria considering the unique characteristics of the watershed environment are needed to effectively prevent/mitigate the damage of floods.

2.2 Data collection

Table 2 shows the major data sets collected for the Johor River Watershed and used for the latter analyses in this research. The daily rainfall data from 1951 to 2007 (57 years) were obtained from the Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE). APHRODITE provides high-precision rainfall data and recently it has been utilized in many hydrological analyses[21-23]. The other weather information data, such as temperature and solar radiation, and the watershed information data based on a geographic information system (GIS), such as a Digital Elevation Model (DEM) and land cover, were also collected for the Johor River Watershed to construct a rainfall-runoff simulation model. The daily flow rate data observed by the Department of Irrigation and Drainage Johor were collected at the Rantau Panjang gauging station (Latitude 01 46 50 and Longitude 103 44 45) from 1964 to 2010 (47 years).

2.3 Rainfall duration design

In this research, four investigations were conducted to determine the most rational rainfall duration for design flood estimation in the Johor River Watershed. The most rational rainfall duration was finally determined based on a comprehensive consideration of the four investigations.

First, the lengths of rainfall event duration were surveyed (Investigation 1) to find the most frequent rainfall duration and grasp the dominant rainfall duration on the basis of historic rainfall events. Second, rainfall time series patterns were investigated by normalizing the rainfall amounts of each event (Investigation 2) to reveal the main rainfall duration of the continuous rainy days by ignoring low rainfall durations. This investigation allowed us to focus on the most significant rainfall duration in the historic rainfall records. In Investigation 2, the centroids of every rainfall time series were estimated to arrange them based on Equation (1) since the rainfall time series has patterns, such as the forward-peaked, centrally-peaked, and backward-peaked rainfall time series. After that, the mean amount of rainfall for each day was calculated. The equation for calculating the x value of the centroid of the rainfall time series is:

$$x_{centroid}=\frac{\sum_{i=1}^{n} i\times R_i}{\sum_{i=1}^{n} R_i} \qquad (1)$$

where R_i is rainfall amount (mm) on the day ith in the rainfall time series. Each rainfall time series was then normalized based on the total amount of rainfall in each event to directly compare the rainfall time series.

The two investigations mentioned above are based on the rainfall characteristics. As the flooding phenomena are governed by a combination of rainfall and watershed characteristics, the runoff characteristics of the target watershed should also be considered to provide reasonable design flood criteria. Thus, the third investigation focused on rainfall-runoff simulations with diverse rainfall amounts and patterns (Investigation 3). Comprehensive hydrologic modeling and simulations enabled us to figure out the critical rainfall amount and duration that caused a certain level of flood peak at a reference river point. Finally, a hydrological frequency analysis was conducted for various rainfall durations, and the results were compared to the frequency analysis

Table 2 Major data sets collected and used in this research

Data type	Data set	Period	Source agency
Rainfall	APHRODITE	1951-2007	APHRODITE's Water Resources
Temperature Solar radiation	Climate Forecast System Reanalysis	2006-2007	National Centers for Environmental Prediction (NCEP)
DEM	SRTM-3	2000	National Aeronautics and Space Administration (NASA)
Land cover	Global Land Cover Product	2006	European Space Agency
Flow rate	Observed daily flow rate	1964-2010	Department of Irrigation and Drainage Johor

results using the historic river discharge data (Investigation 4). The comparison of the two hydrological frequency analysis results allowed us to determine which rainfall duration was the most rational to come up with the most reasonable flood design value.

2.4 Extraction of rainfall events

Prior to conducting the four investigations mentioned above, historic rainfall events were extracted from the collected rainfall data based on several thresholds shown in **Table 3**. First of all, the threshold of the daily rainfall was considered in the extraction process. Since the Johor River Watershed has the specific rainfall characteristic of the consecutive rainy days during the NE monsoon season, determining the daily rainfall threshold to extract an event was one of the important parts of the research. If the 1.0 mm/day threshold of a rainy day that is defined and used in several studies[16,17] is used as the threshold for the extraction of rainfall events, the duration of one rainfall event could vary widely and it would sometimes become remarkably long (e.g., more than one month). In that case, it is difficult to extract an event and determine the critical rainfall duration that causes flooding. In this research, the mean daily rainfall of the watershed average of the Johor River, which was 5.99 mm/day from 1951 to 2007, was used as the threshold of daily rainfall. This means that rainy days where the amount of rainfall was less than 5.99 mm/day were disregarded when extracting a rainfall event. Then, the extracted rainfall events were divided into three classifications based on the thresholds of the total rainfall amount for an event. According to Muhammad (2013)[20] and Abdullah et al. (2016)[5], the flood threshold based on rainfall amount in an event ranged from 140 to 170 mm. This research thus divided the extracted rainfall events into three classes: 100, 150, and 200 mm/event. **Table 3** also shows the number of rainfall events (frequency) extracted for each rainfall amount.

Table 3 Thresholds for the rainfall event extraction and the frequencies of the events

Rainfall amount (mm/event)	Range (mm/event)	Daily Rainfall (mm/day)	Event frequency
100	75-125		124
150	125-175	5.99	30
200	175-225		20

2.5 Hydrologic modeling and parameter setting

To implement rainfall-runoff simulations, this research utilized a GIS-based off-the-shelf hydrological simulation model, the Hydrological Simulation Program-FORTRAN (HSPF). The model has been developed by the U.S. Environmental Protection Agency[24], and it simulates flow rate as well as non-point pollution loads from a watershed to a river based on the watershed information. Many studies have applied HSPF for rainfall-runoff simulation during flood events, and its applicability has already been approved in those studies[25-27]. For the parameter calibration of HSPF, the Parameter ESTimation (PEST) package that provides various efficient optimization algorithms was equipped. The algorithms were proved and utilized in various optimization cases[28-30]. In this research, for calibration the Gauss-Marquardt-Levenberg algorithm[31] was applied to three flood events that occurred in January of 2006, December of 2006, and January of 2007 at the outlet of the upper sub-basin of Kota Tinggi in the Johor River Watershed. The coefficient of determination (R^2), the Nash-Sutcliff Efficiency (NSE), and the index of agreement (D) were all used as the criteria to evaluate the model's performance. The formula of R^2, NSE, and D are respectively described as follows:

$$R^2=\left[\frac{\sum_{i=1}^{n}(Y_i^{obs}-Y^{mean,obs})(Y_i^{sim}-Y^{mean,sim})}{\sqrt{\sum_{i=1}^{n}(Y_i^{obs}-Y^{mean,obs})^2}\sqrt{(Y_i^{sim}-Y^{mean,sim})^2}}\right]^2 \quad (2)$$

$$NSE=1-\left|\frac{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs}-Y^{mean,obs})^2}\right| \quad (3)$$

$$D=1-\frac{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})^2}{\sum_{i=1}^{n}(|Y_i^{sim}-Y^{mean,obs}|+|Y_i^{obs}-Y^{mean,obs}|)^2} \quad (4)$$

where Y_i^{obs} is the ith observation for the constituent being evaluated, Y_i^{sim} is the ith simulated value for the constituent being evaluated, $Y^{mean,obs}$ is the mean of the observed data, and $Y^{mean,sim}$ is the mean of the simulated data in the period under evaluation. The ratings of these criteria were summarized by Moriasi et al. (2007)[32] for R^2 and NSE, and by Krause et al. (2005)[33] for D. In summary, the perfect agreement is achieved when R^2, NSE, and D are equal to 1.0[34]. The hydrographs of the three flood events after the parameter calibration of HSPF will be shown below in the results and discussion section.

2.6 Hydrological frequency analysis

This research conducted two hydrological frequency analyses using both the historic rainfall and river discharge data in the Johor River Watershed. First of all, the probable rainfall values corresponding to the representative design values (e.g., 50-, 100-, and 200-year return periods) were estimated based on the frequency analysis using the historic rainfall data with rainfall durations of 2 to 8 days. Then, the estimated rainfall amounts were input into HSPF, and the peak flows were simulated for each return period of all durations. For the frequency analysis using the river discharge data, the probable river discharge values corresponding to the same return periods with the probable rainfall were estimated. The results were regarded as reference values to evaluate the flood peak amounts from the rainfall-runoff simulations. By comparing the peak flows obtained through the two hydrological frequency analyses, we were able to make certain which rainfall duration was the most rational for providing the most reliable design flood values.

For the hydrological frequency analysis conducted in this research, the Generalized Pareto (GP) distribution, known as an extreme-value distribution, was applied to represent the extreme values of both the historic rainfall and river discharge data in the Johor River Watershed. The GP distribution has been employed for the extreme values and its suitability for both rainfall and river discharge in the Johor River Watershed has already been clarified[14]. When x, a, k, and ξ respectively denote a hydrologic variable, the scale parameter, the shape parameter, and the location parameter, the following equations are used to calculate the GP distribution:

- Probability Density Function

$$f(x)=\frac{1}{a}\left(1-k\frac{x-\xi}{a}\right)^{\frac{1}{k}-1} \qquad (5)$$

- Cumulative Distribution Function

$$F(x)=1-\left(1-k\frac{x-\xi}{a}\right)^{1/k} \qquad (6)$$

- Probable hydrologic value (x_p) that corresponds to the non-exceedance probability (p)

$$x_p=-\frac{a\{(1-p)^k-1\}}{k}+\xi \qquad (7)$$

3. Results and Discussion

3.1 Investigation 1: Lengths of rainfall event duration

The lengths of the rainfall event duration were surveyed to find the most frequent and dominant rainfall duration based on the historic rainfall events extracted by the process described in 2.4. **Fig. 2** shows the results; the ratio of the historic rainfall event durations at 100, 150, and 200 mm/event, respectively. According to the results, the rainfall duration, which ranges from 2 to 7 days at 100 mm/event, 3 to 6 days at 150 mm/event, and 4 and 6 days at 200 mm/event, was dominant. In other words, multiday rainfall events that lasted for more than 2 days were apparently the most frequent historic rainfall events. Therefore, it has been reconfirmed that multiday rainfall events should be taken into consideration when determining the design flood value in the Johor River Watershed. Overall, this investigation confirmed that rainfall events that lasted for 4 to 6 days were particularly dominant in this watershed.

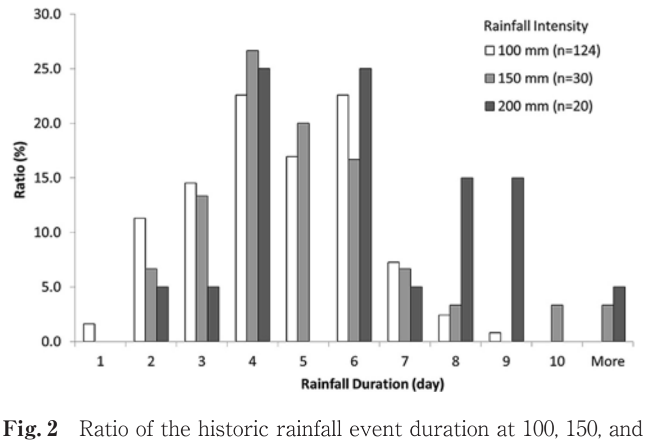

Fig. 2 Ratio of the historic rainfall event duration at 100, 150, and 200 mm/event in the Johor River Watershed

3.2 Investigation 2: Patterns of rainfall time series

The rainfall time series patterns of the historic rainfall events were investigated by normalizing the rainfall amount of each event to disclose the main rainfall duration of the continuous rainy days and

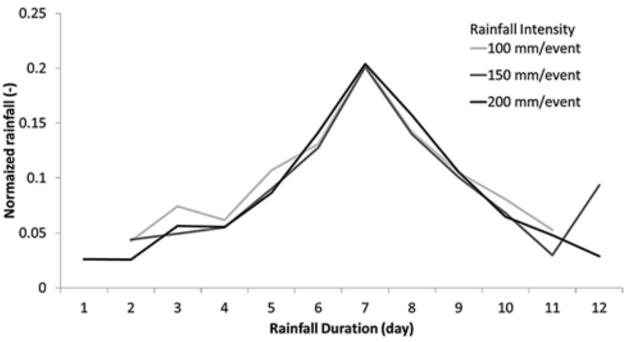

Fig. 3 Normalized rainfall time series based on the total amount of rainfall in the Johor River Watershed

ignoring low rainfall durations. This investigation enabled us to focus on the most significant rainfall duration in the historic rainfall records. **Fig. 3** shows the results of the normalization, which is able to confirm the most significant rainfall duration in the normalized rainfall time series. It shows that the periods from the rising point to the endpoint almost agreed. This means that the periods indicate the main rainfall duration when the low rainfall duration is ignored, and the period would therefore be significant rainfall duration in the rainfall time series. In **Fig. 3**, it was confirmed that the rainfall duration of up to 7 days was the most significant in every time series. Therefore, this investigation revealed the main rainfall duration, which is up to 7 days, when low rainfall was disregarded in the historic rainfall time series of the Johor River Watershed.

3. 3　Investigation 3 : Rainfall-runoff simulations

(1) Evaluation of model performance

Fig. 4 shows the hydrographs of the three flood events simulated by HSPF. The evaluated model's performance criteria（R^2, NSE, and D）for each event are summarized in **Table 4**. These results indicate that the calibrated HSPF has good reproducibility for

Table 4 Model's performance criteria evaluated for the three flood events in the Johor River Watershed

Event	Period	R^2	NSE	D
(A)	January, 2006	0.97	0.97	0.99
(B)	December, 2006	0.87	0.79	0.95
(C)	January, 2007	0.96	0.82	0.97

flood events in the Johor River Watershed. Although all three events, particularly Event A, were simulated well, the simulated peak flows of Events B and C were overestimated when the peak rainfall exceeded 100 mm/day. In other words, the observed peak flows were lower than the simulated flows during the events. It should be noted that there is the Linggui Dam（see **Fig. 1**）, which supplies water to Singapore, in the upper stream of the Linggui tributary. There is a possibility that the river discharge was manipulated by the dam operation so that the peak flows were reduced when the actual floods occurred. However, the dam is perpetually controlled by Singapore, and information on the dam's operations is strictly managed by Singapore. Since this research was not able to obtain this information, the dam was regarded as a natural water body during runoff simulations. Because the dam operation occasionally affects the flow rate of the Johor River, this research leaves the incorporation of the Linggi Dam operation in the modeling process for future research.

(2) Peak flow simulations

By using the formulated HSPF, peak flows with diverse rainfall amounts and rainfall patterns were simulated while considering the rainfall-runoff characteristics of the Johor River Watershed. The amount and duration of the critical rainfall that caused a certain level of flood peak were figured out using the rainfall-runoff simulations. Several combinations of rainfall amount and duration in one event were input

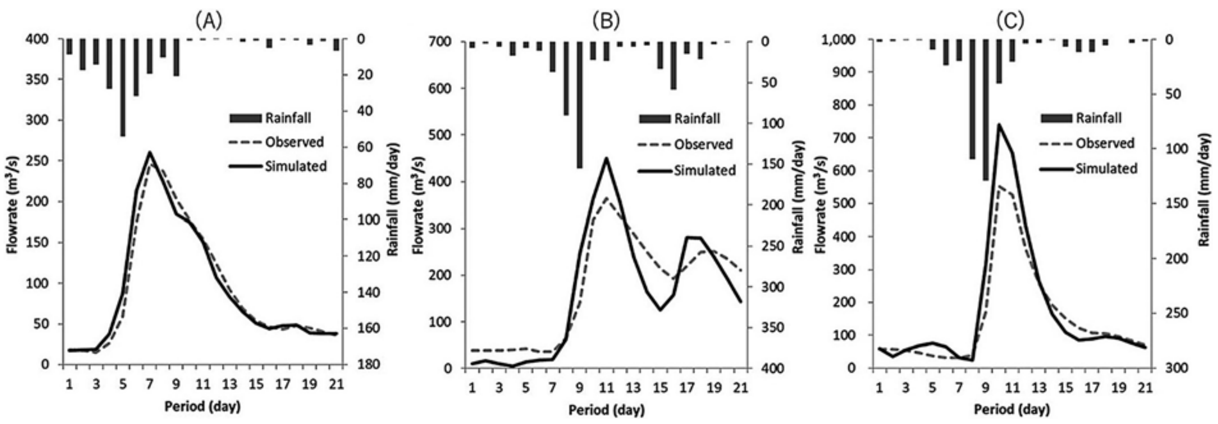

Fig. 4 Hydrographs of three flood events that occurred in（A）January of 2006,（B）December of 2006, and（C）January of 2007 in the Johor River Watershed

into HSPF. The peak flows of each combination were then simulated. The rainfall amounts of 100, 150, and 200 mm/event and rainfall durations of 2 to 8 days were selected as the combinations for the runoff simulations. Moreover, when conducting the runoff simulations, this investigation took into account three patterns of rainfall time series: forward peaked, centrally peaked, and backward peaked, based on the estimated centroids. So far, however, the peak flow threshold, which causes flooding in the Johor River Watershed, has not been studiously inspected and clearly decided on yet. For that reason, 238 m^3/s of peak flow, which is the mean value of the historic annual maximum floods based on the statistics, was employed as the flood threshold value, which may trigger a flood in this investigation. The procedure for obtaining the statistical characteristics of the historical annual maximum floods was based on a study conducted by Ismail et al. (2015)[35]. The return period of the threshold is approximately 2.7 years. If the simulated peak flow exceeded the threshold value, it was regarded as a flood event.

Table 5 shows the results of simulated peak flows for each combination of rainfall amount and duration. In 100 mm events, the rainfall duration of 3 and 4 days is the boundary for causing floods based on the peak flow threshold. In the same way, for 150 mm and 200 mm events, the durations of 5 and 6 days and over 7 days are the boundaries, respectively. Since the flood threshold of the rainfall amount for an event ranged from 140 to 170 mm[20], this investigation suggested that the duration of 5 and 6 days, which was derived from the rainfall-runoff simulations for 150 mm events (ranging from 125 to 175 mm), is the critical rainfall duration when the rainfall-runoff characteristics of the Johor River Watershed are considered using the hydrologic model.

3.4 Investigation 4: Comparison of the hydrological frequency analyses using historic rainfall and river discharge data

In Investigation 4, rainfall duration from 2 to 8 days and return periods of 2.5, 5, 10, 25, 50, 100, and 200 years were considered in the frequency analysis using rainfall data. Then, the estimated probable rainfall amounts were input into HSPF, and the peak flows for each return period of all durations were simulated. At the same time, the peak flows corresponding to 2.5, 5, 10, 25, 50, 100, and 200-year return periods were estimated using the frequency analysis with the river discharge data. The comparison of the peak flows obtained through the two hydrological frequency

Table 5 Simulated peak flows (m^3/s) for each combination of rainfall amount and duration with a (a) Forward-peaked, (b) Centrally-peaked, and (c) Backward-peaked rainfall pattern, and (d) Maximum peak flows extracted from (a), (b), and (c)

(a)	Rainfall Duration (day)						
(mm/event)	2	3	4	5	6	7	8
100	245.8	240.8	206.3	191.3	189.8	164.0	123.8
150	360.6	398.6	364.9	228.6	256.6	181.9	232.2
200	531.3	448.1	395.0	395.0	362.7	345.5	234.3

(b)	Rainfall Duration (day)						
(mm/event)	2	3	4	5	6	7	8
100	324.0	301.0	258.7	192.7	163.3	148.2	135.3
150	360.6	398.6	317.5	239.3	335.5	181.9	232.2
200	531.3	448.1	475.3	395.0	323.3	345.5	254.4

(c)	Rainfall Duration (day)						
(mm/event)	2	3	4	5	6	7	8
100	329.7	248.7	244.4	182.7	179.8	174.8	136.0
150	354.1	448.1	301.7	337.6	222.1	231.4	232.2
200	531.3	244.4	432.3	395.0	400.0	345.5	282.4

(d)	Rainfall Duration (day)						
(mm/event)	2	3	4	5	6	7	8
100	329.7	301.0	258.7	192.7	189.8	174.8	136.0
150	360.6	448.1	364.9	337.6	335.5	231.4	232.2
200	531.3	448.1	475.3	395.0	400.0	345.5	282.4

Note: The values hatched in gray exceed the flood threshold value

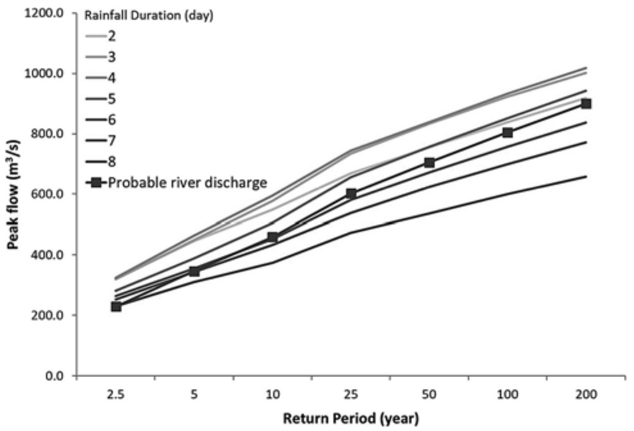

Fig. 5 Results of the peak flows obtained through the two hydrological frequency analyses using both rainfall and river discharge data in the Johor River Watershed

analyses allowed us to make certain which rainfall duration was the most reasonable for providing the most reliable flood design values. **Fig. 5** shows the comparison of the peak flows obtained by the two hydrological frequency analyses. The simulated peak flows in the shortest return period (2.5-year) were relatively convergent. However, the larger differences among the simulated peak flows were observed when the longer return periods were considered. For example, the minimum peak flow for the 2.5-year return period is 230.7 m^3/s at the 8-day rainfall duration, and the maximum peak flow for the 2.5-year return period is 324.5 m^3/s at the 4-day rainfall duration. However, the minimum peak flow for the 200-year return period is 658.3 m^3/s at the 8-day rainfall duration, and the maximum peak flow for the 200-year return period is 1,018.4 m^3/s at the 4-day rainfall duration even though the reference value for the 200-year return period is 899.5 m^3/s. This means that the choice of rainfall duration clearly leads to bigger differences among the peak flows of the longer return periods. In the practical application, if the estimated design flood value is over- or underestimated, it will cause problems[14]; thus, a wise choice of rainfall duration allows the practitioners to conduct rational design flood estimation.

Overall, the peak flows simulated by HSPF from 2- to 5-day rainfall durations indicated entirely higher values than the peak flows estimated by the frequency analysis using the river discharge data. On the other hand, the simulated peak flows for durations of more than 6 days indicated lower values than the estimated peak flows of the longer return periods. This research considered higher return periods, over 50 years, because the 100-year return period has been utilized at a basic level for designing hydraulic structures in Malaysia[10]. In that case, the estimated peak flows lie between 5- and 6-day rainfall durations in the return periods of over 50 years. Therefore, this investigation suggested that 5- to 6-day rainfall duration was reasonable for design flood estimation in the Johor River Watershed.

3.5 Recommended rainfall duration and design flood value for the Johor River Watershed

The most rational rainfall duration for the flood design procedure in the Johor River Watershed was determined based on the comprehensive consideration of the four investigations. Given that each investigation suggested a range of rainfall durations, this research recommends that the overlapped rainfall duration of 5 days should be employed for the design flood estimation in the Johor River Watershed. Since the 100-year return period has been utilized for designing hydraulic structures in Malaysia, this research determined the flood design value based on the simulated peak flow for the 100-year return period. Based on the results shown in **Fig. 5**, the flood design value in the Johor River Watershed was 851.0 m^3/s.

The rainfall duration of 4 days, which output the maximum peak flows, could be used if we follow the conventional idea of the critical rainfall duration that gives the maximum peak flow in the simulation. In reality, however, acceptable design floods that reflect the actual conditions and the rainfall-runoff characteristics of the watershed are required to prevent the locals from wasting resources. In that sense, choosing of the 4-day rainfall duration led to the overestimation (+15.9%) of the design flood value compared to the reference value obtained from the frequency analysis using the river discharge data for the 100-year return period. In addition, the 3-day rainfall duration that was almost equivalent to the time of concentration of the Johor River Watershed also led to the overestimation (+14.7%). The 6-day rainfall duration, on the other hand, was also the overlapped rainfall duration obtained from four investigations. However, the simulated peak flows were underestimated for longer return periods. When we focused on the 100-year return period, the underestimation (−5.8%) of the peak flow compared to the reference value was confirmed, and this might cause excessive disasters. When the safe side is considered, therefore, the 5-day rainfall duration is the most rational when it comes to providing the most reasonable design flood value for the Johor River Watershed.

4. Conclusions

In this research, as one of the most specific climatic characteristics under the monsoon climate, the continuous rainy days were taken into consideration of design flood estimation. Four investigations, including two rainfall characteristics surveys, rainfall-runoff simulations, and the hydrological frequency analysis, were conducted to determine the most rational rainfall duration in the Johor River Watershed. Based on the results of the four investigations, 5 days was the most rational rainfall duration to use in order to provide the most reasonable design flood value for the Johor River Watershed. This research finally clarified the flood design value of 851.0 m^3/s based on the hydrological frequency analyses and the runoff simulations. We propose the methodology and procedures of the four investigations as the platform to be able to determine the rational rainfall duration in the design flood procedure for not only the Johor River Watershed but also for other watersheds in monsoon regions with similar climatic characteristics. Accordingly, there need to be more application studies for other watersheds in monsoon regions to further confirm the applicability of these investigations and to generalize the methodology.

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マレーシア・ジョホール川流域における統合的流域管理へ向けた洪水設計基準の推定

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概　要

本研究では，洪水の頻発するマレーシアのジョホール川流域においてモンスーン特有の長期的な降雨イベントを考慮した合理的な洪水設計基準を構築するため，水文頻度解析における最適な降雨継続期間を決定する方法論を検討した。二種類の降雨特性解析，Hydrological Simulation Program-FORTRAN（HSPF）を用いた流出解析，および水文頻度解析の四段階の解析を行った結果，当該流域では5日降水量を洪水設計へ使用すべきことが示され，流出解析により851.0 m^3/s の洪水設計値を算出した。このように流域の特性を考慮した洪水設計値は，より効率的な河川構造物の設計等へ利用可能である。

キーワード： モンスーン気候，降雨継続期間，洪水設計基準，水文頻度解析，ジョホール川流域