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Reevaluation of Design Flood Discharge under Climate Change: Future Peak Flow Projection in the Johor River Watershed, Malaysia

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Abstract. This study aims to develop the intensity-duration-frequency (IDF) relationships for the historical (1979-2003) and future (2075-2099) scenarios, and to evaluate changes in estimated design flood values and return periods in the Johor River Basin, Malaysia. The hydrological frequency analysis, using historical and future rainfall scenarios, was then conducted to estimate changes in design flood values (peak flows). The Hydrological Simulation Program-FORTRAN was used for runoff simulations. The changes in the return periods of the estimated flood values were assessed using the cumulative distribution function mapping method. As an example of the results under the future scenario, a design flood value with a 5-day rainfall duration will become 992.1 m^3/s (i.e., an increase of 58.1% compared to the historical scenario) based on the future IDF relationship. The return period for this value is 282.8 years based on the historical IDF relationship. This means that the current planning scale, e.g., the 100-year return period commonly used in Malaysia, might not be adequate and should be extended to prevent and/or mitigate the damage from devastating floods under climate change.

Keywords: Climate change; Hydrological frequency analysis; IDF relationship; CDF mapping; Johor River Basin.

1.0 Introduction

The increasing frequency of floods is a serious concern in Malaysia. Malaysia consists of Peninsular Malaysia and the Malaysian portion of Borneo Island, near the equator. The temperature and humidity are thus relatively high year-round. There are two main monsoon seasons, the Southwest (SW) from May to September, and the Northeast (NE) from November to March (Chan, 1995; Julien et al., 2015; Muhammad et al., 2015). Various industries, such as fabrication, rubber, and palm oil, thrive on abundant water resources. Hence, land has been developed at a fast pace over the last few decades, with concomitant urbanization. Almost all Malaysian watersheds have been influenced by these climatic conditions and land development since these industries became active. In addition, climatic and societal conditions have greatly influenced watershed issues, particularly floods. Two major monsoon seasons trigger frequent floods almost every year (Muzamil et al., 2022). Rapid land-use changes driven by industrialization, urbanization, and deforestation intensify the negative consequences of such climatic disasters (Julien et al., 2015; Abdullah et al., 2016). In particular, the Johor River Watershed, located in the southern part of Peninsular Malaysia, has experienced repeated flooding in recent decades due to both monsoon rainfall and urban expansion, making it a representative example of how climate and land-use changes jointly affect hydrological risks in tropical monsoon basins (Abdullah et al., 2016).

To determine design flood values, hydrological frequency analysis is well established in the hydrological engineering field (Mizuki & Kuzuha, 2023). However, a concrete design flood system that considers the monsoon region's unique climatic characteristics, along with the impact of climate change on the area, is needed for Malaysian watersheds. With the changes brought about by global warming, rainfall events —specifically rainfall patterns and heavy rain frequency —will become more consequential (Muhammad et al., 2015). Moreover, future peak flow changes should be investigated alongside future extreme rainfall changes, as local planners and administrators seek insights into how climate change affects the peak flow of a flood event for future river planning and management. Despite the growing urgency, most current design standards in Malaysia rely on historical observations and do not reflect potential future changes in hydrological behavior.

Recent research on river discharge projections has revealed long-term spatiotemporal variations in response to climate drivers. River discharge in monsoon Asia is often synchronized, with megadroughts and large floods simultaneously occurring across multiple basins (Nguyen et al., 2020). Future projections of mean annual discharge in South and Southeast Asia show that it is expected to increase in many basins by the end of the 21st century, with a range of change of 6.3-109% in Southeast Asia, based on the multi-scenario models (Shrestha et al., 2021). In particular, under the Representative Concentration Pathways 8.5 (RCP8.5) scenario, where global warming continues, it is predicted that extreme flood events will occur more frequently, along with increased river flow, in tropical Asia (Müller et al., 2024). These results are essential evidence for the underestimation of the historical stability of long-term water resources and for sustainable basin management in the future. However, while regional trends are becoming clearer, the hydrological impacts at the individual watershed scale remain uncertain, especially in Malaysia, where localized studies are limited.

Studies focusing on a specific river basin, e.g., the Chao Phraya River basin, have predicted future changes, such as delayed rainfall peaks due to increased rainy season precipitation, while dry season discharge is expected to decrease (Champathong et al., 2013; Hunukumbura & Tachikawa, 2012; Kure & Tebakari, 2012). The range of discharge fluctuations varies by river and tributary. While flood peaks are predicted to increase, some branches are showing a decreasing trend, indicating uncertainties in water resource management. Given such basin-specific variations, it is crucial to conduct watershed-level projections to provide robust information for climate-resilient infrastructure design.

Although Malaysian watersheds are vulnerable to floods (Muzamil et al., 2022), no studies have yet applied an approach that compares river conditions and return periods between the historical/control and future periods at a watershed scale. In this study, therefore, runoff simulations are carried out to investigate future peak flow changes using a hydrological simulation model in the Johor River Watershed, Malaysia, as a case study. This study aims to propose a design flood value that accounts for future climate change and to explore ways to improve the current design flood estimation system to reflect projected changes in flood characteristics. By incorporating climate projection data into a physically based hydrological model, this study provides a methodological framework for updating flood design standards under future scenarios.

2.0 Methodology

2.1 Study Area

The target area of this study is the Johor River Watershed in the state of Johor, Malaysia (Figure 1). The Johor River originates from Mt. Gemuruh. The mainstream is 122.7 km long, with a total watershed area of 1,655 km^2 (UNESCO, 1997; Yazawa et al., 2019a). Kota Tinggi is the principal city in the Johor River Watershed; it is located downstream of the Johor River. The Johor River Watershed plays a pivotal role in water supply for both Johor state and Singapore, as the Linggui Dam is located in the upper reaches.

The Johor River Watershed has been one of the most severely damaged areas from flooding. The flood events usually occur during the NE monsoon season (Department of Irrigation and Drainage Malaysia, 2009; Razi et al., 2010). One of the defining characteristics of Malaysian watersheds is the continuous rainfall during the monsoon season (Suhaila & Jemain, 2007; Muhammad et al., 2015; Muhammad & Julien, 2015). Multiday rainfall events are widespread during the monsoon season in the Johor River Watershed, and it is well known that flooding is an unavoidable natural phenomenon given such a rainfall characteristic (Chan, 1995). Furthermore, once flooding occurs, it can last for a week or longer (Julien et al., 2015; Abdullah et al., 2016).

When two devastating floods occurred from December 2006 to January 2007, the Johor district received extreme damage. In the Johor River Watershed, Kota Tinggi suffered severe damage (Department of Irrigation and Drainage Malaysia, 2009). During these events, the observed maximum water levels at Kota Tinggi were reportedly up to 5.0 m in December 2006 and 5.5 m in January 2007. In this area, the dangerous, alert, and normal water levels are 2.8, 2.5, and 2.1 m, respectively (Abdullah & Julien, 2014; Abdullah et al., 2016). Therefore, most of the city was flooded, and many residents had to be evacuated.

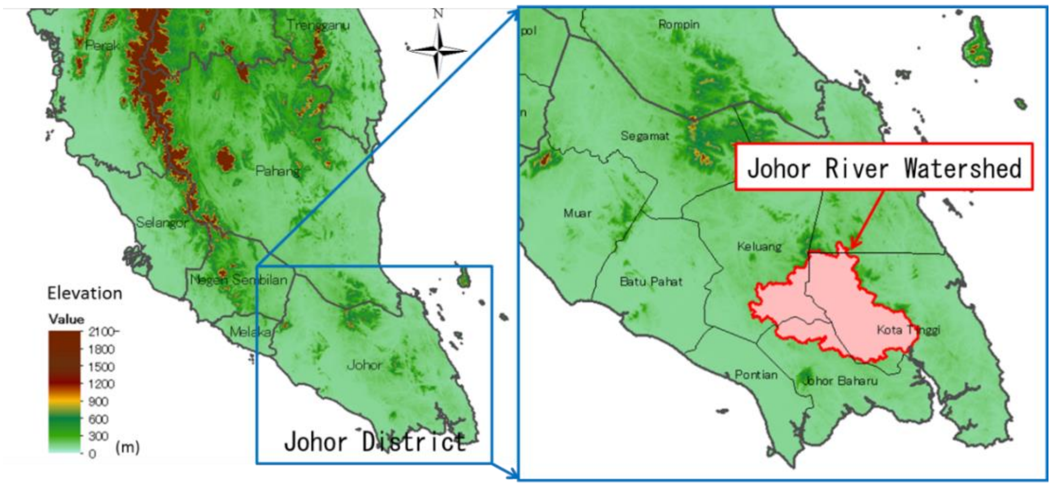

Figure 1. *Location of the Johor River Watershed, located in Southern Peninsular Malaysia (Yazawa, 2017)*

2.2 Data Sources

To implement rainfall-runoff simulations, this study uses a Geographic Information System (GIS)-based hydrological simulation model, the Hydrological Simulation Program-FORTRAN (HSPF). To apply a hydrological model to the Johor River Watershed, this study collected two primary types of data: GIS data based on watershed information (e.g., topography and land cover) and time-series data based on weather information (e.g., rainfall and temperature).

This study used a digital elevation model (DEM) called SRTM-3, obtained from the Shuttle Radar Topography Mission (SRTM) of the National Aeronautics and Space Administration, with a spatial resolution of 3 arc-seconds. The DEM data were edited in ArcGIS to merge split data, reclassify missing values, and remove pits. Figure 2(a) shows the land cover of the Johor River Watershed. The land cover data, known as the Global Land Cover Product, were obtained from the European Space Agency. The upper part of the basin on the north side is mainly occupied by forest, while farmlands of palm oil and rubber plantations mainly occupy the lower part of the basin.

This study obtained daily gridded rainfall data from 1951 to 2007 (57 years) based on Asian Precipitation—Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE, Yatagai et al., 2009; Yasutomi et al., 2011; Yatagai et al., 2012; Rathore, 2014; Singla et al., 2014; Yatagai et al., 2014). The resolution is 0.25° over the Johor River Watershed. Time-series data on maximum temperature, minimum temperature, and solar radiation are required to calculate potential evapotranspiration in the watershed. This study used Climate Forecast System (CFS) Reanalysis data obtained from the National Centers for Environmental Prediction (NCEP). The CFS Reanalysis time series provides highly accurate weather data of high spatiotemporal resolution (Saha et al., 2010). Daily river discharge data observed by the Department of Irrigation and Drainage (DID) Johor were collected at the Rantau Panjang gauging station (Latitude 01 46 50 and Longitude 103 44 45) from 1964 to 2010 (47 years). In this study, the data were used to calibrate and verify HSPF by comparing simulation outputs to objective functions.

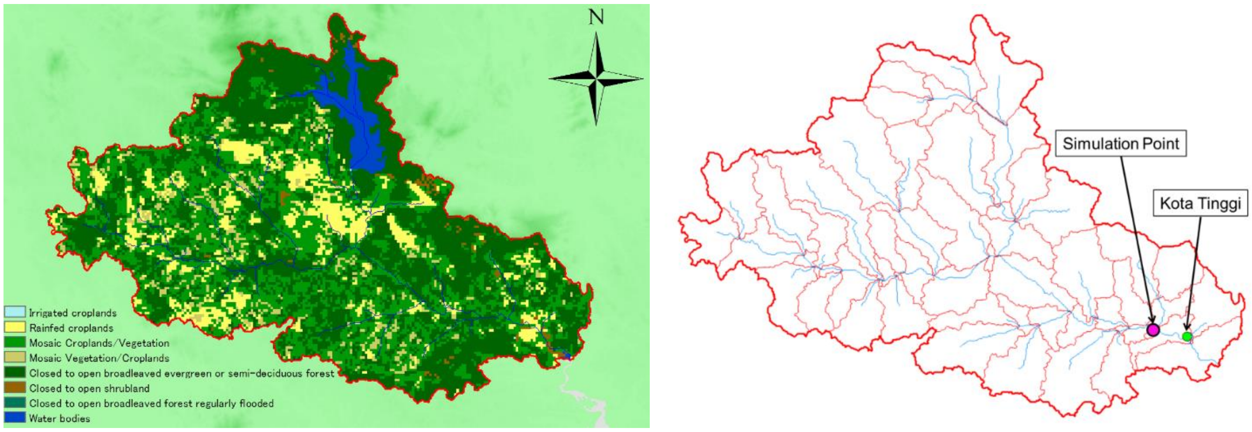

Figure 2. *(a) Topography, river lines, and 59 sub-basins of the Johor River Watershed, and (b) calibration and simulation points in this study*

2.3 Hydrological Simulation Framework

This study employed the previously calibrated HSPF model developed by Yazawa et al. (2019b) for the Johor River Basin. HSPF is a semi-distributed model capable of representing key watershed-scale hydrological processes, including evapotranspiration, infiltration, surface runoff, lateral flow, and base flow (U.S. EPA, 2001; Albek et al., 2004; Hayashi et al., 2004; Abdulla et al., 2009; Liu & Tong, 2011; Akter & Babel, 2012). It integrates land use, soil characteristics, topography, and meteorological inputs within a GIS-based framework to simulate streamflow.
In this study, the calibrated model was used in conjunction with bias-corrected future rainfall scenarios to simulate design flood discharges. Figure 2(b) identifies the outlet point of the upper sub-basin near Kota Tinggi, which was selected for analysis due to its historical susceptibility to flooding. This framework enabled translating rainfall extremes into peak discharge estimates under both historical and projected rainfall conditions.

2.4 Design Rainfall Generation

The outputs of a super-high resolution atmospheric model (AGCM20; Kim et al., 2009, 2010a, 2010b; Kitoh et al., 2016) were used to generate the design rainfall scenarios in this study. AGCM20 has a 20-km spatial resolution and a 1-hour time resolution. Future sea surface temperatures for the projection were estimated from the ensemble under the RCPs (Mizuta et al., 2012). In this study, the rainfall data simulated under the RCP8.5 scenario were used for the analyses. RCP8.5 corresponds to the pathway with the highest greenhouse gas emissions, and the details of the assumptions and conditions of the RCP8.5 scenario are summarized by Riahi et al. (2011).

We utilized the bias-corrected AGCM20 data over the Johor River Watershed (Yazawa et al., 2019b). Yazawa et al. (2019b) conducted a hydrological frequency analysis of rainfall using observed data (i.e., the APHRODITE datasets) and raw AGCM20 outputs for both the control period (1979–2003) and the future period (2075–2099). The biases of the obtained probable rainfall values were then directly corrected using the cumulative distribution function (CDF) mapping method (Yazawa & Shoji, 2023). To assess how the design flood value determined by Yazawa et al. (2019a) may change in the future, the IDF relationship obtained from the hydrological frequency analysis and runoff simulations using APHRODITE's rainfall data for 57 years was used as a historical scenario to differentiate from the control scenario.

Table 1 shows the rainfall scenarios set for the runoff simulations. The annual maximum rainfall with durations of 2 to 8 days was first extracted from three datasets: the observed data (i.e., the APHRODITE datasets for the historical period from 1951 to 2007) and the bias-corrected AGCM20 outputs for both the control and future periods. Then, the Generalized Pareto (GP) distribution was applied to the annual maximum rainfall to estimate the probable rainfall values for the Johor River. Probable rainfall values for durations of 2 to 8 days and return periods of 2.5, 5, 10, 25, 50, 100, and 200 years were derived for the historical, control, and future scenarios using hydrological frequency analysis.

Table 1. *Rainfall scenarios*

Scenario	Data used	Period
Historical	Asian Precipitation—Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE)	1951-2007
Control	Super-high resolution atmospheric model (AGCM20)	1979-2003

Future	2075-2099

2.5 Flood Discharge and Return Period Shift Estimations

Runoff simulations were carried out using HSPF to estimate peak flows using probable rainfall from three rainfall scenarios. After the runoff simulations, the intensity-duration-frequency (IDF) relationships were developed according to the simulated peak flows. Then the changes in the return periods of the peak flows were compared between the historical, control, and future scenarios. Finally, a design flood value for the future was estimated based on the IDF relationships of the simulated peak flows under the future scenario. Comparing the discharge frequency distributions across scenarios, we analyze the shift in return period using CDF Mapping (Yazawa & Shoji, 2023).

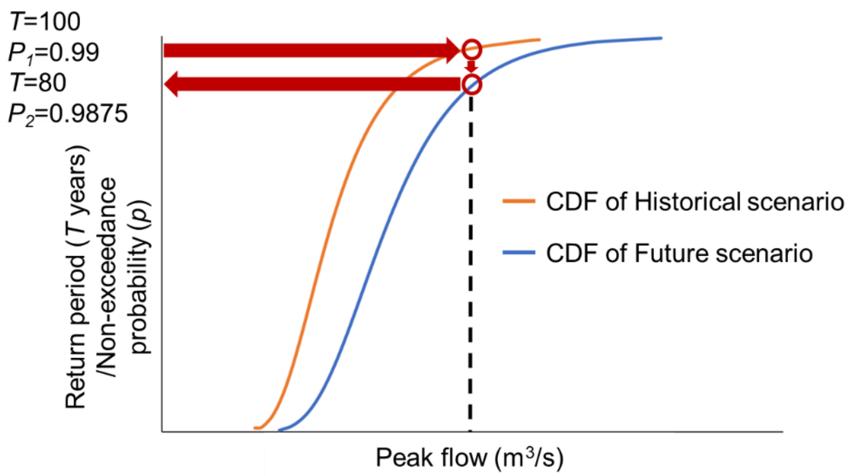

Figure 3. *Cumulative distribution function (CDF) mapping method suggested by Yazawa & Shoji (2023)*

3.0 Results and Discussion

3.1 Future Peak Flow Projections and IDF Curve Comparison

Figure 4 shows the obtained IDF relationships of all scenarios: (a) historical, (b) control, and (c) future, based on runoff simulations. When compared with the IDF curve relationship using probable rainfall estimated from the historical scenario for 57 years [Figure 4(a)], the results shown in Figure 4(b) tend to underestimate peak flows, particularly at shorter rainfall durations within more extended return periods. These differences are likely due to differences in sample size between the historical (N=57) and control (N=25) scenarios. The IDF relationship for the future scenario shows higher peak flows than those of the historical and control scenarios. Notably, the shorter the rainfall duration, the higher the simulated peak flows tend to be.

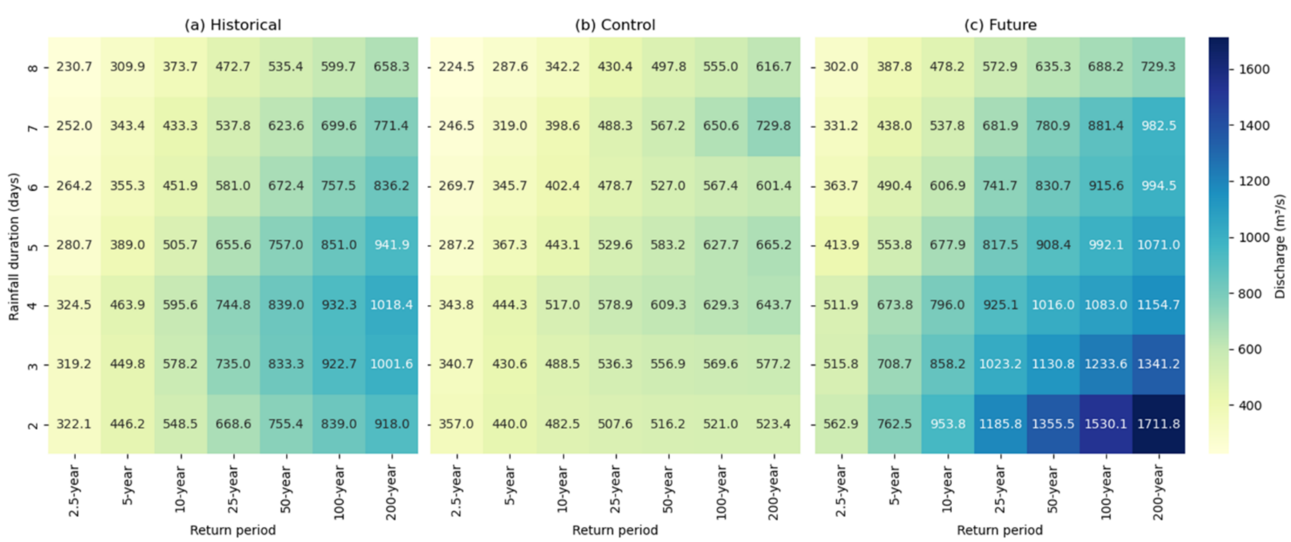

Figure 4. *Intensity-duration-frequency relationship of peak flows of the (a) historical, (b) control, and (c) future scenarios in the Johor River Watershed*

The peak flows of 4-day rainfall duration showed the maximum values in Figure 4(a). The future scenario shows that the highest peak flow occurs at the 2-day duration (i.e., the shortest rainfall duration), and then the peak flow decreases as the rainfall duration increases. Further investigations are required to clarify the reason behind these outcomes. As rainfall intensity increases, it may affect the peak flow of a flood event rather than the rainfall duration in the Johor River Watershed. Considering the impacts of climate change, if we follow the representative design flood criterion determined by Yazawa et al. (2019a), that is, the peak flow from a 5-day rainfall event with a 100-year return period, the design flood value will be 992.1 m^3/s in the future. This is a 58.1% increase over the design flood value of 851.0 m^3/s in the historical scenario.

3.2 Return Period Shift

Figure 5 shows comparisons of peak flow return periods between (a) the control and future scenarios and (b) the historical and future scenarios. In the peak flows with shorter rainfall durations (e.g., 2-6 days), the future return periods reach plateaus around the 50-year return period of the control scenario [Figure 5(a)]. These results indicate that, for example, the frequency of the 100- or 200-year control flood will increase significantly in the future. When the rainfall duration gets longer (e.g., 7 and 8 days), the future return periods increase along with increases in the control return periods. As the worst case, the control flood event for the 100-year return period becomes the event for the 2.8-year return period at the 2-day rainfall duration. Even with longer durations, such as 5 or 6 days, the future return period becomes significantly shorter. This means that 100-year floods at the current level would occur more frequently in the future. Similar situations have already been reported by Milly et al. (2002) in Asia.

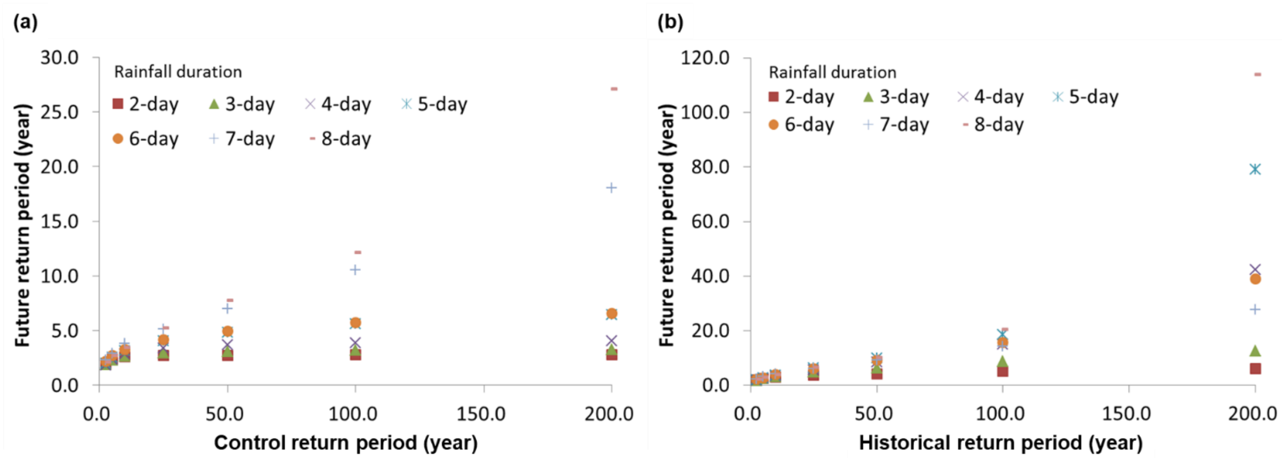

Figure 5. *Comparison of peak flow return periods between the (a) control and future scenarios and the (b) historical and future scenarios in the Johor River Watershed*

Figure 5(b) shows the comparison of return peak flow periods between the historical and future scenarios. According to Yazawa et al. (2019a), the peak flow for a 5-day rainfall duration at the 100-year return period, that is, 851.0 m^3/s, was determined as the design flood value based on the historical rainfall scenario. However, the future return period of the designed flood value becomes 18.5 years. This means that the design flood, determined using historical rainfall data (i.e., 57 years), would become approximately five times as frequent as in the historical situation in the future. In this case, the design flood value determined by Yazawa et al. (2019a) will not work at the end of the 21st century. Therefore, this study proposes a design flood value of 992.1 m^3/s, taking into account the impacts of climate change on the Johor River Watershed. In contrast, the future design flood value of 992.1 m^3/s, which considers the effects of climate change, corresponds to a 282.8-year return period based on the IDF relationship derived from the historical scenario.

3.3 Discussion and Implications

The future design flood value (i.e., 992.1 m^3/s), considering the impacts of climate change, corresponds to a 282.8-year return period based on the IDF relationship obtained from the historical scenario. This means that the current planning scale, that is, the 100-year return period (MSMA, 2000) that has been commonly used in Malaysia, may no longer be sufficient and should be revised or extended to a longer return period (e.g., 200- to 300-year return periods) if planners consider the impacts of climate change and if they can use only historical rainfall data.

Actually, the 100-year return period has recently been extended up to 200 years in some regions of Malaysia for design flood estimation (MSMA, 2012). In the Johor River Watershed, therefore, the same thing could be implemented to prevent and/or mitigate the devastating floods caused by climate change.

In summary, there are two approaches to incorporate climate change impacts into design flood estimation to mitigate the risk of severe flood disasters under future climate scenarios. One way is to use AGCM20 (or GCM/RCM) outputs for hydrological frequency analysis and runoff simulation to estimate the design flood value if planners can obtain them. For planners, however, it may be difficult to use advanced datasets, such as AGCM20 outputs, due to limited availability or concerns about data reliability. In that case, as an alternative, it is better to extend the current planning scale to a longer return period if they can only obtain historical rainfall data. This study proposes extending the planning scale beyond the 282.8-year return period based on the results obtained.

On the other hand, the results of the future rainfall return periods may represent an upper-bound or high-end scenario. This study simulated peak flows using outputs from only one global circulation model, AGCM20, under only one RCP scenario, RCP8.5. These cases resulted from a future scenario simulated under RCP8.5, which represents the highest greenhouse gas emissions and is considered a worst-case projection among the RCP scenarios. To obtain more accurate and reliable results, rigorous analyses, such as ensemble projections using multimodel and/or single-model ensembles, should be performed across various scenarios and conditions. In particular, integrating projections from multiple climate models and across different RCPs would enable a comprehensive assessment of uncertainties in future flood risks and offer more robust guidance for infrastructure design and disaster mitigation planning. In addition, the sample size should be larger than 25 years to ensure statistical reliability for estimating events, such as the 100-year flood.

Regarding the frequency of extreme flood events, Milly et al. (2005) found that the global frequency of devastating floods substantially increased during the twentieth century, and the statistically significant upward trend in flood risk is projected to continue under Global Circulation Model (GCM) simulations. Milly et al. (2002) focused on extreme events and analyzed 100-year floods across 29 basins worldwide. Their analyses revealed that flood return periods decreased from 100 years to less than 12.5 years in half of the basins. In the most extreme cases, the 100-year floods in some Asian basins are expected to recur every 2 to 5 years. According to an ensemble projection by Hirabayashi et al. (2013), significant increases in flood frequency were observed in Southeast Asia under the Representative Concentration Pathway 8.5 (RCP8.5) scenario. The return periods of the annual maximum daily river discharge corresponding to the 100-year flood event were compared between the current (1971–2000) and future (2071–2100) periods in their analyses. Their results showed that the frequency of the 100-year flood at the current level increases (i.e., the return period decreases) in Southeast Asia in the future.

Given that the Johor River Watershed is located in a monsoon climate zone and is highly vulnerable to flooding, projections of increased flood frequency under climate change scenarios are highly relevant. The results of this study, particularly the simulated changes in peak flow return periods presented, can therefore be considered consistent with the findings from other parts of Southeast Asia. This supports the interpretation that future flood risk in the Johor River Watershed may increase substantially, even under a single-model projection framework. These findings underscore the urgency of revising existing flood management and infrastructure planning practices to reflect the escalating risks projected under climate change.

4.0 Conclusion

In this study, the future return periods of 100-year flood events under the historical scenario were investigated using the CDF mapping method to evaluate how frequently such events may occur under future climate conditions. It was revealed that flood events are projected to occur more regularly in the future, particularly when shorter rainfall durations are considered.

Given the design flood criteria determined in the previous study—specifically, the peak flow for a 5-day rainfall event with a 100-year return period—the design flood value is projected to be 992.1 m^3/s in the future, compared to 851.0 m^3/s based on historical data. In addition, the return period of 851.0 m^3/s is expected to shorten to 18.5 years under future conditions. This implies that a flood of the current design scale would occur approximately five times more frequently by the end of the 21st century. This underscores the inadequacy of relying solely on historical data for future flood protection. On the other hand, the return period of 992.1 m^3/s corresponds to a 282.8-year return period when assessed using the historical IDF relationship. This indicates that the current planning scale—based on the 100-year return period commonly used in Malaysia—may no longer be sufficient to prevent or mitigate damage from increasingly severe floods under climate change.

Thus, this study proposes two approaches to incorporate climate change impacts into design flood estimation and to reduce the risk of more severe flood disasters. One approach is to use outputs from AGCM20 (or other GCM/RCM models) for hydrological frequency analysis and runoff simulations to estimate future design flood values, if planners can access such datasets. This approach provides a more dynamic and climate-responsive foundation for infrastructure planning. The other approach is to extend the current planning scale to a longer return period (e.g., 300 years) if only historical rainfall data are available. While more conservative, this approach offers a practical alternative in the absence of climate model data, ensuring enhanced safety margins under climate uncertainty.

5.0 Contribution of Authors

None declared.

6.0 Funding

None declared.

7.0 Conflict of Interest

None declared.

8.0 Acknowledgment

None declared.

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