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Developing flood hazard maps for the Kelantan floodplain using the HEC-RAS 2D model

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Abstract

Since flood disasters bring significant consequences to communities, it is essential to identify effective ways to reduce flood risks. This study aims to develop a flood hazard map for the Kelantan floodplain using a two-dimensional hydraulic modelling technique, integrating HEC-RAS and ArcGIS. Findings indicate that the Kelantan floodplain is highly exposed to severe flood hazards, with a 200-year return period discharge of 17,278.7 m^3/s. The results show that high-impact areas will experience severe consequences, such as house demolitions, financial losses, and psychological trauma. This study not only analyses past flood events but also predicts future flood risk zones. The findings are crucial for enhancing community preparedness by providing a comprehensive flood hazard map, which can assist in pre-disaster planning, disaster response, and post-disaster recovery to help sustain community well-being.

Keywords: Community resilience, disaster risk management, disaster risk reduction, flood disaster, hydraulic modelling, sustainability development

Introduction

Flooding is a significant environmental hazard, and Kelantan, a state in Malaysia, experiences some of the most severe flood events in the country. The region's susceptibility to floods is attributed to its geographic and climatic conditions, which are characterized by two main monsoon seasons: from November to February and from May to September (Mohd Ekhwan, 1998). These periods bring heavy rainfall, causing rivers to overflow and inundate low-lying areas. This phenomenon has led to severe consequences, including loss of life, displacement of people, and damage to infrastructure and property (See Too et al., 2023). The December 2014 floods were particularly catastrophic, affecting over 200,000 people and causing damages exceeding RM 2 billion (Department of Irrigation and Drainage Malaysia, 2022).

Existing literature highlights the multifaceted impact of floods, ranging from economic losses to social and infrastructural disruptions. Lim et al. (2015), Wan Ruslan (2010), and Mohd Ekhwan (1998) discuss the basic dynamics of flood hazards, emphasizing the role of heavy rainfall and water overflow from rivers, lakes, or oceans. However, these studies often lack a detailed exploration of the underlying causes and mitigation strategies specific to regions like Kelantan.

Kelantan’s topography, characterized by hills and mountains, significantly influences water flow during heavy rainfall, exacerbating flood risks. The state's dense forest cover contributes to soil erosion and sediment build-up in rivers, further increasing flood vulnerability (Wan Ruslan, 2017). The 2014 floods underscored the urgent need for effective flood management, highlighting deficiencies in existing infrastructure and emergency response systems. Despite various measures taken by the government and local communities, such as constructing levees, implementing flood warning systems, and developing emergency response plans, the recurrence of severe floods indicates persistent challenges (Siti Sabariah et al., 2021).

Kelantan's flood mitigation efforts are significantly hindered by the absence of detailed flood maps for specific areas, leading to inadequate preparedness and response strategies. For instance, a study focusing on Pasir Mas, Kelantan, highlighted the difficulty in identifying flood-vulnerable zones due to a lack of comprehensive information (Muhamad Azahar, 2020). This deficiency hampers effective communication of flood risks, results in unplanned developments, and contributes to insufficient drainage systems, thereby exacerbating the impact of floods in the region.

Moreover, the absence of accurate flood extent data during significant flood events poses a substantial challenge for effective flood management. The severe floods in Peninsular Malaysia during 2021-2022, which displaced over 20,000 people and resulted in two deaths in Kelantan, underscored this issue (Haziq et al., 2023). The lack of access to affected areas during such events makes it difficult to gather crucial information, further complicating mitigation efforts.

Hence, this study aims to develop flood maps for return periods ranging from 2 to 100 years to identify potential flood-prone areas. Flood hazard mapping is a critical tool for understanding and mitigating flood risks. By creating detailed maps that illustrate the likelihood of flooding based on topography, rainfall, and water flow patterns, communities can make informed decisions about land use, emergency response, and flood protection measures (Tan et al., 2021). These maps help guide infrastructure placement, influence insurance policies, and educate the public on flood preparedness.

Literature review

These case studies highlight the importance of advanced hydraulic modeling techniques in flood risk management across various geographical and climatic contexts. However, Malaysia lacks high-resolution Digital Elevation Models (DEMs) and satellite imagery, making it challenging for authorities to develop accurate flood maps. Floodplain hazard mapping is a critical tool in flood risk management, enabling authorities to identify at-risk areas and implement appropriate mitigation measures. Accurate floodplain maps rely on advanced hydraulic modeling techniques, which help simulate flood extents and depths based on topography, rainfall, and hydrological parameters. These maps are essential for urban planning, emergency response, and infrastructure development, providing stakeholders with valuable insights for decision-making. Traditional flood mapping methods often relied on historical flood data and simple hydraulic models, which could be less predictive of future flood scenarios.

The use of two-dimensional (2D) hydraulic modeling has gained traction in floodplain studies due to its ability to provide detailed flood simulations. However, challenges such as high computational demands and data quality limitations persist. The accuracy of floodplain maps depends on reliable input data, including topography, land use, and hydrological parameters. Future research should focus on integrating real-time data and enhancing computational efficiency to improve large-scale floodplain mapping.

In Malaysia, floodplain mapping has become increasingly important due to frequent and severe flooding events. The Kelantan River basin, for instance, is highly susceptible to monsoon-induced floods, causing significant economic and social impacts. Studies by Zakaria et al. (2013) and Shafie et al. (2014) have utilized hydraulic models to simulate flood scenarios in the Kelantan floodplain, offering valuable insights into flood dynamics and potential mitigation strategies. Similarly, Abdullah et al. (2015) applied hydraulic modeling in the Pahang River basin, demonstrating its effectiveness in simulating flood inundation and supporting flood hazard assessment.

Internationally, Teng et al. (2017) used a 2D flood modeling approach in the Brisbane River catchment, integrating high-resolution LiDAR data and hydrological inputs to enhance flood simulations. Their study provided critical insights into flood risk management and supported the development of effective mitigation strategies. High-resolution topographic data, such as LiDAR, play a crucial role in improving model performance, contributing to more accurate flood hazard assessments. Furthermore, the integration of real-time data assimilation methods, such as incorporating Synthetic Aperture Radar (SAR)-derived flood observations into hydraulic models, has improved the accuracy of flood forecasts. This approach allows for more responsive and dynamic flood risk assessments, which are crucial during rapidly changing flood events.

Despite these advancements, challenges remain in ensuring the availability of high-quality data across diverse geographical regions and in managing the computational demands of complex models. Ongoing research and development efforts are focused on addressing these issues, aiming to further enhance the precision and applicability of floodplain mapping and risk assessment tools worldwide.

Method and study area

Research area

This study focuses on the lower reach of the Kelantan River Basin, particularly the districts of Kota Bharu and Tumpat, which are highly susceptible to flooding. Kota Bharu, the capital city of Kelantan, and Tumpat have experienced significant flood events, severely impacting infrastructure, livelihoods, and local communities. The primary data collection site is the Guillemard Bridge discharge station in Tanah Merah, Kelantan, where the highest recorded maximum discharge rate in 2014 was 18,339.4 m^3/s.

According to Figure 1, the research was conducted in the Kota Bharu and Tumpat Districts. These districts are separated by the Kelantan River, the main river in the region. The research specifically focused on the Kelantan River floodplain, with the study area extending 2.5 km from the riverbank (red line area).

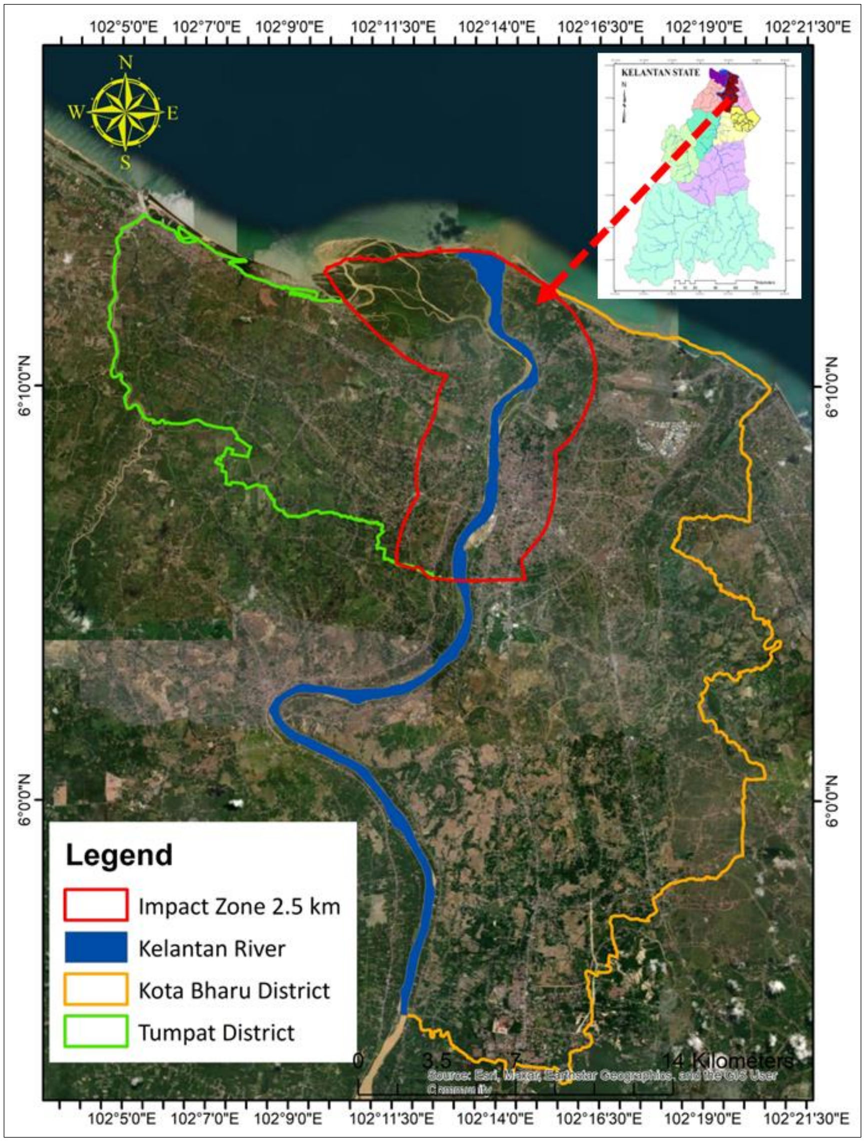


Figure 1. Research location

In December 2014, Kota Bharu experienced its worst flood in decades, which was caused by heavy rainfall and the overflow of the Kelantan River. The flood affected over 200,000 people and caused extensive damage to infrastructure, including roads, bridges, and buildings (Department of Irrigation and Drainage Malaysia, 2022). In 2021, Kota Bharu experienced flash flooding that lasted for several hours and caused damage to homes, vehicles, and businesses. In 2014, Tumpat was severely affected by the floods that also affected Kota Bharu (Harun & Aziz, 2021). Many villages and towns in Tumpat were submerged, and residents were forced to evacuate their homes. The floods also caused damage to infrastructure, including roads and bridges (Hashim & Yusoff, 2015). In 2020, Tumpat was again affected by severe flooding that caused damage to homes, vehicles, and infrastructure, including the main road connecting Tumpat to Kota Bharu (Mohd Razi et al., 2021).

Kota Bharu and Tumpat have experienced a variety of flood types, including riverine flooding, flash flooding, and coastal flooding. This makes them ideal locations for studying the impacts of different types of flooding and developing strategies for man-aging and mitigating flood risk. Both Kota Bharu and Tumpat have experienced rapid urbanization and land use change in recent years, which has increased their vulnerability to flooding (Jamil et al., 2020). By studying these areas, this study can better understand the interactions between urbanization, land use change, and flood risk, and develop strategies for sustainable and resilient development. Developing a flood hazard map and identifying community awareness literacy requires engagement with local communities to under-stand their knowledge, attitudes, and perceptions of flooding. Kota Bharu and Tumpat are home to diverse communities with varying levels of awareness and literacy on flood risk, making them ideal locations for studying community engagement and developing strategies for improving awareness and literacy. Overall, studying Kota Bharu and Tumpat will provide valuable insights into the complex socio-ecological systems that underlie flood risk in Malaysia and contribute to the development of effective strategies for managing and mitigating flood risk in the future.

Hydrological and hydraulic modeling

To enhance traditional flood analysis methods, this study integrates advanced hydrological and hydraulic modeling techniques with geographic information system (GIS) tools. DEM data is used for precise topographical analysis, which is crucial in understanding water flow and identifying potential flood-prone areas. Hydrologic Engineering Center’s River Analysis System (HEC-RAS) is a widely used hydraulic modeling software developed by the U.S. Army Corps of Engineers. It simulates water flow in natural and constructed channels to predict flood extent and water depth under different scenarios. Discharge Frequency Analysis (DFA) is employed to estimate the probability of various flood magnitudes occurring within specific return periods. The Gumbel distribution, a statistical method commonly used in hydrology, is applied to model extreme flood events by analyzing historical flood data. This helps predict the likelihood of future floods of different intensities. By integrating DEM, HEC-RAS, and DFA, high-resolution flood hazard maps are generated to provide a comprehensive assessment of flood risks in Kelantan. These maps serve as crucial tools for urban planning, emergency preparedness, and flood mitigation strategies. This structured approach ensures a detailed and scientifically robust assessment of flood risks, contributing valuable insights for future flood management and mitigation efforts in Kelantan.

Discharge frequency analysis

The discharge data collected by the Malaysian Irrigation and Drainage Department at the Guillemard Bridge station between 1990 and 2017 is analyzed using the Gumbel distribution for extreme value analysis. While traditional models are applied, this study enhances the method by incorporating more recent developments in statistical hydrology and extreme value theory.

The Gumbel distribution model is used for flood frequency analysis. The model's equations and parameters are given below:

$$\mathrm{XT} = X + \mathrm{K}\ \sigma X \qquad [1]$$

Where XT is Gumbel's Distribution in reference to return period; X is the mean value; σX is the standard deviation; and "K" is the factor of frequency in Gumbel method. The mean value and σX are derived from the equation [2] and [3]:

$$\bar{\bar{X}} = \sum X \ N \qquad [2]$$

Where "X" is the discharge value, $\bar{\bar{X}}$ is the mean of the discharge and "N" is the number of samples.

$$\sigma = \sqrt{} \sum (X_i - \bar{\bar{X}})^2 n \ (i-1) \ n \qquad [3]$$

Where σ = standard deviation, "n" is the number of the sample, "X_i" is the value of the sample and $\bar{\bar{X}}$ is the mean value of this sample. The "K" value was calculated using the following equation [4]:

$$K = (Yt-Yn)/Sn \qquad [4]$$

Where YT is the reduced variate which is calculated by using the equation [5]; the Sn and Yn value have been used from Gumbel's extreme value distribution chart that depends on the sample size.

$$YT = [-Ln \ (-Ln^*(T - 1/T)] \qquad [5]$$

This study employs the advanced tools and techniques to enhance the flood risk analysis. Machine Learning Models were implemented as integration of machine learning algorithms to predict flood occurrences and impacts based on historical data and current conditions. Besides, remote sensing were used satellite imagery and remote sensing data to monitor real-time changes in water levels and flood extents. Hydrodynamic modeling applied as advanced hydrodynamic models to simulate water flow and flood propagation with higher accuracy. Last but not least, Community-based participatory approach also been implemented to this study in engaging the local communities in data collection and awareness programs to improve flood preparedness and response strategies. By incorporating these advanced methodologies and tools, this study aims to provide a more comprehensive and accurate assessment of flood risks in Kelantan. This approach not only addresses the limitations of traditional methods but also offers innovative solutions for effective flood management and community resilience building in flood-prone areas.

Results and discussion

Discharge analysis

The analysis of 28 years of discharge data (1990-2017) calculated the Average Recurrence Interval (ARI) using the Gumbel Method. This method is commonly employed for flood frequency analysis due to its reliability in estimating the probability of extreme events. The data highlighted substantial variability in annual maximum discharge, with 2014 recording the highest value (18,339.4 m^3/s) and 2002 the lowest (1,345.4 m^3/s). This dataset enabled a robust statistical analysis of flood recurrence intervals.

Table 1 presents the ranked discharge values, while Table 2 shows the ARI for different return periods. The ARI for a 2-year return period was 4,527.757 m³/s, and for a 50-year return period, it was 15,205.22 m³/s. The predicted maximum discharge for a significant flood event closely approximated the observed discharge in 2014, indicating an increasing trend in discharge values and suggesting a heightened potential for future flood disasters.

The development of a flood hazard map for Kelantan is essential for local governments and communities to use before, during, and after natural disasters. Accurate flood hazard maps can minimize risks and prevent resource wastage, including rescue time and the distribution of emergency assets. These maps, based on on-the-ground conditions, provide more detailed and accurate information than large-scale mapping, making them ideal for flood risk reduction management.

Table 1. Maximum discharge in guilemard station

No	Year	Max discharge	No	Year	Max discharge
1	1990	5435.5	15	2004	4895.2
2	1991	3424	16	2005	4133.7
3	1992	5048.4	17	2006	3891.5
4	1993	10746.3	18	2007	8028.4
5	1994	5052.6	19	2008	4593.9
6	1995	2987.2	20	2009	7786
7	1996	1772.6	21	2010	2339.8
8	1997	2447.5	22	2011	4191.5
9	1998	5189.7	23	2012	4432.9
10	1999	5430.3	24	2013	6215.5
11	2000	5026.9	25	2014	18339.4
12	2001	6111.8	26	2015	3213.9
13	2002	1345.4	27	2016	3007.3
14	2003	3755	28	2017	7128.4

Source: Research data

Table 2 details the ARI for different return periods. The analysis indicates that the ARI for a 2-year return period is 4,527.757 m³/s, for a 5-year return period is 8,071.863 m³/s, and for a 10-year return period is 10,300.66 m³/s. The ARI for 25-year and 50-year return periods are 13,116.39 m³/s and 15,205.22 m³/s, respectively. The predicted maximum discharge for a significant flood event, like the one in 2014, is 17,278.7 m³/s, which closely approximates the actual discharge of 18,339.4 m³/s observed in 2014.

These results indicate an increasing trend in the discharge values over time, suggesting a heightened potential for future flood disasters in the Kelantan River catchment area. This trend underscores the urgent need for improved flood management and mitigation strategies to address the escalating risk.

Table 2. Discharge analysis

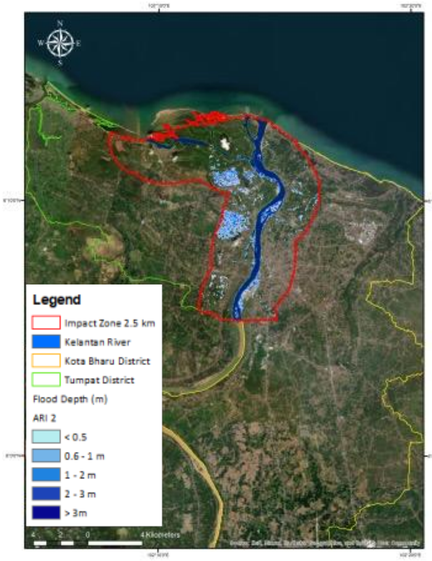
Return Period (ARI)	Mean (Xrt)	Yt*	Yn*	Sn*	Kt*	Sd*	Event Discharge (m^3/s)
2	5213.24	0.31	0.53	1.10	-0.21	3277.42	4527.76
5	5213.24	1.50	0.53	1.10	0.87	3277.42	8071.86
10	5213.24	2.25	0.53	1.10	1.55	3277.42	10300.66
25	5213.24	3.20	0.53	1.10	2.41	3277.42	13116.39
50	5213.24	3.90	0.53	1.10	3.05	3277.42	15205.22
100	5213.24	4.60	0.53	1.10	3.68	3277.42	17278.7

Source: Reseach data

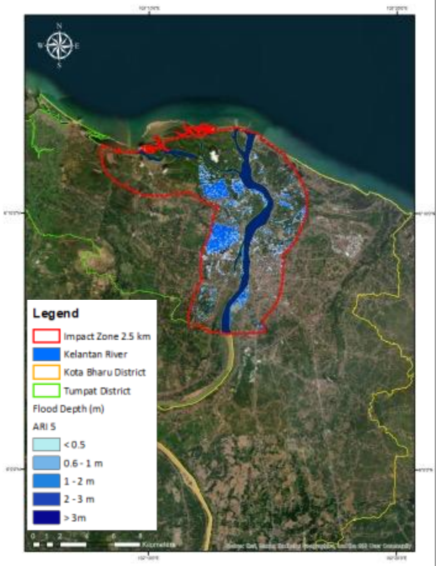
* Yt = Reduced Variate
* Yn = Reduced Mean
* Sn = Reduced Standard Deviation
* Kt = Frequency Factor
* Sd = Standard Deviation

Kelantan floodplain flood hazard maps

A higher ARI denotes a lower probability of such an event occurring in any given year. For instance, a 500-year flood event has a lower annual probability compared to a 100-year event. This metric is essential for floodplain management, guiding decisions on land use planning, flood protection measures, and emergency management. Figure 2 illustrates the ARI values for different flood magnitudes in the lower reaches of the Kelantan River. The data show that a 100-year flood event, similar to the one in 2014, has a 0.3% chance of occurring in any given year, with a discharge of 18,339.4 m^3/s.


N
W
E
S
Legend
Impact Zone 2.5 km
Kelantan River
Kota Bharu District
Tumpat District
Flood Depth (m)
ARI 2
< 0.5
0.6 - 1 m
1 - 2 m
2 - 3 m
> 3m
4 Kilometers

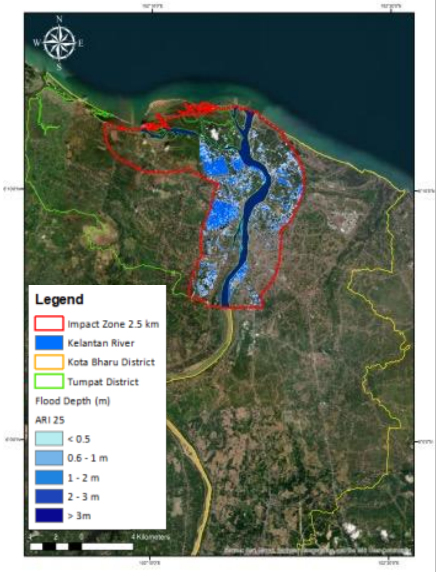
(a)


N
W
E
S
Legend
Impact Zone 2.5 km
Kelantan River
Kota Bharu District
Tumpat District
Flood Depth (m)
ARI 5
< 0.5
0.6 - 1 m
1 - 2 m
2 - 3 m
> 3m
Kilometers

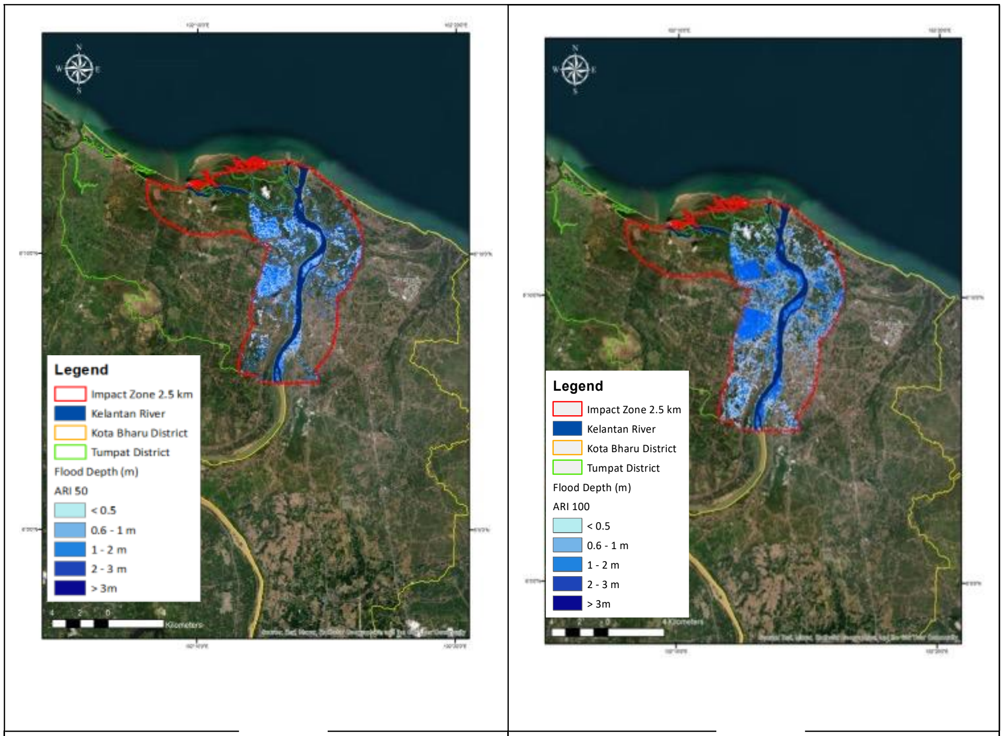
(b)


N
W
E
S
Legend
Impact Zone 2.5 km
Kelantan River
Kota Bharu District
Tumpat District
Flood Depth (m)
ARI 10
< 0.5
0.6 - 1 m
1 - 2 m
2 - 3 m
> 3m
Kilometers

(c)


N
W
E
S
Legend
Impact Zone 2.5 km
Kelantan River
Kota Bharu District
Tumpat District
Flood Depth (m)
ARI 25
< 0.5
0.6 - 1 m
1 - 2 m
2 - 3 m
> 3m
4 Kilometers

(d)



(e) (f)

Figure 2. Average Recurrence Interval (ARI) of lower reach of Kelantan River

In Figure 2, the data shows that ARI 2 does not affect many areas with flood waters, and the flood water level is not very high. Typically, ARI 2 occurs during heavy rainfall and mainly inundates low-lying areas. Additionally, communities in flood-prone areas, as shown in ARI 2, are usually more resilient and well-prepared to face flooding. On the other hand, when compared to areas with flood potential under ARI 100, the difference in extent and water level is significant. ARI 100 represents a severe flood event, impacting both high and low-lying areas. This type of flood is rare but can have a massive impact when it does occur. The flood discharge level of ARI 100 is similar to the 2014 flood, where the Kelantan River's discharge was approximately 18,000 m^3/s. That event was a tragic moment in Kelantan's history, as the high discharge rate led to widespread river overflow and causing severe flooding. The 2014 flood, which closely resembles the ARI 100 flood simulation map, resulted in dozens of casualties and billions of ringgits in property damage. Severe floods like ARI 100 typically occur during high tides or dams break that may leading to catastrophic consequences.

The findings of this study underscore the increasing magnitude and frequency of flooding in the Kelantan River Basin, largely driven by climatic and environmental changes. The close match between predicted and observed discharge values for major flood events confirms the reliability of the Gumbel distribution method for flood frequency analysis. However, flood risk management should not rely solely on past data but also integrate predictive models, community engagement, and robust mitigation strategies to enhance resilience.

Climate change significantly influences rainfall patterns, river discharge rates, and flood frequencies (Lariyah et al., 2022). Future flood mitigation must incorporate climate-responsive planning. By utilizing General Circulation Models (GCMs) and Regional Climate Models

(RCMs), policymakers can forecast long-term precipitation and sea-level rise trends, allowing for proactive flood mitigation strategies. For example, projections indicate a 10% increase in annual rainfall over the next 50 years, which must be factored into infrastructure planning and flood hazard mapping. Flood-prone areas, such as Kota Bharu and Tumpat, require zoning regulations that prevent the construction of critical infrastructure in high-risk zones (See Too et al., 2023). Additionally, urban expansion should incorporate green infrastructure such as wetlands, retention ponds, and permeable surfaces to reduce runoff and enhance water absorption.

Traditional flood models are limited in their ability to process large datasets and predict flood patterns with high accuracy (Margarita et al., 2024). The adoption of advanced hydrological and machine learning models can significantly improve flood preparedness and mitigation. Algorithms such as Random Forest and Neural Networks can analyze historical flood data, rainfall trends, and land-use changes to predict peak discharge events more accurately (Robert et al., 2024). This reduces false alarms and enhances early warning system efficiency. Hydrodynamic models like MIKE SHE, coupled with HEC-RAS, simulate water flow, soil moisture, and urbanization effects, helping authorities design flood mitigation structures like levees, embankments, and flood diversion channels (Fred & Kyung, 2024). Besides, an IoT-based sensor network along the Kelantan River could provide continuous data on river discharge, rainfall, and water levels. This data, processed through predictive analytics, can issue automated flood warnings, allowing authorities and communities to respond proactively rather than reactively.

However, scientific models and infrastructure alone cannot fully mitigate flood risks without strong community engagement and localized flood management efforts (Samiri et al., 2024). This study emphasizes the role of local communities in flood preparedness and response (Watkins and Collins, 2024). Flood hazard maps should incorporate community knowledge and real-time observations. Engaging local residents in GIS-based flood mapping workshops ensures that maps accurately reflect on-the-ground conditions. Establishing community flood response teams can enhance preparedness, evacuation coordination, and first-aid response. For example, localized flood monitoring groups in Kelantan could receive training in interpreting flood warnings, conducting evacuations, and assisting vulnerable populations. Flood literacy programs should educate residents on flood risk, evacuation procedures, and emergency preparedness (Rameli et al., 2024). Workshops in schools, mosques, and community centers can ensure widespread awareness and readiness. Community-driven efforts, such as mangrove reforestation, riverbank stabilization, and drainage maintenance, can reduce flood intensity and protect critical ecosystems that naturally mitigate flood risks.

To effectively reduce flood risk in Kelantan, this study recommends:

1. Enhanced Coordination Between Government and Local Communities: Joint flood response teams between the National Disaster Management Agency (NADMA), local authorities, and community groups can improve communication and resource mobilization.
2. Investment in Sustainable Infrastructure: The government should prioritize the construction of multipurpose retention basins, flood bypass channels, and eco-friendly embankments that align with sustainable urban development goals.
3. Strengthening Flood Early Warning Systems (FEWS): Investing in automated flood forecasting tools, mobile alert systems, and community alarm networks can increase response times and minimize losses.

4. Regular Flood Drills and Simulations: Conducting annual community flood drills ensures that residents, schools, and businesses are prepared for evacuation and emergency response.
5. Policy Integration with Climate Adaptation Strategies: Flood management should be integrated into Malaysia’s National Climate Change Adaptation Plan, ensuring that development projects account for future climate risks.

Conclusion

Flooding remains a critical environmental and socio-economic challenge in Kelantan, with devastating impacts on communities, infrastructure, and local economies. This study underscores the urgent need for advanced flood risk management strategies by developing high-resolution flood hazard maps using HEC-RAS 2D modeling and GIS techniques. The results reveal a significant flood hazard in the Kelantan floodplain, particularly in high-impact zones, where frequent and severe floods continue to threaten lives, properties, and livelihoods.

By analyzing historical flood data and simulating flood scenarios for return periods ranging from 2 to 100 years, this study provides scientific validation for flood predictions and offers critical insights into flood dynamics in the region. The integration of hydraulic modeling, GIS-based mapping, and statistical analysis enhances the accuracy of flood risk assessment and contributes to informed decision-making for flood mitigation and disaster preparedness. The flood maps generated in this study provide detailed visual representations of flood-prone areas, helping authorities and policymakers in land-use planning, emergency response, and long-term mitigation efforts. The study confirms the effectiveness of hydraulic modeling techniques in identifying flood hazard zones, highlighting their importance for future flood risk studies in Malaysia.

This study provides a solid foundation for flood risk assessment in Kelantan, offering both scientific insights and practical recommendations. However, addressing flood risks requires a multi-disciplinary approach, combining cutting-edge technology, community participation, and strong policy frameworks. Future research should continue to explore climate resilience strategies, advanced hydrological modeling, and real-time flood response systems to minimize disaster impacts and enhance flood resilience in Kelantan and beyond.

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