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Hydrological-Hydraulic Flood Simulation For Carey Island Under Different Design ARI

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Abstract

Periodic monitoring of environmental changes is crucial for effective flood risk management. Shifts in factors such as land use, annual rainfall patterns, and sea-level rise can significantly increase the potential for flooding. In response to these challenges, this study employs the HEC-HMS and HEC-RAS models to simulate the hydrological and hydraulic conditions of the Carey Island catchment. The objective is to analyze the island's vulnerability to fluvial flooding under current and future environmental scenarios. The results obtained the maximum discharge of 91.5 m^3/s *at Basin 116 for 3 hr rainfall simulation while the maximum discharge of 75.1* m^3/s *at Basin 116 for 6 hr rainfall simulation. According to flood simulation results under various discharge scenarios, the narrow river cross-section and limited flow capacity are the main causes of the minor flooding that occurs at lower discharges and the significant upstream flooding that occurs as discharge 500* m^3/s.

Keywords: *Flood risk management, Carey Island, HEC-HMS, HEC-RAS, Flood Distribution*

1. INTRODUCTION

Flooding stands out as one of the most destructive natural disasters we face, often triggered by heavy rainfall, storm surges, or rivers overflowing their banks (Boambang, et. Al., 2023)). The consequences can be dire, leading to loss of life, displacement of communities, and significant property damage, particularly in urban areas where drainage systems are lacking (Romali et. al., 2018). Factors like deforestation and poor land management only heighten the risk of flooding. To combat this, various management strategies are employed, including the construction of reservoirs, drainage systems, early warning systems, and flood barriers (Brunner, et. al., 2015). Unfortunately, with climate change on the rise, we can expect flooding to become an even bigger issue worldwide. Climate change is ramping up flooding due to more severe weather, rising sea levels, inconsistent rainfall, and melting glaciers. Southeast Asia, particularly areas near rivers like the Mekong, faces significant risks. Human actions, such as deforestation and inadequate flood management, only heighten these dangers on a global scale. To combat flooding, we need to implement early warning systems, build stronger defenses, and restore natural ecosystems. As the threats from climate change intensify, it's crucial that we take greater action and raise awareness. In Malaysia, the Northeast Monsoon, which runs from November to March, brings a lot of rain to Malaysia, leading to frequent flooding, particularly in states like Terengganu, Pahang, Kelantan, and Selangor (Naeem, et. al., 2021). These flash floods, made worse by climate change, have resulted in significant losses—up to RM6 billion (Abd-Aziz, et. al., 2024). To tackle these challenges, initiatives like early warning systems, sustainable infrastructure, and GIS-based studies are being implemented to manage flood risks and enhance climate adaptation efforts (Abd-Aziz, et. al., 2024). The unpredictable flood causes the flood prone area keeps changing through time. This causes previously safe areas could become vulnerable, and previously flood-prone areas might become less risky. One significant consequence is that disaster planning and preparation are becoming more complex. Therefore, in order to continue improving flood mitigation and management planning, it is imperative that the current flood risk area to be updated. In numerical methods, flood simulation typically involves both hydrological and hydraulic model analyses. One of the most versatile hydrological models available is the Hydrologic Engineering Center's

Hydrologic Modeling System (HEC-HMS), developed by the U.S. Army Corps of Engineers (USACE). First released in 1992 as a replacement for the older HEC-1 software, HEC-HMS was designed to simulate rainfall-runoff processes under a wide range of conditions (Sahu et al., 2020). The latest version, 4.2.1, offers a comprehensive set of features including precipitation input specification, runoff volume estimation, excess rainfall transformation, channel routing, baseflow modeling, and water control simulations (Yilma and Kebede, 2023). This version allows users to tailor model configurations based on available data, study objectives, and specific spatial or temporal requirements. Unlike HEC-1, HEC-HMS also supports additional components such as distributed runoff modeling with precipitation inputs, a soil-moisture accounting method for simulating responses under wet or dry conditions, and an auto-calibration feature to optimize model parameters using hydrometeorological data (Sahu et al., 2020). HEC-HMS has been widely used to assess flood frequency, urban flooding scenarios, reservoir spillway capacity, stream restoration planning, and the development of flood warning systems, making it a critical tool for integrated water resources and flood risk management. Numerous studies have highlighted the versatility of HEC-HMS in simulating hydrological processes across diverse regions. Gao et al. (2017) and Romali et al. (2018) demonstrated its effectiveness in modeling peak flows and validating against observed flood events in China and Malaysia, respectively. The model's integration with remote sensing and satellite data was explored by Darji et al. (2024) and Salih et al. (2024), who used UAVs, Google Earth Engine, and IMERG precipitation data to improve dam breach forecasting and flash flood prediction. Hybrid approaches, as shown by Nguyen et al. (2023) and Kassem et al. (2023), combined HEC-HMS with artificial neural networks and satellite datasets (AgERA5) to enhance forecasting accuracy in reservoir and ungauged basin modeling. Studies by Yilma et al. (2023), Frysali et al. (2023), and Cho (2023) further demonstrated its applicability in both gauged and ungauged catchments, using tools like HEC-GeoHMS, DSSVue, and diverse precipitation inputs. Meanwhile, Kencanawati et al. (2023) confirmed the model's sensitivity to field-based hydrological parameters, such as runoff coefficients under varying discharge conditions. Outcome of the hydrological model which usually involves point discharge distribution being used to simulate the flow distribution using hydraulic model. HEC-RAS, developed by the U.S. Army Corps of Engineers, is an advanced tool for hydraulic modeling and water resource analysis. HEC-RAS is an useful tool to simulate both steady and unsteady flows in river systems and floodplains. It can handle 1D, 2D and 1D-2D models, which makes it perfect for everything from simple to complex terrains. Some of its main uses include flood risk mapping, urban planning, and emergency response. Plus, it can model sediment transport and water quality, which is a big help for environmental assessments and managing water resources (Brunner, et. al., 2015). Numerous studies have demonstrated the effectiveness of HEC-RAS, often integrated with GIS and remote sensing, in simulating flood behavior, mapping flood extents, and supporting risk mitigation. For instance, Yakhlefoune et al. (2023), Rauf et al. (2021), and Keumalasari et al. (2024) used HEC-RAS and 2D modeling to simulate flood inundation in various watersheds, showing critical flood depths, infrastructure limitations, and strong correlation with historical flood events. Similarly, Xafoulis et al. (2022) combined 1D/2D HEC-RAS with DEM data and HEC-HMS to generate flood hazard maps and develop early warning systems. Studies by Sutapa et al. (2019) and Darajatun et al. (2020) focused on dam and reservoir operations, using HEC-RAS to assess the impact of storage and flow routing on downstream flooding. Additional works by Nurabriansyah et al. (2024) and Olteanu et al. (2024) highlighted the model's utility in complex urban and transboundary settings, considering tidal, storm surge, and multi-risk scenarios. The aim of this research is identify hydrological and hydraulic condition of Carey Island using HEC-HMS model and HEC-RAS model respectively. This study used different design ARI and two-dimensional hydraulic calculation for flood distribution in Carey Island in order to provide insight into areas that are susceptible to flooding.

2. METHODOLOGY

Carey Island, located in Selangor between Banting and Port Klang, is largely dominated by oil palm plantations and is susceptible to sea-level rise and tidal influences. While major flooding is generally controlled (Baharuddin et al., 2013), the island's unique character lies in both its environmental and cultural significance, being home to the indigenous Mah Meri community, known for their traditional wood carvings and ceremonial masks that attract tourism. The study area spans approximately 32,000 acres and remains largely undeveloped, preserving its natural and agricultural features. As illustrated in Figure 1, the Carey Island catchment is defined by a single main river system that connects upstream to the Langat River and downstream to the Malacca Strait, forming a distinct flow direction influenced by both fluvial and tidal conditions.

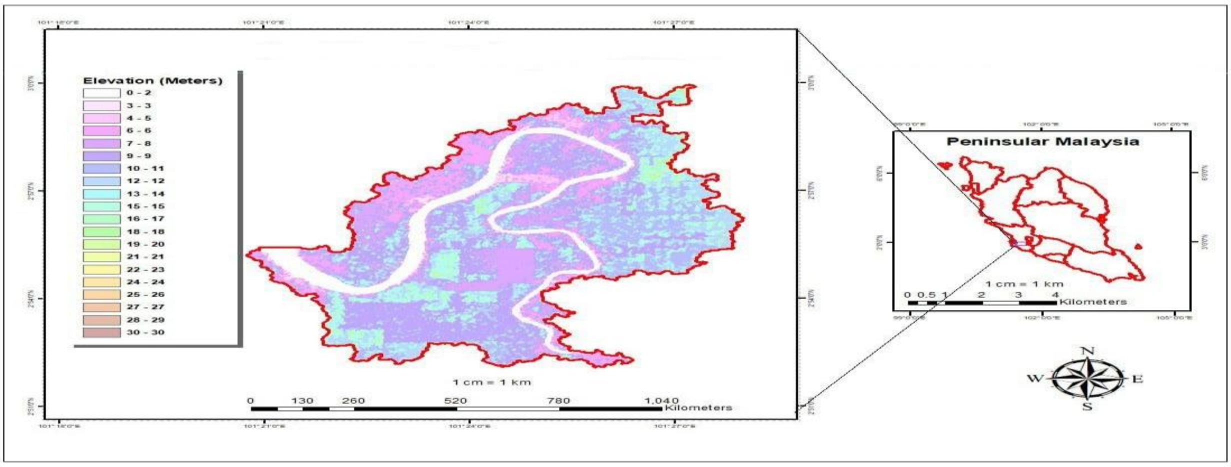


Fig. 1 Catchment area for Carey Island

For the topographic input, a 30-meter resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was utilized. Land use classification was derived from recent high-resolution Google Earth imagery. HEC-HMS and HEC-RAS were employed as the hydrological and hydraulic models, respectively, for this study. Hydrological simulation using HEC-HMS was carried out based on several Annual Recurrence Interval (ARI) scenarios defined in DID (2021). The resulting discharge outputs were then used as inputs for two-dimensional hydraulic simulations in HEC-RAS to assess flow distribution and inundation characteristics within the Carey Island catchment. A detailed overview of the methodological workflow is presented in Figure 2.

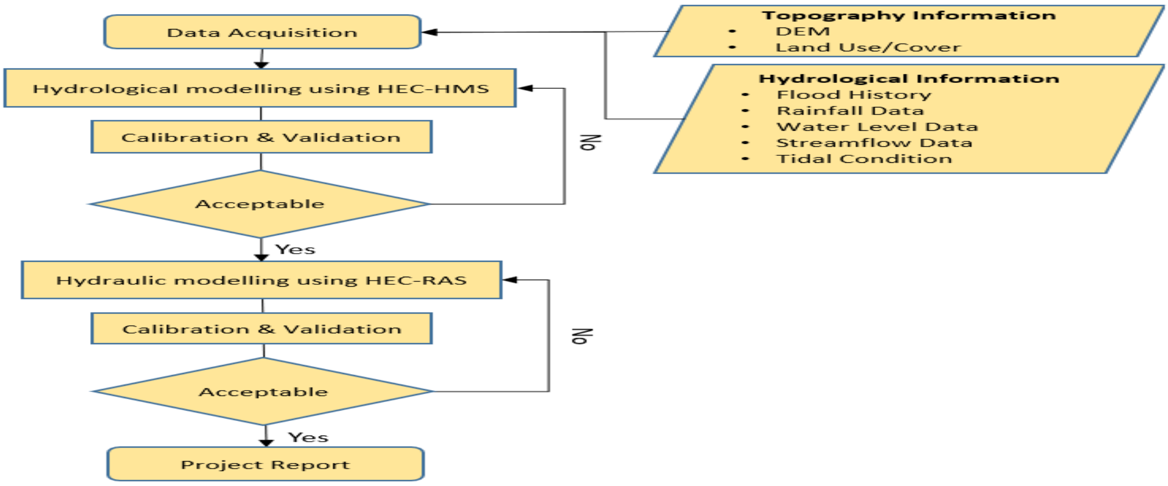


Fig. 2 Research Methodology

RESULT AND DISCUSSION

Based on Fig. 3 and Fig. 4, the maximum peak discharge for each sub-basin occurs under the 100-year return period simulation. This is because rainfall events associated with a 100-year return period are typically more intense and severe, resulting in greater rainfall volume and, consequently, higher peak discharges. The increased intensity and duration of these less frequent storms produce a stronger hydrological response, especially in urbanized or saturated areas where runoff tends to increase non-linearly with rainfall. Additionally, when comparing the 6 hr simulations, the maximum peak discharge under the Climate Change Factor (CCF) scenario at Basin 16 (8.03 km^2) is 75.1 m^3/s, which is notably higher than the 6 hr Depth-Duration-Frequency (DDF) scenario at the same basin, which recorded 53.2 m^3/s. This indicates that projected rainfall intensities under climate change scenarios could lead to significantly higher runoff volumes than those predicted using DDF approaches

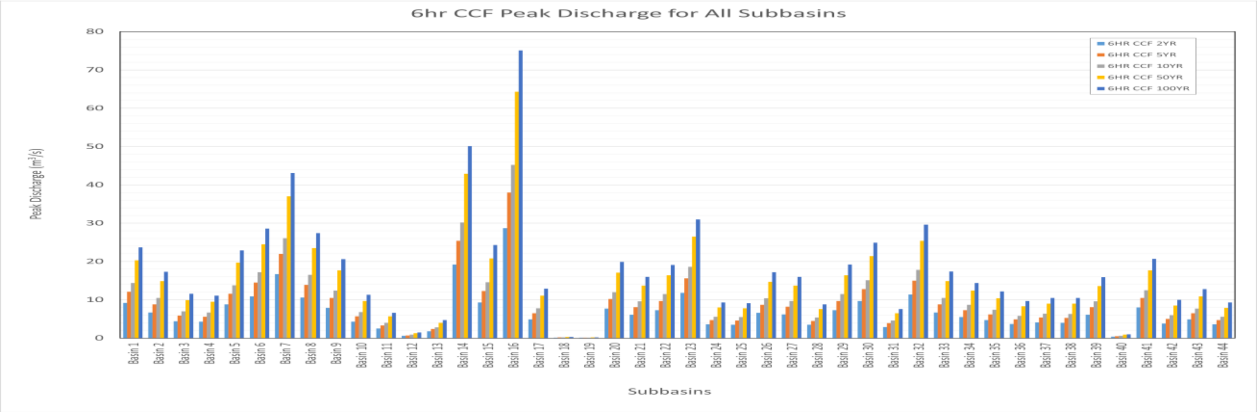


Fig. 3 Peak discharge for 6hr CCF

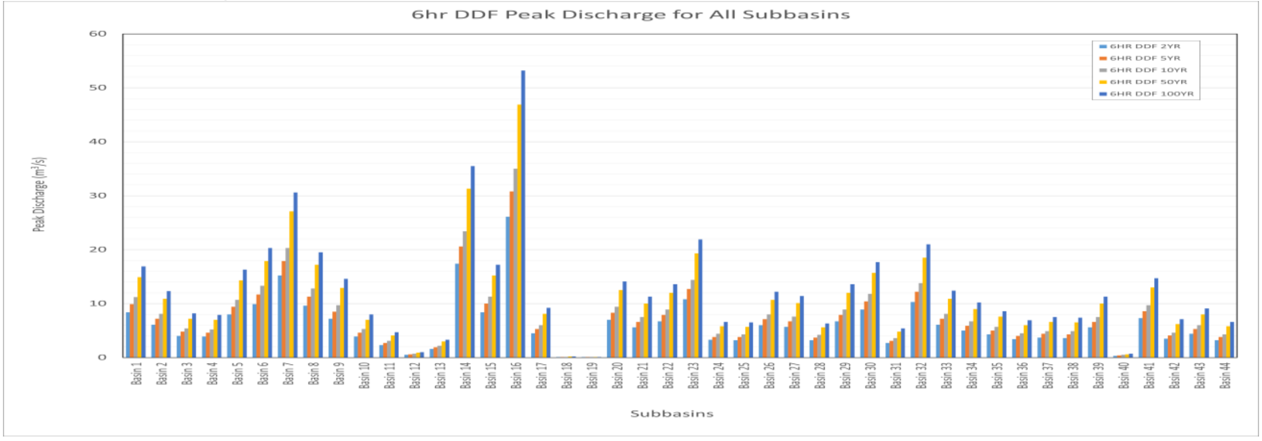
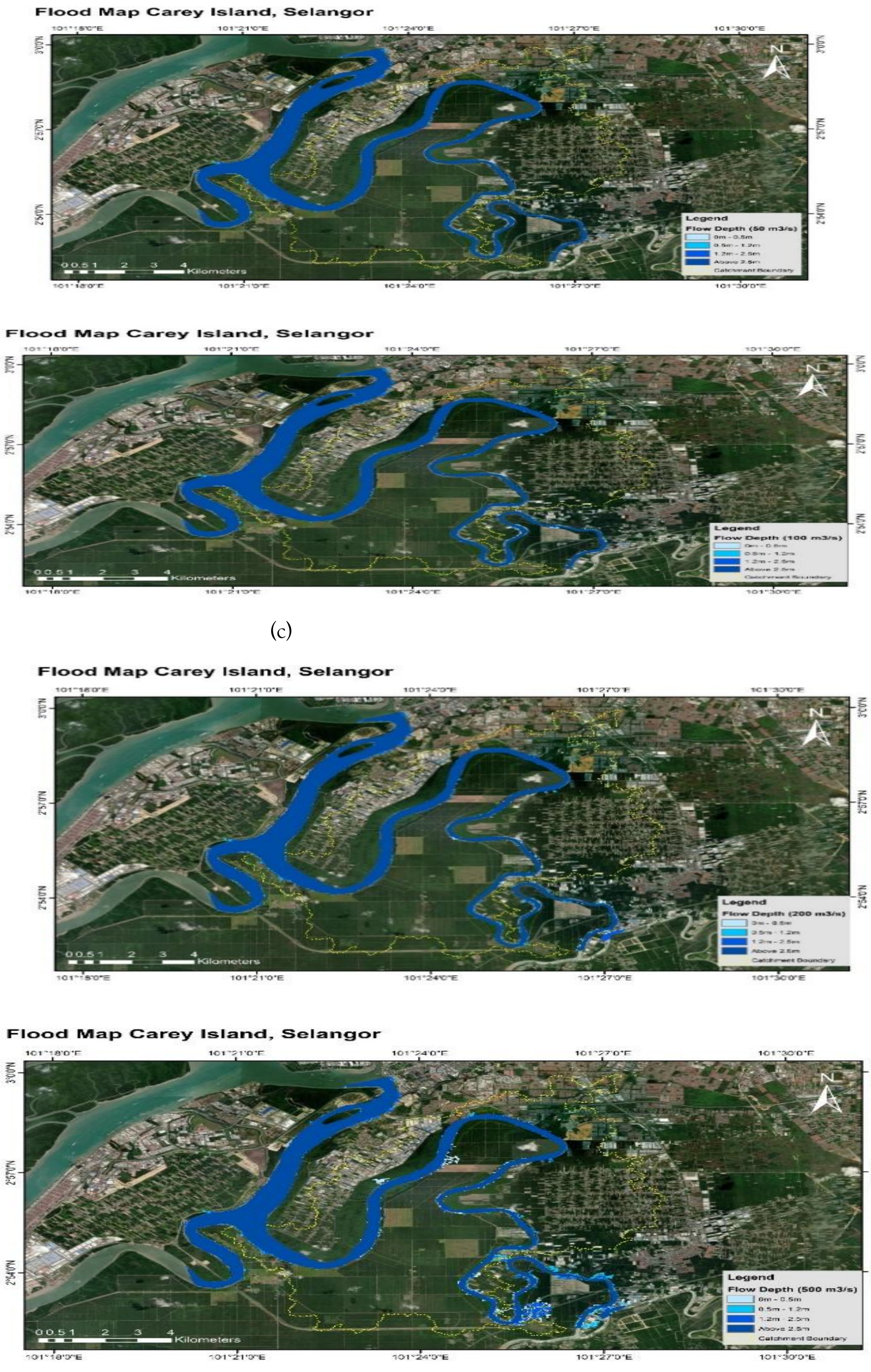


Fig. 4 Peak discharge for 6hr DDF

In terms of hydraulic results, within the watershed boundary marked by a yellow dotted line, floodwaters (shaded in blue) primarily remain within the river channel under a lower discharge of 5 m³/s, with only slight overflow near the banks and flood depths generally below 2.5 m. This indicates that the river system can manage such flow conditions without significant inundation. However, under high discharge scenarios reaching 500 m³/s, significant flooding is observed—particularly in the upstream and downstream areas of Carey Island. During these extreme events, the combination of intense rainfall, tidal influences, and river flow leads to extensive inundation, especially in the southern and southeastern regions of the island. These findings highlight the complex interplay between hydrological and coastal processes in influencing flood extent and severity. Details of the flood distribution are illustrated in Figure 5.

(a) (b)



(c) (d)

(e) (f)

Fig. 5 (a) Flood Map of Carey Island 5 m^3/s, (b) 10 m^3/s, (c) 50 m^3/s, (d) 100 m^3/s, (e) 200 m^3/s, (f) 500 m^3/s

3. CONCLUSION AND RECOMMENDATION

Carey Island faces several potential flood-inducing factors, including inflow from the upstream main river, tidal influences from the downstream coastal boundary, and a generally flat topography dominated by agricultural land use. This study aimed to analyze fluvial flooding across the Carey Island catchment under various Average Recurrence Intervals (ARIs), using integrated hydrological and hydraulic modeling approaches. The highest peak discharge was recorded at Basin 16 with 75.1 m^3/s under the 6 hr CCF scenario for a 100-year return period, compared to 53.2 m^3/s under the 6 hr DDF scenario. The resulting difference of 21.9 m^3/s highlights the significant impact of projected climate change on future runoff conditions. The flood map for Carey Island indicates inundated areas with floodwater discharges reaching up to 500 m^3/s in critical locations. The most affected zones are primarily concentrated in the central and southern regions of the island, especially near the main river channel and surrounding agricultural areas. Within the watershed boundary, flood depths range from shallow inundation (0–0.5 m) to severe flooding exceeding 2.5 m, posing a considerable risk to the local environment and infrastructure. While the current model provides valuable insights into flood behavior under varying scenarios, several improvements are recommended to enhance simulation accuracy and reliability. These include incorporating higher-resolution DEMs to better capture subtle terrain features, particularly in the flat and low-lying landscape of Carey Island. More detailed land use classification, improved representation of tidal effects, and analysis of the hydrological interaction between the main river and the upstream Langat River should also be integrated. Additionally, due to the island's extensive agricultural coverage and flat topography, pluvial flooding should be considered, as it may substantially contribute to localized inundation. In conclusion, the integration of HEC-HMS, HEC-RAS, and ArcGIS has proven to be an effective approach for simulating flood conditions and assessing risk in coastal catchments like Carey Island. This methodology not only aids in understanding complex flood dynamics but also provides a valuable tool for urban planning, disaster preparedness, and the development of early warning systems.

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