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Granular Hydrological Profiling and Morphological Impact Assessment for Flood Propagation Analysis: A Segment-Based Approach in the Muda River Basin

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ABSTRACT

Recurring floods in Malaysia's Muda River Basin pose significant risks to agriculture and water security. These challenges are often compounded by the limitations of traditional, lumped-basin hydrological models, which frequently overlook localized topographical variations and rapid morphological changes caused by anthropogenic activities. This study establishes a granular hydrological framework that systematically segments the river's main trunk into 11 distinct operational sections. Using geospatial delineation and real-time flow monitoring, the research analyses slope gradients, water balances, and channel geometry across each segment. Results reveal substantial topographical disparities that dictate the basin's hydraulic behaviour. Upstream segments exhibit steep gradients (averaging 3.70%), which accelerate flow velocity and reduce residence time. In contrast, downstream reaches exhibit a 0% gradient, creating critical hydraulic bottlenecks susceptible to stagnation and tidal influence. Consequently, this study advocates for a strategic shift from generalized basin management to segment-specific operational strategies. Ultimately, this research validates the necessity of transitioning to dynamic, AI-integrated monitoring systems capable of adapting to the river's evolving physical anatomy.

1. Introduction

Flooding remains one of the most frequent and destructive natural disasters affecting tropical river basins, posing severe risks to infrastructure, and community livelihoods [7]. In Malaysia, the Sungai Muda Basin serves as a critical water resource for the northern states of Kedah, Perlis, and Penang, sustaining extensive agricultural irrigation and domestic supply [1]. However, the basin faces recurrent and catastrophic flood events, most notably in 1988, 1998, and 2003, which have highlighted the limitations of existing flood mitigation strategies [12; 14]. While recent advancement

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has focused on algorithms optimization and generalized hydrological modeling, there remains a critical need to understand the localized physical dynamics of the river. Traditional models often treat river reaches as static or uniform channels, failing to account for the complex, site-specific interactions between topographical gradients, anthropogenic morphological changes, and flood propagation velocities [10; 9]. The hydrological behavior of the Sungai Muda (Fig.1) is heavily influenced by its distinct physical anatomy, which transitions from mountains highlands to coastal plains [5; 15]. Standard flood forecasting often relies on rainfall-runoff relationship that may overlook these granular spatial variations [8]. To address this, a study adopts a systematic river segmentation approach, dividing the main trunk of Sungai Muda into 11 distinct segments ranging from 2.5 km to 25 km in length was proposed. This segmentation allows for a micro-analysis of flow dynamics, utilizing flow monitoring sensors at the inlet and outlet of each segment to calculate a precise water balance. This method isolates the influence of tributaries and quantifies water extraction for industrial, domestic, and agricultural use within specific reaches, providing a diagnostic tool that aggregate basin model often lack.

A primary focus of this granular profiling is the analysis of elevation and slope variances, which dictate hydraulic behavior. The river exhibits drastic topographical contrasts, ranging from an average slope of 3.70% in the upstream Hulu Sg Muda segment, which facilitates rapid runoff, to a 0% gradient in the downstream Jambatan Merdeka segment, rendering it highly susceptible to stagnation and backwater effects. Such variations significantly impact the "residence time" of floodwaters and the effectiveness of gravity-based drainage.

Furthermore, this study investigates the impact of anthropogenic activities on the river's morphology, a factor frequently omitted from static hydraulic models. Evidence suggests that sand mining activities have drastically altered the river cross-section, widening the channel to approximately 370 meters in certain sections. These morphological distortions fundamentally change sediment transport dynamics and flow velocity profiles, causing historical calibration data to become obsolete. By integrating detailed segment-based profiling with morphological assessment, this research aims to provide a robust, spatially aware framework for flood propagation analysis. This approach offers vital insights for optimizing gate operations and zoning policies, ensuring that flood management strategies are adapted to the rapidly evolving physical reality of the Muda River Basin.

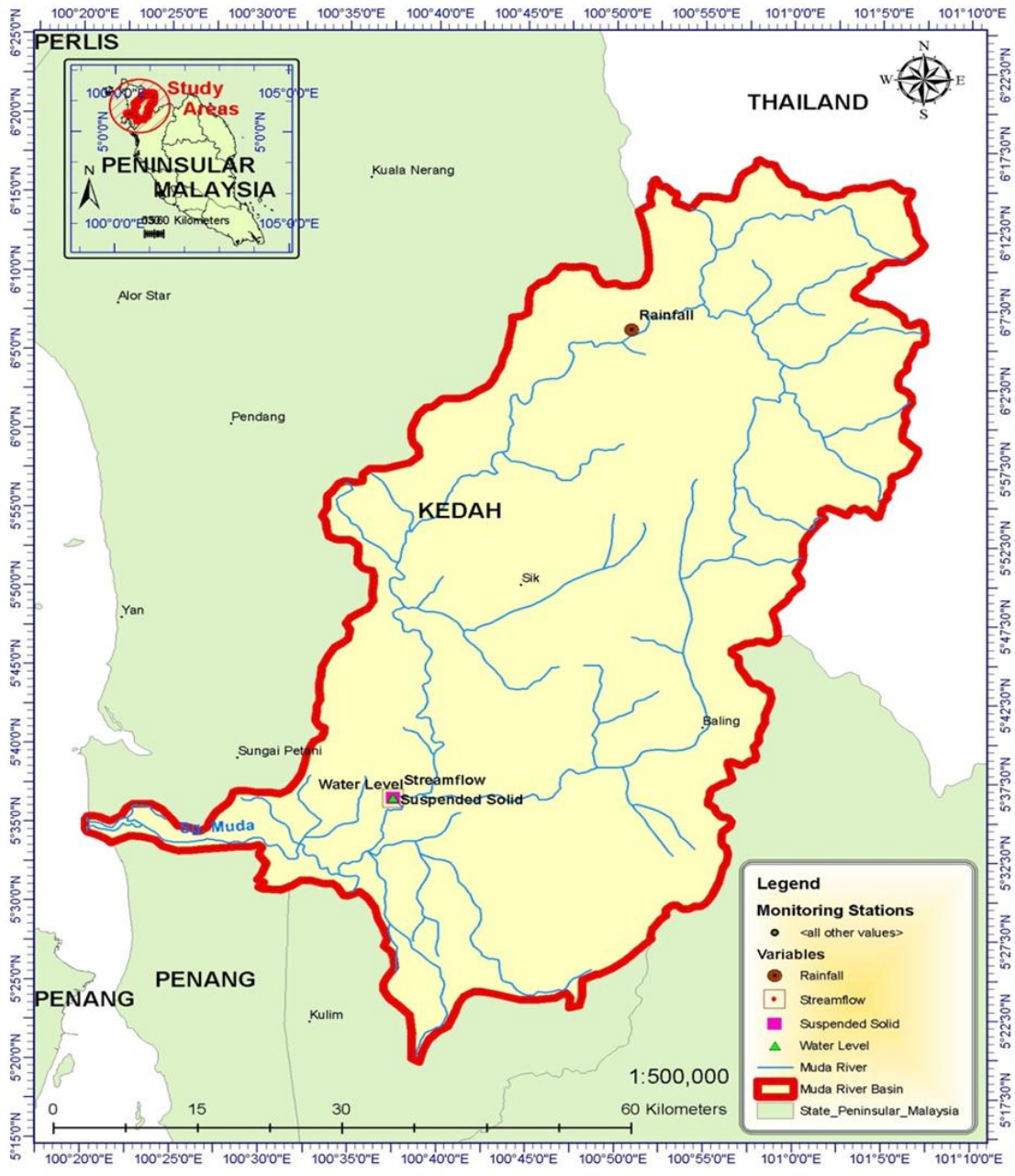


Fig. 1. Muda River Basin and Monitoring Stations

2. Methodology

2.1 Systematic River Segmentation Strategy

To address the limitations of generalized catchment-based simulations, this study adopted a systematic segmentation approach for the main trunk of the Sungai Muda river. Unlike traditional models that aggregate flow data across vast areas, this methodology isolated the river's main stem into 11 distinct segments to facilitate granular monitoring of flow dynamics and water usage. This segmentation strategy was designed to isolate the influence of tributaries, ensuring that their flows are measured independently before entering the main system, thereby allowing for precise accounting in downstream calculations [13]. Each segment is bounded by a pair of flow monitoring

sensors in which one installed at the upstream inlet and another at the downstream outlet. These sensors function to capture site-specific hydrological behavior.

2.2 Geospatial Delineation and Granularity

The spatial delineation of the river segments was executed using Google Earth Pro (Version 7.3.6.9796, 64-bit) utilizing the specific 'Path' function to trace the river's natural course. The lengths of these segments were calculated using the software's properties feature, resulting in segments ranging from 2596 meters (segment 7: Upstream Jambatan Syed Omar) to 25,172 meters (Segment 6: Downstream Sg. Ketil). The segmentation boundaries were anchored by identifiable infrastructure landmarks, such as bridges, water transfer intakes, and confluence points, to link digital data with real-world operational sites. The spatial structure was preserved in KMZ file formats to visualize the monitoring network and support the Artificial Intelligence Flood Routing (ALiR) model.

2.3 Segmental Water Balance Calculation

A diagnostic water balance equation was applied to each segment to quantify water extraction and loss. By measuring the differential between the inlet and outlet sensors, the study estimated total water abstraction for industrial, domestic, and agricultural irrigation purposes. The flow balance for each segment was calculated using Eq. 1

$$Flow_{se\#ment} = Flow_{in} - Flow_{out}(Industrial + potable\,consumption + irrigation) \quad (1)$$

Notably, evaporation losses were excluded from this calculation model. This methodological decision was based on the assessment that the river channel's surface area is too marginal to contribute significantly to overall water loss compared to large water bodies like reservoirs. This approach allows for the identification of critical pressure points and potential unauthorized withdrawals within specific river reaches [6].

2.4 Topographical and Gradient Analysis

To model flood propagation velocity and residence time accurately, the study extracted detailed physical characteristics for all 11 segments, including elevation changes, maximum and average slope gradients, and average river widths. These parameters serve as foundational inputs for hydraulic modeling to determine energy loss and flow resistance [2]. The analysis revealed significant topographical variations across the basin:

I. Upstream Dynamics (Segments 1-3): Segment 1 (Hulu Sg. Muda) exhibits a steep average slope of 3.70%, facilitating rapid runoff and shorter residence times. Segment 3 (Upstream Jeniang Water Transfer) records the highest average slope in the midstream section at 4.30%, indicating high-velocity flows and increased erosion potential.
II. Transitional Midstream (Segments 4-8): The gradient gradually moderates in the midstream, with Segment 8 (Downstream Jambatan Syed Omar) showing an average slope of 2.50%
III. Downstream Stagnation (Segments 9-11): The lower reaches exhibit critically low gradients. Segment 9 drops to an average slope of 0.10%, while Segment 11 (Upstream Jambatan Merdeka) is characterized by a 0% slope. This flat profile renders the

downstream area highly vulnerable to prolonged inundation, backwater effects, and tidal influences.

2.5 Integration with Anthropogenic Morphological Assessment

The methodology also incorporated an assessment of anthropogenic impacts on river morphology. Visual analysis identified that activities such as sand mining have widened the river channel to approximately 370 meters in certain sections, deviating significantly from the original river path. This morphological data was integrated into the profiling to account for changes in sediment transport dynamics and flow velocity profiles that static historical models fail to capture.

3. Results

3.1 Topographical Gradient Analysis and Hydraulic Segmentation

The spatial segmentation analysis of the Sungai Muda main trunk reveals drastic variations in topographical gradients that fundamentally dictate the river's hydraulic behavior. As summarized in Table 4.2, the river transitions from a high-energy, steep-gradient system in the upstream reaches to a stagnant, zero-gradient system in the coastal lowlands.

Upstream Dynamics (Segments 1–3): Segment 1 (Hulu Sg. Muda) is characterized by an average slope of 3.70% and a maximum slope of 16.60%, facilitating high-velocity runoff and short residence times. The steepest average gradient in the midstream section is observed in Segment 3 (Upstream Jeniang Water Transfer) at 4.30%. These steep gradients suggest that the upper basin functions primarily as a conveyance zone where rapid flow propagation occurs, increasing erosion potential and sediment transport during high-discharge events.

Transitional Midstream (Segments 4–8): The midstream segments exhibit a gradual reduction in slope, transitioning from 3.80% at Segment 4 to 2.50% at Segment 8 (Downstream Jambatan Syed Omar). While the gradient here is more moderate, it remains sufficient to support consistent flow movement, although the potential for localized overbank flooding increases as the river interacts with expanding agricultural zones.

Downstream Stagnation (Segments 9–11): A critical hydraulic bottleneck is identified in the lower reaches. Segment 9 (Downstream Jambatan Sidam) exhibits an exceptionally low average slope of 0.10%, while the terminal Segment 11 (Upstream Jambatan Merdeka) flatlines at 0% slope. This complete lack of gradient impairs the river’s ability to drain excess volumes via gravity, rendering the area highly vulnerable to backwater effects, tidal influence, and prolonged inundation during storm surges.

3.2 Flood Propagation and Routing Dynamics

The impact of these topographical variances on flood propagation was quantified through a flood routing analysis between Titi Beris (upstream) and Jambatan Sidam (downstream). The analysis determined a travel time of approximately 42 hours and 45 minutes over a distance of 127 kilometers.

The hydrograph comparison presented in Figure 4.27 illustrates the attenuation and translation of the flood wave as it moves through the segmented system. The steep upstream gradients documented in Segments 1 through 3 contribute to the rapid initial peak observed at Titi Beris. However, as the flood wave enters the flatter downstream segments (Segments 9–11), the storage effects of the river channel become dominant, modifying the timing and magnitude of the peak

discharge arriving at Sidam. This lag time of over 40 hours provides a critical operational window for the automated regulation of mechanical infrastructure, specifically allowing for anticipatory gate adjustments at the barrage before the peak flow arrives.

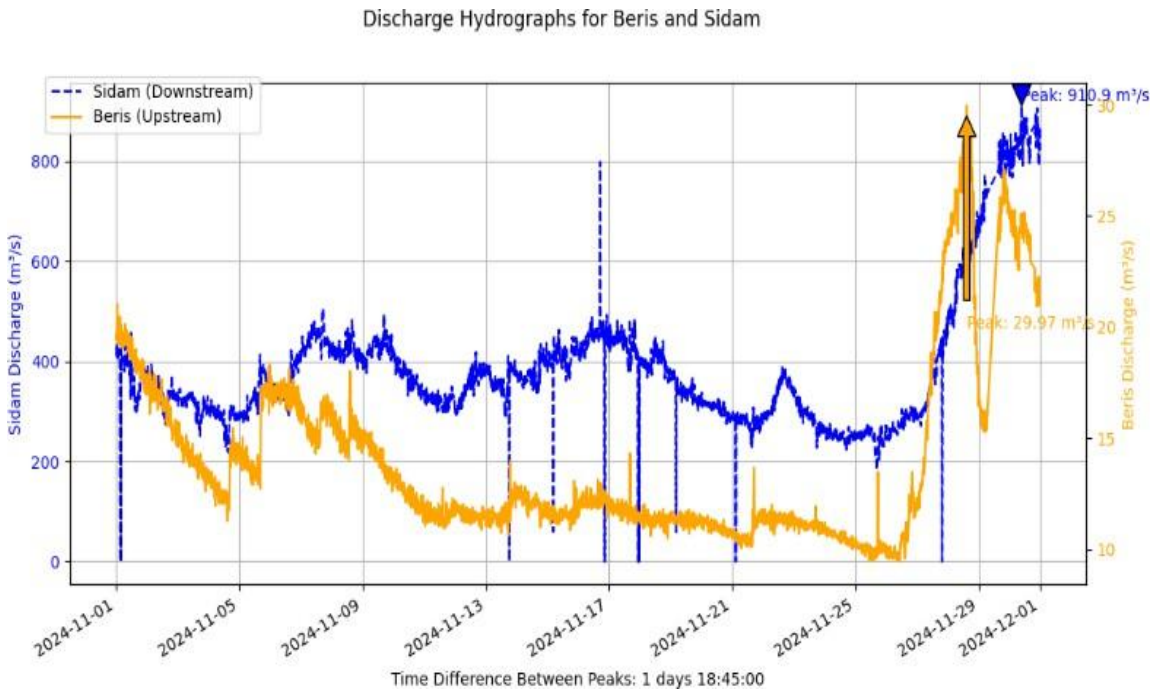


Fig. 1. Raw comparison of the actual hydrograph peaks at SIDAM and Titi Beris

3.3 Anthropogenic Morphological Modifications

A significant finding of the segment-based profiling is the detection of severe morphological alterations driven by anthropogenic activities, specifically sand mining. Visual analysis from Figure 4.45 reveals that sand mining activities have drastically distorted the river's cross-sectional geometry, widening the channel to approximately 370 meters in certain sections.

This widening represents a significant deviation from the river's original natural path and has profound hydraulic consequences. The expanded width changes the velocity profile of the river, potentially reducing flow velocity in widened sections and increasing sediment deposition, which complicates flood routing predictions [11]. On top of that, the artificial widening contributes to channel instability and bank erosion, leading to misdirected flows during peak discharge events [4]. Conventional hydrological models calibrated on historical, static channel geometries fail to account for these rapid physical changes. The study confirms that static calibrations deteriorate in predictive effectiveness when subjected to such modern disturbances, necessitating the use of dynamic, machine-learning-driven optimization that adapts to real-time physical conditions.

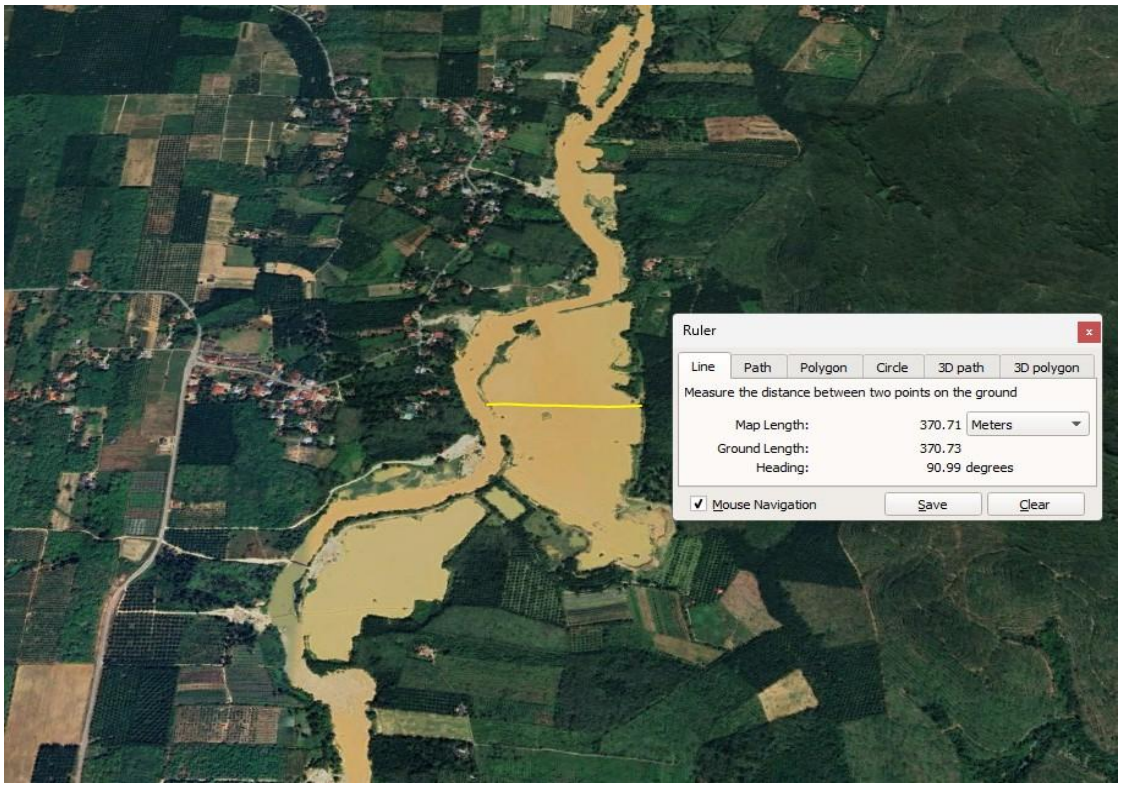


Fig. 2. Sand Mining causes the river width to change

3.4 Implications for Operational Control

The integration of granular slope analysis with morphological assessment underscores the necessity for segment-specific gate operation strategies. The 0% slope at Segment 11 dictates that drainage in this section cannot rely solely on gravity during high tide intervals, necessitating precise, automated control of tidal gates to prevent saline intrusion and facilitate forced drainage when possible. Furthermore, the evidence of river widening validates the study's shift away from static rainfall-runoff models toward the PRIME system's real-time flow monitoring, which continuously recalibrates based on current channel conditions rather than outdated topographical data. This adaptive approach ensures that flood forecasting remains accurate even as the river's physical anatomy continues to evolve due to human activity [3].



Fig. 3. Segment 11 - Upstream Jambatan Merdeka

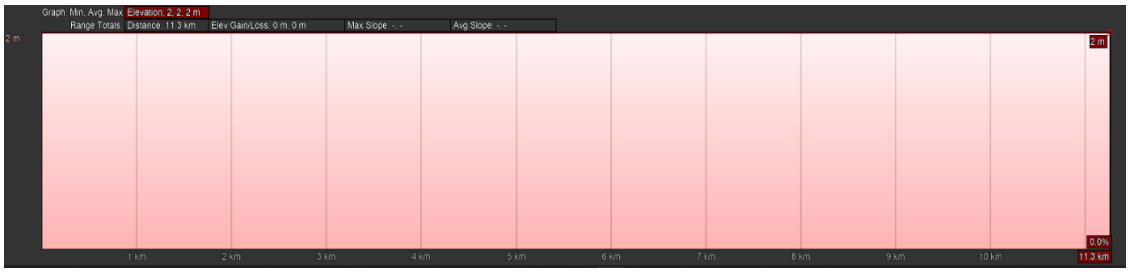


Fig. 4. Segment 11 - Upstream Jambatan Merdeka Elevation Profile.

3.5 Limitations of the Study

While the segment-based profiling provides critical spatial insights, several limitations must be acknowledged. First, the temporal scope of the monitoring data relies on specific flood events (e.g., December 2020 and September 2024), resulting in limited hydrological calibration periods that may not capture the full spectrum of decadal climate variability. Second, there are inherent uncertainties in the morphological measurements. The reliance on geospatial tools (such as Google Earth Pro) to estimate segment lengths and river widening introduces a degree of measurement uncertainty compared to high-resolution, ground-truthed LiDAR or bathymetric surveys. Future iterations of this framework would benefit from empirical ground-truthing to refine cross-sectional geometries.

4. Conclusions

This study successfully established a granular hydrological framework for the Muda River Basin by implementing a systematic, 11-segment monitoring approach. This methodology overcomes the limitations of generalized, lumped-basin models by isolating flow dynamics and quantifying water balances at a micro-level. The analysis confirmed that critical topographical disparities from steep upstream conveyance zones to near-stagnant downstream storage zones, fundamentally dictate the basin's hydraulic behaviour. Furthermore, the assessment of anthropogenic impacts revealed that river widening from sand mining has severely altered flow velocity profiles, rendering static historical calibration models inadequate. Ultimately, the study concludes that flood management strategies cannot be uniform across a basin; they must be segment-specific and dynamically adaptable to evolving channel geometries.

To build upon this segment-based framework, future research should prioritize the integration of Artificial Intelligence (AI) and machine learning (such as LSTM networks) to automate real-time flood forecasting within these specific segments. Additionally, establishing long-term sediment transport monitoring is crucial to accurately track the ongoing morphological degradation caused by sand mining. Finally, incorporating climate change scenario modelling will be vital to test the resilience of this segmentation framework against future extreme weather conditions and rising sea levels affecting the downstream tidal zones.

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Conflict of Interest Statement
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Author Contributions Statement

Author 2 conceptualized and designed the study, supervised the project, and reviewed the manuscript. Author 1 conducted the experiments and data analysis. Author 3 contributed to data interpretation and wrote the initial draft of the manuscript. All authors contributed to manuscript revision, read, and approved the final version.

Data Availability Statement

All data generated or analyzed during this study are included in this published article. Additional datasets are available from the corresponding author upon reasonable request. Where applicable, publicly available datasets used in the study are cited in the references.

References

[1] Abdullah, Mohd Firdaus, Mohd Noor, Tan Chee Seng, and Wan Khairuddin Wan Ibrahim. "The Water War between Kedah-Penang in Malaysia: The Relation in the Management of Sungai Muda Raw Water, 1965–1985." *Geopolitics Quarterly* 20, no. 2 (2024): 151-170. https://doi.org/10.22034/igq.2024.180173

[2] Ahmed, Mohd Nadim, Berlin Mohanadhas, and Narayanan Natarajan. "Experimental analysis of the hydraulics of overland flow under different slope gradients and flow conditions." ISH Journal of Hydraulic Engineering 32, no. 1 (2026): 97-121. https://doi.org/10.1080/09715010.2025.2584052

[3] Dwivedi, Dipankar, Ronald E. Poeppl, and Ellen Wohl. "Hydrological connectivity: a review and emerging strategies for integrating measurement, modeling, and management." Frontiers in Water 7 (2025): 1496199. https://doi.org/10.3389/frwa.2025.1496199

[4] Ferguson, R. I. "Channel form and channel changes." In British rivers, pp. 90-125. Routledge, 2024. https://doi.org/10.4324/9781003464914-4

[5] Ghani, Aminuddin Ab, Rabie Ali, Nor Azazi Zakaria, Zorkeflee Abu Hasan, Chun Kiat Chang, and Mohd Sanusi S. Ahamad. "A temporal change study of the Muda River system over 22 years." Intl. J. River Basin Management 8, no. 1 (2010): 25-37. https://doi.org/10.1080/15715121003715040

[6] Giberson, Alexander. "Rivers With Borders: Bi-National Water Management Model for the St. Mary-Milk Basins." (2026). https://dx.doi.org/10.11575/PRISM/51057

[7] Jaafar, Jurina, Nur Syamimi Norisman, Zulhafizal Othman, and Nur Qudus. "Flood risk trend by using PCA and SPC analysis at Muda River, Kedah." Environment-Behaviour Proceedings Journal 8, no. 23 (2023): 39-49. https://doi.org/10.21834/ebpj.v8i23.4501

[8] Jehanzaib, Muhammad, Muhammad Ajmal, Mohammed Achite, and Tae-Woong Kim. "Comprehensive review: Advancements in rainfall-runoff modelling for flood mitigation." Climate 10, no. 10 (2022): 147. https://doi.org/10.3390/cli10100147

[9] Lee, Seung-Jun, Tae-Yun Kim, Jisung Kim, and Hong-Sik Yun. "A High-Resolution LiDAR-GIS Framework for Riverine Flood Risk Prediction and Prevention Under Extreme Rainfall." Sustainability 18, no. 7 (2026): 3390. https://doi.org/10.3390/su18073390

[10] Nazari, Behzad, Ebrahim Ahmadisharaf, Paul D. Bates, Hamid Moradkhani, Venkatesh Merwade, Thomas Wahl, Yu Zhang et al. "Synergistic integration of flood inundation modeling methods: A review of computational, data-driven, observational and experimental, and conceptual models." Reviews of Geophysics 64, no. 1 (2026): e2025RG000898. https://doi.org/10.1029/2025RG000898

[11] Serra-Llobet, Anna, George Mathias Kondolf, Fernando Magdaleno, and Duncan Keenan-Jones. "Flood diversions and bypasses: Benefits and challenges." Wiley Interdisciplinary Reviews: Water 9, no. 1 (2022): e1562. https://doi.org/10.1002/wat2.1562

[12] Weng, Chan Ngai. "Sustainable management of rivers in Malaysia: Involving all stakeholders." International Journal of River Basin Management 3, no. 3 (2005): 147-162. https://doi.org/10.1080/15715124.2005.9635254

[13] Yang, Dongxu, Baowei Yan, Donglin Gu, Jianbo Chang, and Shixiong Du. "A hybrid deep learning-Muskingum framework for enhanced runoff prediction: Model coupling and hydrological process integration." Journal of Hydrology: Regional Studies 63 (2026): 103077. https://doi.org/10.1016/j.ejrh.2025.103077

[14] Yu, Jinhui, Yichen Li, Xiao Huang, and Xinyue Ye. "Data quality and uncertainty issues in flood prediction: a systematic review." International Journal of Digital Earth 18, no. 1 (2025): 2495738. https://doi.org/10.1080/17538947.2025.2495738

[15] Zakariah, Muhammad Noor Amin, Norsyafina Roslan, Norasiah Sulaiman, Muhammad Amzar Aznan, and Bilal Al Farishi. "Hydro-geochemical assessment of groundwater quality of Muda River Basin, Kedah Malaysia." Malaysian Journal of Fundamental and Applied Sciences 21, no. 1 (2025): 1513-1528. https://doi.org/10.11113/mjfas.v21n1.3368