Evaluating Calibration Potential in River Hydraulic Modelling Based on Critical Slope: A Case Study of Sungai Pahang Basin

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Evaluating Calibration Potential in River Hydraulic Modelling Based on Critical Slope: A Case Study of Sungai Pahang Basin

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Abstract: *River hydraulic modelling is challenging due to the difficulty of accurately replicating hydraulic behaviors and matching simulated water levels with recorded measurements, necessitating rigorous calibration feasibility assessments. In this study, we present a novel approach to determine the calibration limit for sub-catchments in a river basin using an equation derived from Continuity, Conveyance, Froude, and Manning's formulae. The slope parameter, derived under the assumption of critical flow conditions, serves as an indicator for calibration feasibility. If the river slope exceeds the critical slope, calibration is deemed impossible due to the supercritical conditions. This approach was tested in the Sungai Pahang Basin as a case study. Preliminary results confirmed the methodology's effectiveness in identifying calibration limits, proving that it is a useful tool for determining the feasibility of calibration. This method can save time and resources by identifying infeasible calibration scenarios early in the modelling process.*

Keywords: River Hydraulic Modelling, Calibration Feasibility, Flow Conditions, Slope Analysis

1. INTRODUCTION

River hydraulic modelling is essential for conducting effective analyses. It is primarily used for flood analysis and water resource management. River hydraulic modelling is challenging because it involves numerous factors to accurately replicate the conditions of a river basin. The instability in the river model can disturb the modelling and calibration process.[1] [2] [3]. To develop a reliable river hydraulic model, the parameters must be adjusted so that the simulated flow and water levels at the catchment outlet match observed values[4].

This adjustment process is known as calibration. However, there are instances when the simulated values cannot align with the measurements, despite multiple adjustments and combinations of model parameters.[5] [6]. As a result, the modeller may not achieve a high-performance model even after numerous calibration attempts. This uncertainty makes the calibration process time-consuming and unpredictable.

Several factors can make calibration impossible. For example, if the measurement data is invalid, it becomes difficult to simulate the actual situation accurately, as there is no proper reference[1].[7]. Therefore, data assessments are conducted prior to modelling to ensure the validity of the data used. Such assessments are standard practice in hydrological and river modelling. For instance, the rainfall runoff ratio is often used as an indicator of a hydrological model's calibration capability. If the calculated rainfall-to-runoff ratio based on observed data is unreasonable for the particular region, then calibrating the catchment may be pointless.

This study proposes an alternative solution to determine whether a catchment can be calibrated. Specifically, it uses the slope parameter as an indicator to determine the calibration limit. By assessing the slope parameter, modellers can quickly identify whether calibration is feasible, which ultimately saves time and resources. The slope parameter aids urban water management [8] by identifying where hydraulic modeling is feasible. It helps pinpoint areas where calibration may fail due to supercritical flow conditions, allowing for more efficient resource allocation. This improves flood risk assessment and infrastructure design, enhancing urban resilience to flooding. In this study, we introduce a novel approach to determine the feasibility of calibration for sub-catchments in a river basin using an equation derived from Continuity, Conveyance, Froude, and Manning's equations. The slope parameter, derived under the assumption of critical flow conditions, serves as an indicator for calibration feasibility.[9][10].

If the river slope exceeds the critical slope, calibration becomes unfeasible due to the presence of supercritical conditions. Conversely, calibration tends to be achievable when the river slope magnitude is below the critical slope. This method can save time and resources by identifying infeasible calibration scenarios early in the modelling process. By using the slope parameter as a calibration indicator, this study provides a practical and efficient solution to a common problem in river hydraulic modelling, potentially improving the accuracy and efficiency of future modelling efforts.[11][12]

2. STUDY AREA

Fig. 1 to Fig. 3 depicts the study area of this research, focusing on the Sungai Pahang Basin. The Pahang River Basin, situated in Pahang state, the second largest state in Malaysia, spans geographic coordinates between 101° 30' E - 103° 30' E longitude and 3° 00' N - 4° 45' N latitude.

Encompassing a total catchment area of 28,682 km², the basin's primary highland regions include the Titiwangsa Range on the western side, the Tahan Range in the central north, and the East Coast Range in the northeast. These highlands, with elevations ranging from 1,000 m to 2,180 m, contribute significantly to the basin's topographical diversity.[13][14]

Topographically, the upper catchment is marked by steep, dissected slopes, while the lower catchment is predominantly flat and swampy. The Pahang River, the longest river in Peninsula Malaysia, flows 459 km from its origin at the confluence of the Jelai and Tembeling rivers in the Titiwangsa Mountains to its mouth at the South China Sea.[15][16][17]

For this study, the Pahang River Basin serves as the focal point for critical slope analysis, crucial for understanding river hydraulic model instability. Specifically, the upstream subcatchment, Sungai Jelai, and the downstream subcatchment, Sungai Bera, were selected for detailed analysis. Within each subcatchment, a single river reach was initially chosen for sample calculations.

The analysis focused on the uppermost and lowermost cross sections of each selected river reach, providing critical insights into the hypsometric and slope characteristics essential for assessing hydraulic stability.

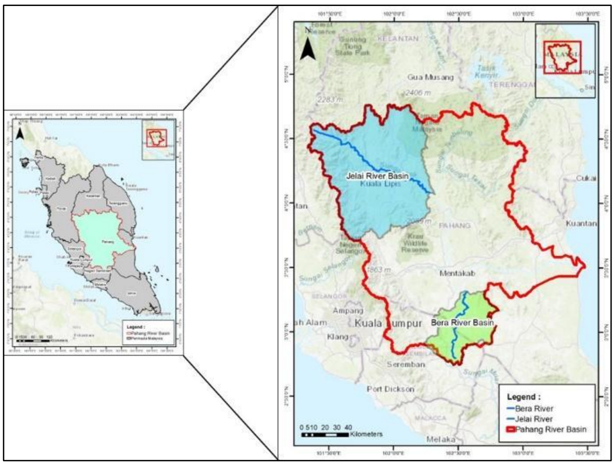

Fig. 1 Study area in Pahang River Basin

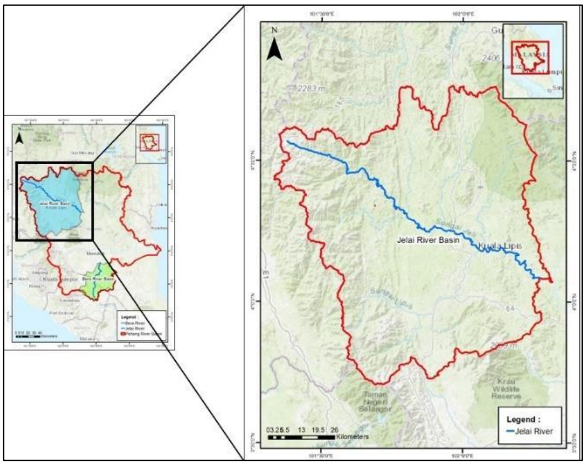

Fig. 2 Jelai River Basin

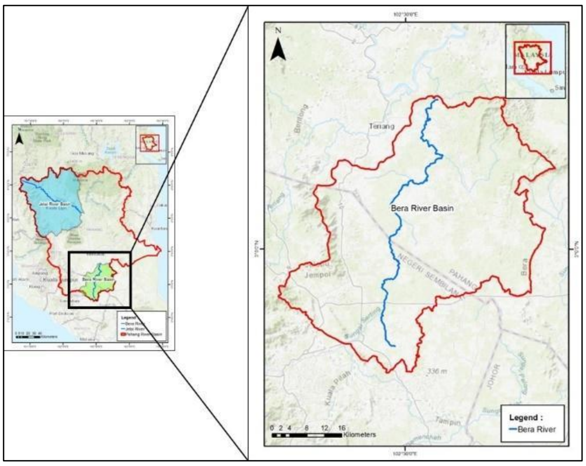

Fig. 3 Bera River Basin

3. METHODOLOGY

3.1 Data

Our analysis primarily focuses on the river's physical properties, including river cross sections, length, elevation, cross-sectional area, and water depth, alongside hydraulic properties such as channel conveyance. For this purpose, we obtained the latest river survey data for the year 2020 from the Drainage and Irrigation Department of Malaysia (DID). For example, the lower most river cross section data of Sungai Bera is presented in Table. 1 and plotted in Fig. 4.

Table 1. River cross section data of Sungai Bera.

Offset (m)	X coordinate (m)	Y coordinate (m)	Bed level (m)
0	503905.2	374591.6	23.194
9.142	503910.3	374599.2	23.202
17.663	503915.9	374605.6	23.377
26.973	503922.4	374612.3	23.868
36.48	503928.3	374619.7	24.104
45.723	503934.4	374626.7	24.485
54.063	503940.3	374632.6	24.913
60.521	503944.8	374637.2	24.271
77.017	503956.1	374649.2	14.855
90.542	503964	374660.2	12.515
103.509	503970.4	374671.5	17.155
127.001	503982.8	374691.4	25.633
132.864	503986.1	374696.3	25.126
143.715	503992.4	374705.1	25.31
153.595	503998	374713.2	25.411
163.258	504003.5	374721.2	25.168
172.538	504008.6	374728.9	24.841
183.481	504014.9	374737.9	24.485

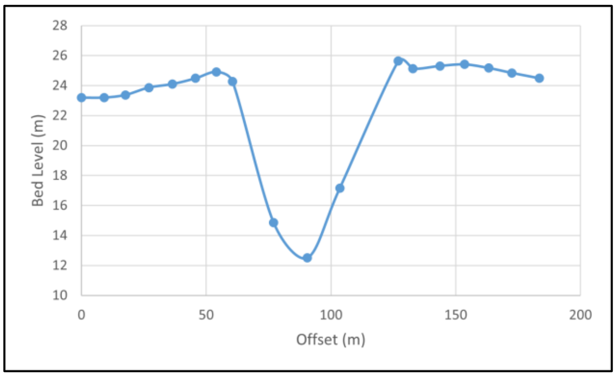

Fig. 4. Bed level of each offset point along the cross section of Sungai Bera.

3.2 Input Parameter Extraction

We utilized hydrodynamic modelling software, including Info Works Integrated Catchment Model (ICM) and Mike 11, to calculate the necessary parameters for the selected river cross sections. The cross-sectional data were imported into these modelling tools, enabling the generation of detailed graphs.

From these graphs, we extracted the area and conveyance of the selected river cross sections, providing crucial insights for our analysis. Fig. 5 and Fig. 6 illustrate the relationship between water level and cross-sectional area, and between water level and conveyance, respectively, for the lowermost cross section of Sungai Bera.

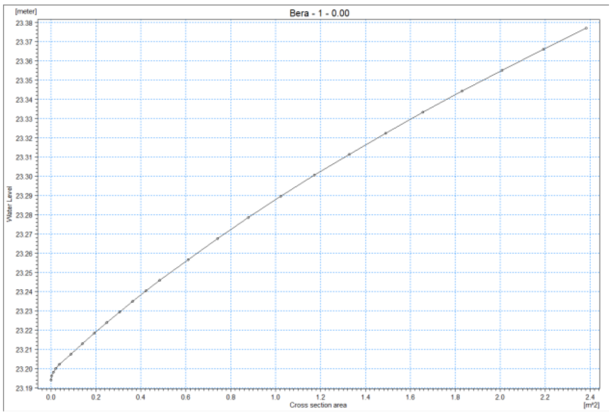

Fig. 5. Relationship between the water level and cross section area of Sungai Bera’s lowermost cross section.

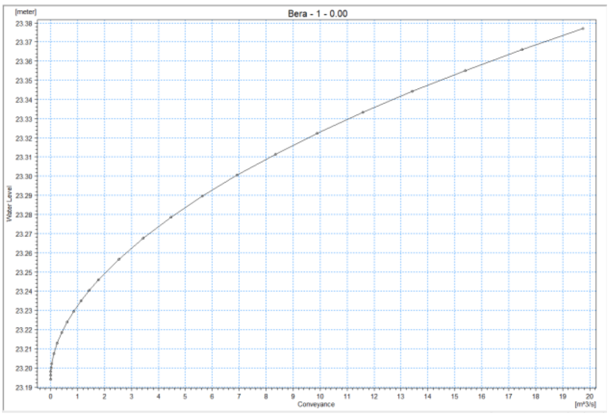

Fig. 6. Relationship between the water level and conveyance of Sungai Bera’s lowermost cross section.

Table 2. Extracted input parameters for the selected cross sections.

River	Length, L (m)	Elevation, E (m)	Cross Section
Jelai	159,289	1230.707	Uppermost
			Lowermost
Bera	97,807	28.563	Uppermost
			Lowermost
River	Cross Section	Cross Section Area, A (m^2)	Conveyance, K (m^3/s)
Jelai	Uppermost	23.918	922.891
	Lowermost	1,979.800	331,722.427
Bera	Uppermost	63.357	2622.640
	Lowermost	2.382	19.752

3.3 River hydraulic equations

The primary goal of this study is to derive a critical slope equation using fundamental river hydraulic equations, including Continuity, Conveyance, Froude, and Manning's equations.[18] Detailed descriptions of each equation are provided as follows.

Firstly, the continuity equation in river hydraulics states that the rate of flow of water through any cross-section of a river is equal to the product of the cross-sectional area and the flow velocity. Mathematically, it can be expressed as:

$$Q = VA$$

where,

Q is the discharge (m^3/s)
A is the cross-sectional area of the river channel (m^2)
V is the flow velocity of the water (m/s)

Secondly, channel conveyance in river hydraulics refers to the capacity of the channel to convey water. It is a measure of the efficiency with which a river channel can transport flow and is influenced by the channel's shape and roughness[19].Mathematically, channel conveyance, K is often related to the hydraulic radius, R and Manning's roughness coefficient, n by the following equation:

$$K = \frac{1}{n} A R^{\frac{2}{3}}$$

where,

K is the conveyance (m^3/s)
n is the Manning's roughness coefficient (dimensionless)
A is the cross-sectional area of the river channel (m^2)
R is the hydraulic radius, ratio of cross-sectional area to wetted perimeter (dimensionless)

Thirdly, the Froude number (F_r) in river hydraulics is a dimensionless number used to characterize the flow regime in open channels[9]. It is defined as the ratio of flow velocity, V to the square root of the product of gravitational acceleration, g and the hydraulic depth, D:

$$F_r = \frac{V}{\sqrt{gD}}$$

where,

F_r is the Froude number (dimensionless)
V is the flow velocity (m/s)
g is the gravitational acceleration ($9.81 m/s^2$)
D is the hydraulic depth (ratio of cross-sectional area to the top width of the flow)

The Froude number helps classify flow conditions as follows:

$F_r < 1$: Subcritical flow (slow flow, significant water depth influence)
$F_r = 1$: Critical flow (velocity equals wave speed).
$F_r > 1$: Supercritical flow (fast flow, wave speed exceeds flow velocity).

The last equation, which is Manning’s, is is a fundamental relationship used in open channel hydraulics to calculate the flow velocity, V or flow discharge, Q, based on the (cross section area of river, A if Q is calculated) hydraulic radius, R, slope, S, and Manning's roughness coefficient, n.[20] It is expressed as:

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$
$$Q = \frac{1}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}}$$

where,

V is the flow velocity (m/s)
Q is the flow discharge (m^3/s)
n is the Manning's roughness coefficient (dimensionless)

A is the cross-sectional area of the river channel (m^2)
R is the hydraulic radius, ratio of cross-sectional area to wetted perimeter (dimensionless)
S is the channel slope, the drop in elevation per unit length of channel, (dimensionless)

3.4 Critical Slope Derivation

The steps of deriving the critical slope from the river hydraulic equations explained earlier are described as follows:

Step 1

The Continuity equation is Q = VA. Substitute Manning's equation, V = $\frac{1}{n}R^{\frac{2}{3}}S^{\frac{1}{2}}$ into Q = VA and it becomes Q = $(\frac{R^{\frac{2}{3}}S^{\frac{1}{2}}}{n})$A. Shuffle the parameters in Q = $(\frac{R^{\frac{2}{3}}S^{\frac{1}{2}}}{n})$A and it becomes Q = $\frac{1}{n}AR^{\frac{2}{3}}S^{\frac{1}{2}}$.

Step 2

Substitute Conveyance equation, K = $\frac{1}{n}AR^{\frac{2}{3}}$ into Q = $\frac{1}{n}AR^{\frac{2}{3}}S^{\frac{1}{2}}$ and it becomes Q = $KS^{\frac{1}{2}}$.

Step 3

Substitute Continuity equation, Q = VA into Q = $KS^{\frac{1}{2}}$ and it becomes VA = $KS^{\frac{1}{2}}$.

Step 4

The Froude number equation is $F_r = \frac{V}{\sqrt{gD}}$. When there is critical flow, F_r becomes 1. So, 1 = $\frac{V}{\sqrt{gD}}$ and if this equation is expressed in terms of g and D, it becomes V = $\sqrt{gD}$.

Step 5

Substitute V = $\sqrt{gD}$ into VA = $KS^{\frac{1}{2}}$ and it becomes $\sqrt{gD}$A = $KS^{\frac{1}{2}}$. When this equation is expressed in terms of g, D, K and A, it becomes $S_c = \frac{gDA^2}{K^2}$.

Therefore, the derived critical slope is as follows:

$$S_c = \frac{gDA^2}{K^2}$$

4. RESULTS AND DISCUSSION

This section presents the result of the validation process for deriving the critical slope equation through dimensional analysis. Additionally, it demonstrates the results by applying this validated equation in determining the calibration limits within the subcatchments of Sungai Jelai and Sungai Bera. The validation action through dimensional analysis ensures the reliability of the critical slope equation, while its implementation helps to identify precise calibration limits, thereby enhancing the effectiveness of hydraulic modelling in these subcatchments.

4.1 Dimensional analysis

The units of parameters for the derived critical slope equation, $S_c = \frac{gDA^2}{K^2}$ are as follows:

Where:

S_c = dimensionless
g = $\frac{m}{s^2}$
D = m
A = m^2
K = $\frac{m^3}{s}$

When the units are substituted into the derived equation,

$$= \frac{\frac{m}{s^2}.m.(m^2)^2}{(\frac{m^3}{s})^2}$$

$$= \frac{\frac{m^1}{s^2}.m^1(m^2)^2}{(\frac{m^3}{s^1})^2}$$

$$= \frac{\frac{m^1.m^1.m^4}{s^2}}{(\frac{m^3}{s^1})^2}$$

$$= \frac{\frac{m^6}{s^2}}{\frac{m^6}{s^2}}$$

Since both the numerator and denominator have the same units, they cancel each other out, resulting in a dimensionless quantity. This outcome validates the concept of the critical slope by demonstrating consistency across the hydraulic equations.[21] Consequently, it confirms that the critical slope equation can be reliably used to identify the calibration limits of a subcatchment. This dimensional consistency is crucial for ensuring the accuracy and applicability of the critical slope in hydraulic modelling and analysis.

4.2 Critical Slope Calculation

The values of input parameters of the subcatchments are demonstrated in Table 3.

Table 3. Input parameters required for critical slope calculation.

River	Cross Section	Water Depth, D (m)	Cross Section Area, A (m2)	Conveyance, K (m3/s)
Jelai	Uppermost	2.318	23.918	922.891
	Lowermost	5.342	589.847	331722.427
Bera	Uppermost	2.487	63.357	2622.64
	Lowermost	0.033	2.382	19.752

Table 3. provides information on specific cross sections within the study area. The cross section with the chainage ID of Sg. Telom (CH8100) represents the most upstream location of Sungai Jelai, while Sg. Jelai (CH00) marks the most downstream point. Similarly, in the Sungai Bera subcatchment, Sg. Serting (CH69500) is situated at the most upstream location, and Sg. Bera (CH500) at the most downstream point. These chainage IDs and their corresponding values were extracted from hydrodynamic modelling tools and are crucial for calculating the critical slope of each subcatchment. The detailed calculations for determining the critical slope based on these upstream and downstream cross sections are as follows:

The critical slope of Sungai Jelai, S_{cJelai},

$$S_{cJelai} = \frac{gDA^2}{K^2}$$

$$S_{cJelai} = \frac{9.81(\frac{2.318+5.342}{2})(\frac{23.918+589.847}{2})^2}{(\frac{922.891+331722.427}{2})^2}$$

$$S_{cJelai} = 0.00013$$

The critical slope of Sungai Bera, S_{cBera},

$$S_{cBera} = \frac{gDA^2}{K^2}$$

$$S_{cBera} = \frac{9.81(\frac{2.487+0.033}{2})(\frac{63.357+2.382}{2})^2}{(\frac{2622.64+19.752}{2})^2}$$

$$S_{cBera} = 0.00765$$

The purpose of dividing the sum of the uppermost and lowermost cross sections by two is to calculate the average critical slope for the river reach. This approach provides a representative value that reflects the overall slope characteristics of the reach, rather than focusing solely on the extreme values at the ends.

By obtaining this average critical slope, we can more effectively compare it to the actual river slope values along the reach. This comparison is crucial for assessing the flow dynamics and stability of the river, ensuring that the average critical slope serves as a meaningful benchmark for evaluating whether the river conditions are likely to transition between subcritical and supercritical states.

Based on the calculation, the critical slope of Sungai Jelai (0.00013) is smaller than that of Sungai Bera (0.00765). The concept of critical slope represents a specific channel gradient at which the flow transitions between subcritical (slow and deep) and supercritical (fast and shallow) states. In the Sungai Jelai subcatchment, this transition occurs at a lower threshold compared to the Sungai Bera subcatchment. This implies that even a slight increase in the river slope in Sungai Jelai can cause the flow conditions to shift to a supercritical state, where the water moves faster and shallower. This observation aligns with the flow characteristics typically found in upstream catchments or elevated terrains, where the river gradients are steeper and the flow velocities are higher.

In contrast, the Sungai Bera subcatchment requires a much steeper slope to reach the same transition point. The higher critical slope value indicates that the flow remains subcritical over a wider range of slopes before becoming supercritical. This distinction is crucial for understanding and managing the flow dynamics within each subcatchment, as it influences flood risk, erosion potential, and the overall behavior of the river system under varying conditions.

By analyzing and comparing these critical slopes, we gain valuable insights into the hydraulic behavior of the rivers, which can inform better design and management practices for maintaining stable and efficient flow conditions.

4.3 River slope calculation

The actual slope of the river reaches found in the two selected subcatchments are calculated to be compared with the calculated critical slopes. Table 4 shows the length and elevation of the selected river reaches to calculate the actual slope of the river reaches. Fig. 7 and Fig. 8 demonstrate the representation of river reaches of Sungai Jelai and Sungai Bera.

Table 4. Length and elevation of the selected river reaches

River	Length, L (m)	Elevation, E (m)
Jelai	159,289	1230.707
Bera	97,807	28.563

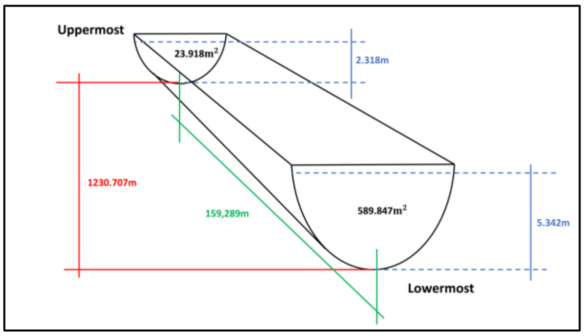

Fig. 7. Representation of Sungai Jelai river reach.

River slope of Sungai Jelai, S_{rJelai}

$$S_{rJelai} = \frac{Elevation\ of\ Sungai\ Jelai}{Length\ of\ Sungai\ Jelai}$$

$$S_{rJelai} = \frac{1230.707}{159289}$$

$$S_{rJelai} = 0.00773$$

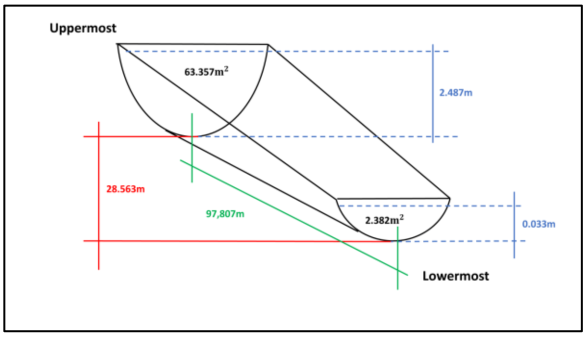

Fig. 8. Representation of Sungai Bera river reach.

River slope of Sungai Bera, S_{rBera}

$$S_{rBera} = \frac{Elevation\ of\ Sungai\ Bera}{Length\ of\ Sungai\ Bera}$$

$$S_{rBera} = \frac{28.563}{97807}$$

$$S_{rBera} = 0.00029$$

4.4 Calibration Limit Identification

Fig. 9 provides the graphical view of the comparison done between the critical and river slopes of Sungai Jelai and Bera river reaches.

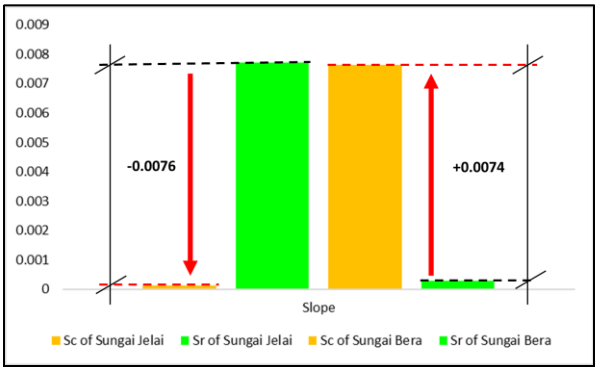

Fig. 9. Comparison between critical and river slopes of Sungai Jelai and Bera river reaches.

Based on Fig. 9, in the case of Sungai Jelai, the river slope (S_r) is greater than the critical slope (S_c), which suggests that calibration of the hydraulic model in this catchment is not feasible. This disparity indicates that the flow conditions in Sungai Jelai are more likely to be supercritical, where water moves rapidly and exhibits turbulent behavior. Under such conditions, achieving an accurate and reliable calibration is challenging because the model may not be able to capture the complex flow dynamics accurately. Supercritical flow occurs in steep channels. Small disturbances in supercritical flow can either be dampened or amplified into roll waves, depending on the stability of the flow. In shallow, steep channels, the surface velocity of the flow may become slower than the wave speed [22] .Consequently, even if a calibration procedure is attempted, the model's performance is likely to be suboptimal and may not provide reliable results for predicting flow behavior or assessing flood risks. This clearly shows that the calibration phases have high uncertainty and high sensitivity [23]. The flow condition of the Sungai Jelai River could become subcritical if the actual river slope is lowered by more than 0.0076.

On the other hand, in the case of Sungai Bera, the river slope is smaller than its critical slope. This indicates that the flow conditions are more likely to remain subcritical, characterized by slower and deeper water movement. Such conditions are generally more stable and predictable, making it feasible to perform calibration effectively. The lower river slope compared to the critical slope suggests that the model can be tuned to accurately reflect the observed flow conditions, leading to higher performance and reliability. This enables more precise predictions and better management of the river system. The flow condition of the Sungai Bera River could become supercritical if the actual river slope is increased by more than 0.0074, which could turn the river system to be hardly calibrated.

In summary, the comparison of river slope to critical slope serves as a key indicator of the calibration potential for hydraulic models. In Sungai Jelai, the higher river slope relative to the critical slope precludes effective calibration, resulting in potential inaccuracies in model performance. Conversely, the lower river slope in Sungai Bera, relative to its critical slope, indicates favorable conditions for calibration, allowing for more accurate and reliable modelling outcomes.

This research focused on using the actual river slope to assess calibration feasibility. However, future studies could expand by analyzing terrain slope as well as performed by [24] Terrain slope can provide additional insights into the calibration process, as it reflects the broader topographical context affecting water flow. By considering terrain slope, researchers can better understand the relationship between landscape features and hydraulic conditions, offering a more comprehensive view of where calibration is feasible and where it might be challenging. This approach could lead to improved modeling accuracy and more effective water management strategies.

A previous study [25] employed the Froude number to establish the minimum flow required for maintaining good biological quality in riverine environments. While this approach provides valuable insights, it primarily focuses on flow dynamics without considering the influence of topographical features. Our study aims to build on this foundation by introducing a novel approach that evaluates flow conditions through the lens of slope aspects. By analyzing the critical slope of the river basin, this method not only determines flow conditions but also serves as an indicator for model calibration limits.

This new perspective is particularly significant for the Sungai Pahang Basin case study, where the interplay between slope and flow is crucial for accurate hydraulic modeling. By incorporating slope aspects, this study provides a comprehensive understanding of flow conditions, leading to more precise model calibration. This approach enhances predictive accuracy and improves river system management. By considering both river slope and critical slope, this research offers a holistic approach to evaluating and calibrating hydraulic models, ultimately contributing to better-informed decision-making in river management.

5. CONCLUSION

The derived equation provides convincing results and aligns well with theoretical expectations. However, future research should expand to include a more extensive range of study areas and catchments to validate and refine these findings further. It is essential to develop a comprehensive index or set of criteria that can accurately indicate the capability limits of river hydraulic calibration.

To enhance the reliability of our calculations, future studies should incorporate more cross sections along the river reaches. Increasing the number of sampled cross sections will improve the robustness of the results, leading to more dependable conclusions about the hydraulic behavior of the rivers.

In addition, developing detailed river models for the two subcatchments, Sungai Jelai and Sungai Bera, will be crucial for testing the hypothesis that the relationship between river slope and critical slope determines calibration potential. Specifically, the hypothesis suggests that if the river slope is smaller than the critical slope, effective calibration cannot be achieved, resulting in lower model performance. Conversely, if the river slope is larger than the critical slope, the subcatchment can be successfully calibrated, leading to higher model performance.

These future models will provide a practical framework for verifying this hypothesis, offering insights into the conditions under which hydraulic models can be accurately calibrated. By confirming or refining this hypothesis, we can improve our understanding of the factors that influence model performance and develop more effective strategies for river management and flood prediction.

Overall, this research lays the groundwork for more detailed and expansive studies. By increasing the geographical scope, incorporating more cross-sectional data, and rigorously testing hypotheses through advanced modelling, future research can significantly enhance the precision and applicability of river hydraulic calibration. This will ultimately contribute to better management practices and improved predictive capabilities in riverine environments.

6. REFERENCES

[1] M. A. Mohd Anuar, M. S. Mohd Adnan, and F. H. Lim, “Uncertainty in River Hydraulic Modelling: A Review for Fundamental

Understanding," in *Lecture Notes in Civil Engineering*, Springer Science and Business Media Deutschland GmbH, 2022, pp. 215–220. doi: 10.1007/978-981-16-7920-9_14.

[2] N. Azidawati Haron, M. Sofiyan Sulaiman, B. Yusuf, and M. Mohsen Abood Abayati, "Evaluation Of River Stability By Morphological Assessment," *Infrastructure University Kuala Lumpur Research Journal V*, 2018, [Online]. Available: https://www.researchgate.net/publication/328852325

[3] J. K. Sharkey, "Investigating Instabilities with HEC-RAS Unsteady Flow Modeling Investigating Instabilities with HEC-RAS Unsteady Flow Modeling for Regulated Rivers at Low Flow Stages for Regulated Rivers at Low Flow Stages," 2014. [Online]. Available: https://trace.tennessee.edu/utk_gradthes/3183

[4] J. J. Warmink, M. J. Booij, and S. Hulscher, "Side channel dynamics View project Remote Sensing for Distributed Hydrologic Models: New Satellite Data, Model Parametrization and Spatial Metrics to Calibrate and Evaluate Models-Special Issue in Remote Sensing (MDPI) View project," 2007. [Online]. Available: https://www.researchgate.net/publication/241875354

[5] W. Hazdy Azad, L. Mohd Sidek, H. Basri, C. Ming Fai, S. Saidin, and A. Jalil Hassan, "2 Dimensional Hydrodynamic Flood Routing Analysis on Flood Forecasting Modelling for Kelantan River Basin," *MATEC Web of Conferences*, vol. 87, 2017.

[6] L. M. Sidek *et al.*, "High-resolution hydrological-hydraulic modeling of urban floods using infoworks icm," *Sustainability (Switzerland)*, vol. 13, no. 18, Sep. 2021, doi: 10.3390/su131810259.

[7] B. M. Victor Ponce, I. Member, P. J. Porras, and A. Member, "Effect of Cross Sectional Shape on Free Surface Instability," *Journal of Hydraulic Engineering*, vol. 121, no. 4, pp. 376–380, 1995.

[8] B. Venkatesh, R. Velkennedy, S. Murugan, and A. Velmurugan, "Indicator for formulating and measuring the Urban Sustainability Index: A Review," in *International Exchange and Innovation Conference on Engineering and Sciences*, Kyushu University, 2023, pp. 447–452. doi: 10.5109/7158038.

[9] A. J. Lee and B. Spa, "The hydraulics of steep streams Imaging Services North," 1998. [Online]. Available: www.bl.uk

[10] by Grant, "Critical Flow Constrains Flow Hydraulics in Mobile-Bed Streams : a New Hypothesis," 1999.

[11] P. K. Swamee, "Critical slope equations for open channels," *ISH Journal of Hydraulic Engineering*, vol. 8, no. 2, pp. 44–49, 2002, doi: 10.1080/09715010.2002.10514715.

[12] G. E. Grant, "Critical flow constrains flow hydraulics in mobile-bed streams: A new hypothesis," *Water Resour Res*, vol. 33, no. 2, pp. 349–358, 1997, doi: 10.1029/96WR03134.

[13] NWRS, "Review of the National Water Resources Study (2000-2050) and Formulation of National Water Resources Policy," Kuala Lumpur, 2011.

[14] Pan Ia Lun, M. Barzani Gasim, M. Ekhwan Toriman, S. Abd Rahim, and K. Amri Kamaruddin, "HYDROLOGICAL PATTERN OF PAHANG RIVER BASIN AND THEIR RELATION TO FLOOD HISTORICAL EVENT," *Jurnal e Bangi*, vol. 6, no. 1, pp. 29–37, 2011.

[15] M. K. A. Kamarudin, M. E. Toriman, N. A. Wahab, H. Rosli, F. M. Ata, and M. N. M. Faudzi, "Sedimentation study on upstream reach of selected rivers in Pahang River Basin, Malaysia," *Int J Adv Sci Eng Inf Technol*, vol. 7, no. 1, pp. 35–41, 2017, doi: 10.18517/ijaseit.7.1.971.

[16] M. K. A. Kamarudin *et al.*, "Assessment of river plan change using RS and GIS technique," *J Teknol*, vol. 76, no. 1, pp. 31–38, Sep. 2015, doi: 10.11113/jt.v76.2940.

[17] M. K. A. Kamarudin *et al.*, "Hydrological and climate impacts on river characteristics of pahang river basin, Malaysia," *Heliyon*, vol. 9, no. 11, Nov. 2023, doi: 10.1016/j.heliyon.2023.e21573.

[18] R. T. Milhous, "On grain roughness in rivers and streams," 2015.

[19] L. H. Robert, "Hydraulic Design of Flood Control Channels," Washington, 1991.

[20] J. P. Prancevic and M. P. Lamb, "Unraveling bed slope from relative roughness in initial sediment motion," *J Geophys Res Earth Surf*, vol. 120, no. 3, pp. 474–489, Mar. 2015, doi: 10.1002/2014JF003323.

[21] P. M. Kanellopoulos, "Incipient Motion Under Shallow Flow Conditions," 1998.

[22] J. C. Y. Guo, "Roll Waves in High Gradient Channel," 1999.

[23] S. Gibson, "Calibrating a Steady Flow Hydraulics Model," 2017.

[24] A. E. Bocobo, S. P. Camatura, A. M. G. Forcadas, and A. P. Sajonia, "Impact Assessment of Land Use and Land Cover Change of Agusan River Basin to Climate Using Geospatial Techniques And Regression Analysis," in *International Exchange and Innovation Conference on Engineering and Sciences*, Kyushu University, 2023, pp. 214–220. doi: 10.5109/7157974.

[25] Y.-C. Chen, J.-Y. Lin, E. H. Tsao, and J.-C. Huang, "Minimum Flow Estimated by the Froude Number," 2005.

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