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MORPHODYNAMIC CHARACTERISTICS OF A SANDY BED MEANDERING CHANNEL AT DIFFERENT DISCHARGES

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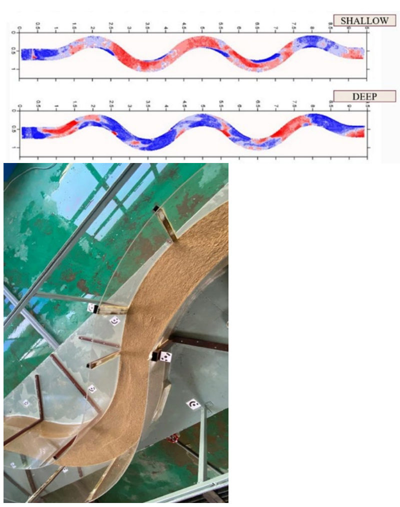
Graphical abstract



Abstract

Transportation of sediment is a critical issue in riverine environments, particularly in meandering channels where flow dynamics are complex. However, information regarding erosion and deposition processes in meandering channels is still limited. Therefore, an experimental investigation on the influence of discharge variation on the morphodynamics of a meandering channel has been carried out. The experimental investigation was conducted at the Hydraulic and Hydrology Laboratory, UTM Johor Bahru. The study investigates the flow profiles and the morphological changes of inbank flow conditions represented by shallow and deep flow depths. The findings revealed that Manning's *n* in a deep flow depth was 60.12% higher than a shallow flow depth. Moreover, velocity at the channel bend was increased by 8.3% to 14.6% compared to the crossover along the channel. This indicates that the geometrical planform plays a crucial part on the variability of velocity in the channel. Therefore, the outcomes of this study could provide more effective river management strategies to resolve erosion and deposition issues in river engineering studies.

Keywords: Meandering channel, mobile bed, fixed walls, inbank flow, Manning's *n*, velocity distribution, morphological changes

Abstrak

Pengangkutan sedimen adalah isu kritikal dalam persekitaran sungai, terutamanya dalam saluran berliku di mana dinamik aliran adalah kompleks. Walau bagaimanapun, maklumat mengenai proses hakisan dan pemendapan dalam saluran berliku masih terhad. Oleh itu, satu penyiasatan eksperimen tentang pengaruh variasi kadaralir ke atas morfodinamik saluran berliku telah dijalankan. Siasatan eksperimen tersebut telah dijalankan di Makmal Hidraulik dan Hidrologi, UTM Johor Bahru. Kajian tertumpu kepada keadaan aliran dan perubahan morfologi dalam tebing yang diwakili oleh kedalaman aliran cetek dan dalam. Penemuan mendedahkan bahawa Manning's n dalam kedalaman aliran yang dalam adalah 60.12% lebih tinggi daripada kedalaman aliran cetek. Selain itu, halaju di selekoh saluran telah meningkat sebanyak 8.3% kepada 14.6% berbanding dengan persilangan di sepanjang saluran. Ini menunjukkan bahawa bentuk pelan geometri memainkan peranan penting dalam kebolehubahan halaju dalam saluran. Oleh itu, hasil kajian ini dapat menyediakan strategi pengurusan sungai yang lebih berkesan untuk menyelesaikan isu hakisan dan pemendapan dalam kajian kejuruteraan sungai.

Kata kunci: Saluran berliku; dasar mudah-alih; dinding tetap; aliran dalam tebing; Manning's n, taburan halaju; perubahan dasar

1.0 INTRODUCTION

Meandering rivers are a prevalent feature of fluvial systems worldwide, and researchers continue to actively explore the complex hydraulic processes to gain a better understanding of the behaviour and impacts on surrounding structures. Among the most frequently discussed topics related to meandering rivers are their complex hydraulics, including the interplay between water and sediment movement, and their collective influence on the river morphology and the surrounding environment [1]. Sedimentation in these channels can significantly affect water quality, yet detailed information on sedimentation processes in meandering channels is still lacking due to its complexity and stochastic nature [2].

Sediment transport is a fundamental process in streams, influenced by factors such as flow direction, channel shape, gradient, flow rate, and sediment size [3]. The velocity of flow dictates the level of sedimentation and erosion [3]. Additionally, Manning's roughness coefficient plays a crucial role in flow resistance and consequently modifies the river bed form, shape, and geometry [4, 5].

Various laboratory experiments have been conducted to understand velocity patterns in meandering rivers. For example, Termini [6] investigated the distribution of bed shear stress located at bends in a meandering channel, while Ferreira da Silva and Ebrahimi [7] investigated flow patterns in a meandering channel and their interaction with the bed formation. Pradhan et al., [8] investigated three-dimensional turbulence flow properties in meandering channels under subcritical flow conditions, emphasising the influence of centrifugal force on turbulence distribution at bends.

This research aims to enhance the knowledge on the hydraulics in a meandering channel. Thus, the objective of this research is to investigate the flow profiles and the morphological changes along the meandering channel at shallow and deep flow depth conditions. By providing new insights and perspectives on these topics, we seek to contribute to the ongoing understanding of meandering river dynamics and assist researchers in advancing their knowledge in this field.

2.0 METHODOLOGY

2.1 Experimental Set-Up and Data Collection

A physical meandering flume was constructed at the Hydraulics and Hydrology Laboratory at Universiti Teknologi Malaysia, Skudai, Johor Bahru. A 10 m long, 0.3 m wide and 0.6 m deep meandering flume was constructed with a longitudinal gradient of 1:800 with three identical meanders as shown in Figure 1. Identical meanders are used to enable consistent analysis across different sections of the channel. This laboratory flume was designed with a scale ratio of 1:9 compared to the flume facilities at Loughborough University [9].

A transparent plexiglass was used as the side walls of the flume to facilitate visual observation of the bed profile pattern along the flume following the method described in Jumain, et al. [10]. Two individual tanks were attached at the flume end as the inflow and outflow tanks. An adjustable tailgate was installed at the downstream section to control the flow depth in the channel to achieve a quasi-uniform flow condition.

A sand layer with a uniform mean grain size of 0.8 mm was carefully prepared and levelled in the meandering flume, ensuring even distribution. To achieve a consistent depth of 0.2 m sand layer, the sand was compacted and levelled using a screed board following the longitudinal slope of the planform. A sediment trap sieve bag was located at the downstream area.

The Digital Closed Range Photogrammetry (DCRP) technique was employed to capture the initial sediment bed state. DCRP technique uses digital cameras which can provide millimetre accuracy and this technique is widely applied in various applications including bed morphology change monitoring [11, 12].

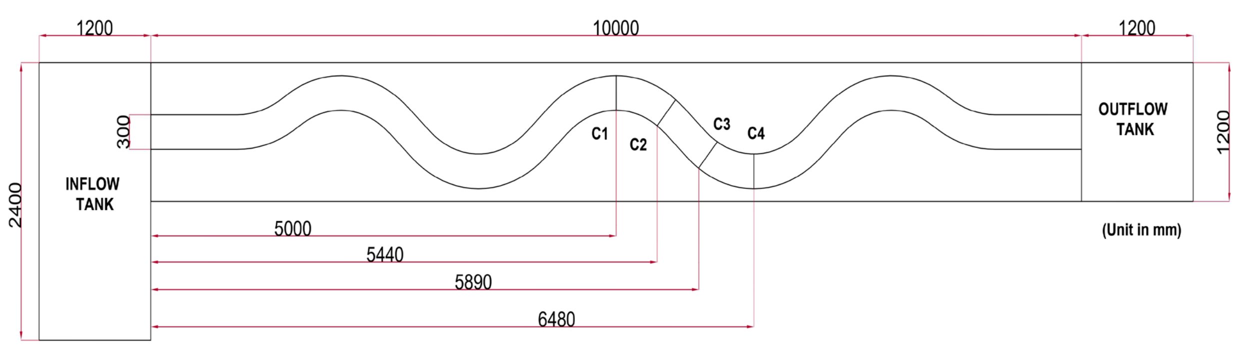


Figure 1 Plan view of the experimental setup.

Water discharge was set at 7 L/s using a Micronics PF330 portable flowmeter and was left to run for 6 hours. The flow depth was set at 8 cm with an aspect ratio, *B/H* of 3.8 to simulate a shallow flow condition. Flow depth was checked regularly to ensure the flow remained quasi-uniform until representative bed forms developed.

The sediment trap sieve bag was monitored and weighed periodically over the interval of 30 minutes throughout the experiment. After weighing, the sediment was placed back at the upstream inlet to ensure equilibrium of sediment entering and exiting the channel, following the method used in the previous experiment [13].

Once a steady quasi-uniform flow condition was achieved, velocity measurements were taken using an Electromagnetic Current Velocity Sensor ACM3-RS, displaying velocities in 3D, XYZ directions. Data collections were taken at desired points, which include crossovers and bends. C1 and C3 are the channel bends while C2 and C4 are the crossovers. Table 1 provides detailed information regarding the sample stations, where x is the station length from downstream (outflow tank) and L is the total length of flume.

Table 1 Location of data collection.

Station	Planform	x/L
C1	Bend	0.50
C2	Crossover	0.54
C3	Crossover	0.59
C4	Bend	0.65

Lastly, the DRCP technique was implied once again to capture the bed profile image as the final state of the bed for a shallow flow condition. The same procedure was repeated to simulate a deep flow condition by using a flow discharge of 11.4 L/s. The flow depth was set at 16 cm with an aspect ratio, *B/H* of 1.9.

2.1 Sediment Transport

The meandering channel is composed of uniformly graded sand d_{50} of 0.8 mm. Sediment on the channel bed will start to move once the flowing water exceeds a certain threshold of motion, known as the incipient motion [14]. The ratio magnitude between gravity and force-induced drag acting on the sediment generates a dimensionless number called the Shields parameter or dimensionless shear stress.

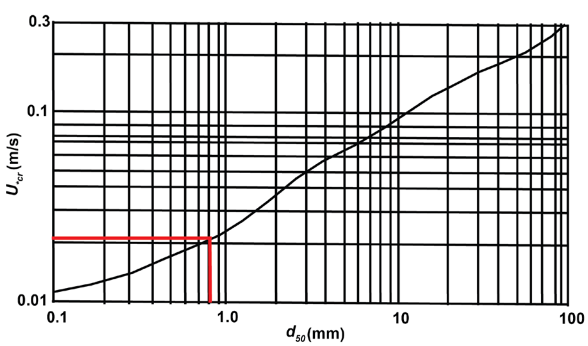


Figure 2 Shield Diagram for uniform graded sediment [9].

The Shields diagram as shown in Figure 2 was used to determine the critical shear velocity for uniform sand. Based on the graph plotted for d_{50}= 0.8 mm, the critical flow velocity, u_{*cr} was found to be 22 mm/s. The average critical flow velocity, u_{cr} for both flow conditions were calculated by using Eq. 1 [9, 15].

$$\frac{u_{cr}}{u_{*cr}} = 5.75\, log\left(5.53\ \frac{H}{d_{50}}\right) \tag{1}$$

Where u_{cr} is the average critical flow velocity, $u_{*cr,}$ is the critical flow velocity, H is the flow depth and d_{50} is the mean particle size. For both shallow and deep flow conditions, the calculated average critical flow velocities, u_{cr} were 0.33 m/s and 0.37 m/s, respectively. If the measured velocity exceeds the calculated average critical flow velocity, sediment erosion and deposition along the channel are anticipated.

3.0 RESULTS AND DISCUSSION

3.1 Manning's *n*

In meandering channels, flow patterns are often unclear, and few studies focus on how flow is distributed between crossovers and bends [16]. This study examined flow characteristics in a meandering flume under shallow and deep flow conditions. The Froude numbers, *Fr* were significantly higher in a shallow flow compared to a deep flow condition, where the percentage difference was up to 78%. In both conditions, subcritical flows occurred throughout the channel. The Reynolds numbers, *Re* ranging from 16,459 to 23,897 for both flow conditions, indicated turbulent flow in the channel.

The flow resistance in an open channel for both shallow and deep flow conditions was calculated by using Manning's equation. The standard equation for calculating Manning's roughness for open channel flow is given in Eq. 2 where n is Manning's roughness coefficient, U is the mean streamwise velocity (m/s), R is the hydraulic radius (m), and S_o is the channel bed slope.

$$n \;=\; \frac{R^{\frac{2}{3}} S_o^{\frac{1}{2}}}{U} \tag{2}$$

Figure 3 shows the flow resistance for both shallow and deep flow conditions along the flume length, *x/L*. In a shallow flow, Manning's n peaked at 0.022 at crossover C3 and lowest at 0.017 at bend C4. Similarly, in deep flow, the maximum and minimum Manning's n were 0.031 and 0.028 respectively at crossover C3 and bend C4. Flow resistance in a channel usually increases with bends or meanders due to the effect of centrifugal forces and secondary flow [17].

Another observation is the percentage difference of Manning's n for both flow conditions varied across the channel. The percentage difference ranged from 37.56 % to 60.12 %, with the highest at bend C4, and the lowest at crossover C3. Throughout the channel, n was consistently higher in deep flow compared to shallow flow. This suggests that significant additional resistance occurs in deep flow condition due to the increased surface contact area of the walls with the water. Manning's n depends on various factors, including the surface roughness of the meandering bed and walls. This finding aligns with the research by Tahmid, et al. [18], where Manning's n increases as flow depth increase.

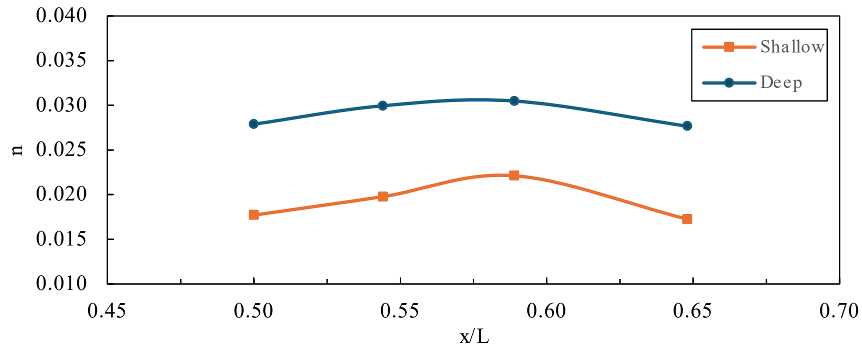


Figure 2 Manning's *n* for shallow and deep conditions.

3.2 Depth-Averaged Velocity

Depth-averaged velocity, U_d is an important parameter in the analysis of open channel flow dynamics, especially when comparing flow characteristics between straight and meandering channels. U_d is controlled by the flow relative depths, *Z* and channel aspect ratio, *B/H* to visualise the distribution of flow in the channel. In straight channels, U_d typically peaks at the central station due to the uniformity of the flow path. However, in meandering channels, the highest U_d are often observed at the bends [19].

In this experiment, U_d was measured at desired locations as shown in Figure 1, focusing on bends and crossovers. Figure 3 illustrates the U_d under both deep and shallow flow conditions. In shallow flow, U_d ranged from 0.25 m/s to 0.31 m/s, while in deep flow, U_d varied from 0.23 m/s to 0.25 m/s. The experiment recorded that U_d in shallow flow conditions are 8.4% to 26.1% higher than in deep flow conditions, with the maximum percentage difference occurring at bend C4. U_d at bends C1 and C4 significantly exceeded those at the crossovers C2 and C3 under both flow conditions. The variation of U_d at different locations along the curvature is a known behaviour of meandering channels, where curvature-induced forces alter the U_d distributions [1]. In a shallow flow, the difference in U_d between crossovers and bends is up to 28.1%, while in a deep flow condition is only 10.2%. This quantitative analysis emphasizes the importance of considering both depth and curvature in flow dynamic studies.

The difference between U_d at crossovers and bends suggests heightened resistance at crossovers. This finding is consistent with a study by Lugina, et al. [17], which showed that U_d is higher at outer bends compared with crossover due to the effect of channel meanders and flow resistance. Insights into velocity distribution and its underlying factors provide a valuable understanding of flow behaviour within meandering channels. Understanding these dynamics is important for predicting sediment transport, erosion, and deposition patterns in a channel.

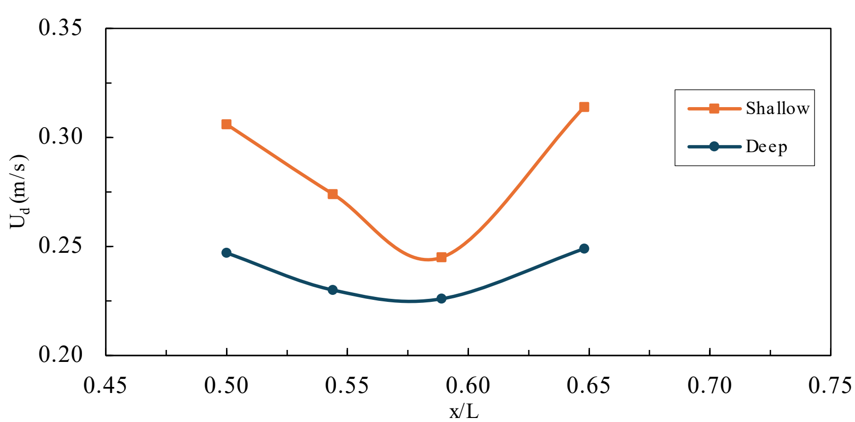


Figure 3 Depth averaged velocities for both deep and shallow flow conditions.

3.3 Sediment Dynamics

Sediment grains on the riverbed move under certain conditions of flowing water. The study of entrainment thresholds for sediment transport in meandering channels is ongoing due to the complex interactions between lift force, drag force, sediment weight, and the forces from surrounding grains [14].

Shields (1936) first described the threshold shear stress in a uniform sedimentary bed [20].

For both shallow and deep flow conditions, the calculated u_{cr} were 0.33 m/s and 0.37 m/s, respectively. In a shallow flow condition, stations C1 and C4, situated at bends were observed to have higher velocity compared to the u_{cr} of 0.33 m/s. The highest velocity, U_{max} recorded for the low flow condition was 0.40 m/s, located at the inner bend of station C4. Meanwhile, in a deep flow condition, data collected for all four stations were below the u_{cr}, with the U_{max} of 0.33 m/s at station C4.

Table 2 summarises the critical flow velocity and maximum velocities for both flow conditions. Based on these calculations, it is expected that sediment movement occurs in the shallow flow conditions at stations C1 and C4, while in a deep flow condition, no sediment movement occurs. These findings suggest that river bends are more susceptible to sediment movement due to high velocities. Moreover, this study highlights the influence of flow depth on sediment transport, with shallow flows being prone to sediment transport compared to deeper flows.

Table 2 Comparison between maximum velocity recorded and critical flow velocity.

Condition	Station	U_{max} (m/s)	u_{cr} (m/s)
Shallow	C1	0.37	0.33
	C2	0.31	
	C3	0.31	
	C4	0.40	
Deep	C1	0.31	0.37
	C2	0.26	
	C3	0.28	
	C4	0.33	

3.4 Bed Morphology

Bed morphology plays a crucial role in understanding the dynamics of sediment transport. To provide a detailed understanding of sediment deposition and erosion at specific points, cross-sectional profiles at stations C1 to C4 are presented in normalised bed level changes, *ΔZ/Z* as shown in Figure 4. *ΔZ* is the changes in bed level, while *Z* is the initial bed level. Various patterns of bed profiles are formed for each flow condition and location along the meandering channe

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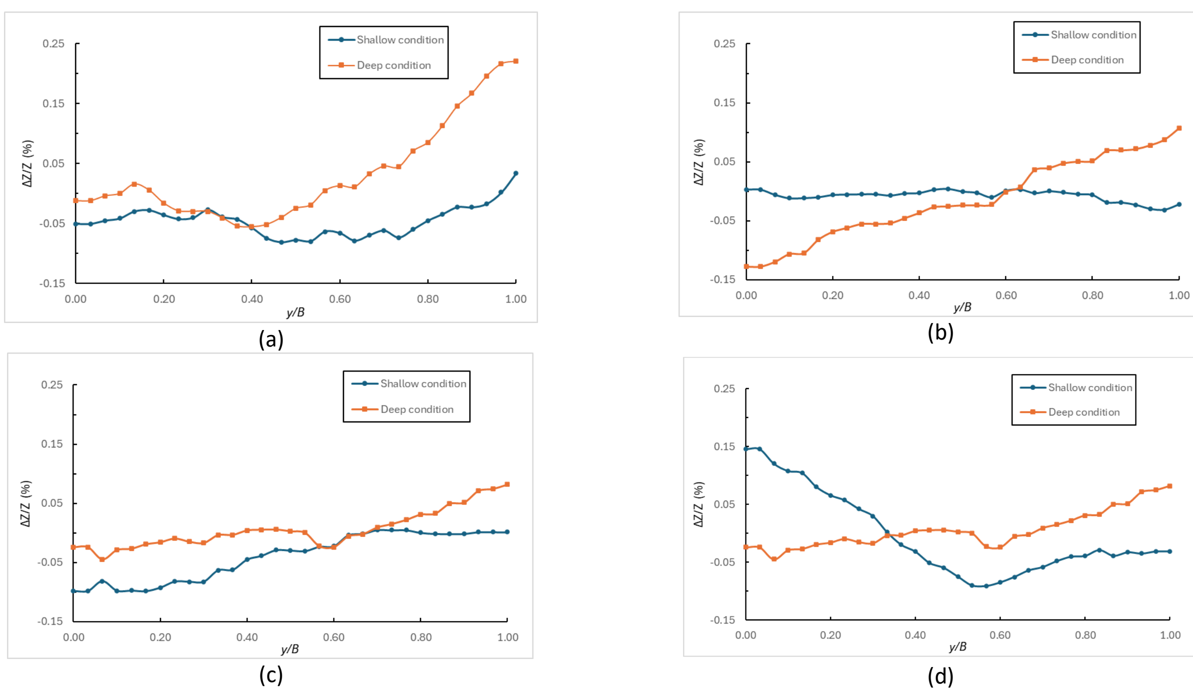

Figure 4 Cross-sectional profiles at different stations of (a) C1, (b) C2, (c) C3 and (d) C4.

The maximum sediment deposition *ΔZ/Z* was 0.22 % at inner bend C1 under a deep flow condition. In contrast, the maximum sediment erosion *ΔZ/Z* recorded was -0.12 % under a deep flow condition at crossover C2. This implies that unstable condition of sand bed occurred in a high flow depth since more sediment transport and bed level changes occurred. Shallow flow condition exhibits a more stable and uniform bed level, with lesser bed level changes especially at the crossover. Table 3 summarised the observed erosion and deposition levels along the channel during shallow and deep flow depths. It can be noticed that erosions are greater compared to deposition in a shallow flow condition influenced by higher velocity in the channel. Meanwhile, deep flow condition resulted in almost equal erosion and deposition levels.

Table 3 Observed erosion and deposition levels for shallow and deep flow conditions.

Station	Shallow		Deep	
C1	- 1.46	+ 0.04	- 0.42	+ 1.39
C2	- 0.25	+ 0.02	- 1.17	+ 0.72
C3	- 1.26	+ 0.02	- 0.29	+ 0.46
C4	- 1.02	+ 0.33	- 1.02	+ 0.90

To illustrate the detailed bed morphology throughout the channel, the DCRP technique was employed. DCRP images of the flume bed at various stages processed using Agisoft Metashape and Surfer softwares are shown in Figure 5. In a shallow flow condition, the DCRP image reveals widespread of erosion occurring along the channel, with pronounced effects observed at the outer bends. This is due to the u_{max} at bends C1 and C4 being higher compared with the u_{cr}. High velocities at these bends generate strong erosional forces that remove sediment from the bed.

DCRP images show that sedimentation processes occurred prominently at inner bends where flow velocity decreases, allowing sediments to settle. This pattern aligns with findings by Seminara, et al. [21] which stated that in channels with constant curvature and flat beds, the highest velocities are typically near the outer bends. Field research at Babon River, Indonesia, further supports this, indicating sedimentation at inner bends and erosion at outer bends [22].

However, in deep flow conditions, erosion is less pronounced and limited to specific areas such as crossover points. In contrast, sedimentation is more prevalent along the channel compared to a shallow flow. This reduction in erosion can be attributed to the threshold velocity of the sediment to move. The u_{cr} in a deep flow condition, which was 0.37 m/s is much higher compared with the u_{max} recorded, which was 0.31 m/s. High velocity influences the erosion processes in bed, while low velocity relates to the deposition of bed sediment.

This distinction highlights the complex interaction between flow depth, velocities, and sediment transport dynamics. These factors significantly influence the distribution of sediment transport processes within the channel. Advanced imaging techniques such as DCRP, coupled with theoretical insights and empirical data provide a comprehensive understanding of bed morphology processes under varying flow conditions. This approach yields valuable insights into the dynamics that govern fluvial systems.

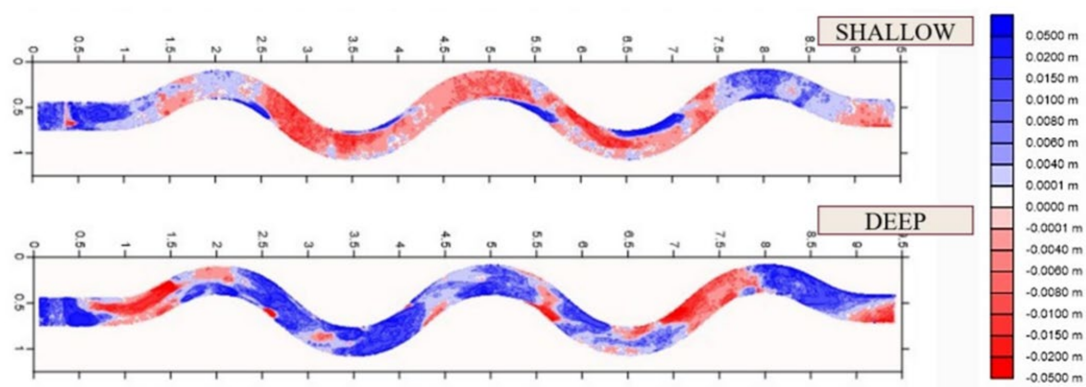

Figure 5 Digital closed range photogrammetry image of post-shallow flow and post-deep flow.

4.0 CONCLUSION

The experimental investigations on the influence of discharge variation on the morphodynamics of a meandering channel have been carried out. Thus, the conclusion that can be drawn: (i) Manning's *n*, in deep flow were higher compared to shallow flow due to the greater flow depth and volume of water interacting with the channel boundaries, (ii) meander planform significantly influenced the depth-averaged velocity along the channel, (iii) the changes of bed morphological were influenced by variations of velocities along the channel which resulted in erosion and deposition of sediment.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

References

[1] Pan, Y., Liu, X., & Yang, K. 2022. Effects of discharge on the velocity distribution and riverbed evolution in a meandering channel. *Journal of Hydrology*, 607.

[2] Rismani, N., Afzalimehr, H., Asghari-Pari, S.-A., Nazari-Sharabian, M., & Karakouzian, M. 2024. Influence of a Meandering Channel on the Threshold of Sediment. *Water,* 16(15): 2162.

[3] Dey, S. 2014. *Fluvial Hydrodynamics*.Springer

[4] Ferguson, R. I., Hardy, R. J., & Hodge, R. A. 2019. Flow resistance and hydraulic geometry in bedrock rivers with multiple roughness length scales. *Earth Surface Processes and Landforms,* 44(12): 2437-2449.

[5] Elmoaty, M. S., & Elsamman, T. 2020. Manning roughness coefficient in vegetated open channels. *Water Science.* 34(1): 124-131. DOI:10.1080/11104929.2020.1794706

[6] Termini, D. 2015. Momentum transport and bed shear stress distribution in a meandering bend: Experimental analysis in a laboratory flume. *Advances in Water Resources*, 81, 128-141.

[7] Silva, A. M., & Ebrahimi, M. 2017. Meandering morphodynamics: Insights from laboratory and numerical experiments and beyond,. *Journal of Hydraulic Engineering,* 143(9): 03117005.

[8] Prandhan, B., Pradhan, S., & Khatua, K. K. 2024. Experimental investigation of three-dimensional flow dynamics in a laboratory-scale meandering channel under subcritical flow condition. *Ocean Engineering*. 302: 117557.

[9] Ismail, Z. 2007. *A study of overbank flows in non-vegetated and vegetated floodplains in compound meandering channels.* Loughborough University.

[10] Jumain, M., Ibrahim, Z., Makhtar, M. R., Ishak, R., Rusli, N. M., & Salleh, M. Z. 2022. Spatio-Temporal Patterns of Saltwater Intrusion in A Narrow Meandering Channel. *International Journal of Integrated Engineering.* 14(9): 188-194.

[11] Udin, W. S., Ahmad, A., & Ismail, Z. 2014. Assessment of digital camera in mapping meandering flume using close range photogrammetric technique. *Science & Technology*. 22(1).

[12] Ibrahim, Z., Sa'ari, R., Jumain, M., MAsri, M. N., Aris, M. A., Amzah, N. A., . . . Alias, N. 2020. The Hydraulics and Morphodynamics of a Flooded Meandering Channel. *Proceedings of AICCE'19,* 53: 1459-1472. DOI:10.1007/978-3-030-32816-0_111

[13] Jumain, M., Ibrahim, Z., Ismail, Z., Harun, S., Makhtar, M. R., Rahman, M. S., . . . Anuar, M. Z. 2018. Transportation Of Bed Load And Its Formation For Inbank Flow: A Physical Modelling Approach. *Malaysian Journal of Civil Engineering,* 27(2).

[14] Spiliotis, M., Kitsikoudis, V., Kirca, V. O., & Hrissanthou, V. 2018. Fuzzy threshold for the initiation of sediment motion. *Applied Soft Computing,* 72: 312-320.

[15] Jumain, M. 2017. *Flood Hydraulics In Riparian Vegetated Mobile And NonMobile Bed Straight Channels.* Universiti Teknologi Malaysia.

[16] Kumar, A., Pradhan, B., & Khatua, K. 2022. *Analysis of Flow Properties Along a Rectangular Meandering Channel in A Gravel Bed.*

[17] Lugina, F. P., Uchida, T., & Hatono, M. 2021. Effect of channel meander on flow resistance. *Journal of Japan Society of Civil Engineers,* 77(2): I865-I870.

[18] Tahmid, A., Rahman, M. H., Mounota, S., & Ahsan, K. A. 2021. Relationship between Manning Roughness Coefficient and Flow Depth in Bangladesh Rivers. *Malaysian Journal of Civil Engineering,* 33(3): 51-58.

[19] Pradhan, A., Khatua, K. K., & Dash, S. S. 2015. Distribution of depth-averaged velocity along a highly sinuous channel. *Aquatic Procedia*, 4: 805-811.

[20] Beheshti, A., & Ataie-Ashtiani, B. 2008. Analysis of threshold and incipient conditions for sediment movement. *Coastal Engineering*, 55(5): 423-430.

[21] Seminara, G., Lanzoni, S., & Tambroni, N. 2023. *Theoretical Morphodynamics: River Meandering*. Firenze University Press DOI:10.36253/979-12-215-0303-6

[22] Pinasti, N. W., Wijayanti, E., Nurfaida, W., Sulaiman, M., & Kurniawan, A. 2024. Flow patterns at river bends and its response to surrounding infrastructures. I*OP Conference Series: Earth and Environmental Science,* 1311(1). DOI:10.1088/1755-1315/1311/1/012002