Hydrodynamic and Sedimentological Impacts of Intake Gate Opening Adjustments for Flood Mitigation in Water Systems

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ABSTRACT

Sediment management poses a significant challenge in hydraulic systems, affecting the water flow efficiency, structural durability, and operational reliability. The operation of the intake gate greatly influences the sediment characteristics, including the transport, deposition, and distribution patterns. This study investigates how different intake gate openings impact the sediment behavior in hydraulic systems to improve the operational strategies and reduce sediment-related problems. An experimental method was employed using a scaled physical model in controlled laboratory conditions, where various intake gate configurations were tested at consistent flow rates to simulate real-world hydraulic structures. Sediment samples were analyzed for grain size distribution, deposition patterns, and transport process dynamics. Data were gathered through direct measurements and video recordings, and then processed using sediment analysis software. The results showed that larger intake openings promote the sediment transport downstream and reduce the localized deposition near the intake. Conversely, smaller openings lead to sediment accumulation at the gate, increasing the risk of blockage and operational inefficiencies. Over time, these patterns evolve, potentially causing long-term sediment accumulation or channel scouring depending on the frequency and the way the gate is adjusted. Based on these findings, the study proposes adaptive, long-term sediment management approaches, including periodic gate operation adjustments, sediment flushing protocols, and comprehensive monitoring systems. These strategies aim to balance the sediment transport and deposition over extended operational periods, enhancing the performance and sustainability of hydraulic infrastructure, such as irrigation channels, reservoirs, and hydropower plants.

Keywords-sediment characteristics; intake gate opening; sediment transport; hydraulic systems; sediment management

I. INTRODUCTION

Water systems are essential for supporting various human activities, including irrigation, hydropower generation, and urban water supply. The effective operation of these systems is vital for maximizing the water resource use and promoting sustainable management. However, sediment accumulation poses a significant challenge, decreasing the system efficiency and raising the maintenance costs [1, 2].

Sediment transport and deposition are natural processes in hydraulic systems; however, excessive sedimentation can disrupt the water flow, damage the infrastructure, and decrease the storage capacity in reservoirs. To address these issues, it is essential to have a thorough understanding of the sediment dynamics under different operational conditions [3]. The hydraulic structures, such as intake gates, are crucial components of the water systems that influence the flow behavior and sediment movement. By adjusting the openings of the intake gates, operators can control the water flow and sediment transfer, which directly affects the system efficiency and maintenance requirements [4].

Hydrodynamic forces determine how sediment particles are transported, deposited, or resuspended. Factors, like flow velocity, turbulence, and gate operation, significantly influence the sediment transport patterns. Sedimentological features, such as the grain size and cohesion, further complicate these interactions [5].

The sediment transport in hydraulic systems has been examined. Authors in [6] demonstrated the relationship between the flow velocity and sediment deposition in reservoirs. Similarly, authors in [7] highlighted the role of the gate operation in reducing the sediment accumulation near the intake structures. While these studies provide valuable insights, they often focus on specific cases without addressing comprehensive strategies for different conditions.

Despite the advancements in sediment management techniques, challenges persist due to the absence of standardized guidelines for intake gate operations under varying hydrological and sediment conditions [8]. Many previous studies have focused on sediment transport, with a limited emphasis on how the gate adjustments simultaneously impact the hydrodynamics and sediment behavior. A greater understanding is, thus, necessary to balance the sediment transport and deposition, which is crucial for maintaining the system efficiency and structural durability [9-11]. This study fills this gap by examining how changes in intake gates impact the sediment movement under various flow conditions. It offers insights that can support more effective management strategies, reduce the maintenance costs, and improve the long-term sustainability of hydraulic system infrastructure.

This study aims to analyze the hydrodynamic and sedimentological effects of modifying intake gate openings in water systems by examining the sediment transport and deposition patterns across different gate configurations. The selected study area represents a typical hydraulic structure that frequently encounters sediment accumulation near the intake gates, resulting in blockages and a decreased flow capacity, particularly during flooding events. By examining how different gate openings influence the sediment dynamics under various flow conditions, the research provides knowledge into optimizing the gate operations for better sediment management. These findings are particularly relevant for applications, such as irrigation channels, hydropower plants, and reservoir systems, where sediment-related issues frequently arise. Ultimately, the study improves the efficiency, sustainability, and resilience of hydraulic infrastructure while promoting environmental preservation. The results are also expected to help in creating technical guidelines for intake gate operation. Additionally, they provide a scientific foundation for future improvements in sediment control strategies. This study also links the theoretical hydrodynamic analysis with real-world engineering applications in sediment management.

II. MATERIALS AND METHODS

A. *Research Location*

The research was conducted at Benteng Weir on the Saddang River in Sulawesi, a movable weir constructed in 1937 by the Dutch Colonial Government to regulate the water flow (Figure 1). Located in the Benteng Subdistrict of Pinrang Regency, about 13 km from Pinrang City and 196 km north of Makassar, the weir plays a vital role in water management and irrigation for the nearby agricultural areas. Despite its historical significance and ongoing maintenance, the weir now faces challenges, such as sedimentation, structural aging, and inefficiencies in the flow regulation, especially during periods of increased water demand and seasonal discharge fluctuations. These problems emphasize the need for continuous assessment and improvements to maintain the weir's sustainable functionality in irrigation and flood control.

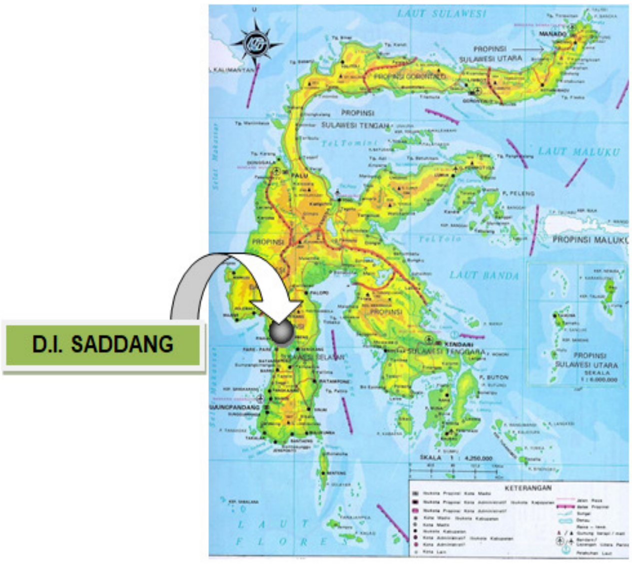

Fig. 1. Research location.

B. *Data Collection Technique*

To obtain the necessary data for this research, three methods were employed: literature review, secondary data collection, and primary data collection. The literature review collected information from previous studies and scientific articles to establish a solid theoretical foundation. The secondary data collection involves obtaining relevant data from existing institutions or previous research studies to provide a context and facilitate the comparative analysis. These methods helped establish the background knowledge essential for the prese4nt study.

Primary data were collected through field measurements focusing on the flow velocity and sediment concentration at Benteng Weir on the Saddang River. The flow velocity was measured directly with a current meter, which provided precise water speed readings and helped evaluate the flow distribution across the channel's wet cross-section. These real-time observations gave a clear understanding of the sediment transport behavior and hydraulic conditions at the site.

The flow velocity measurements in this study were performed using a current meter following a structured procedure. First, the channel depth was recorded to ensure correct instrument placement. The flow velocity was then measured vertically at three main cross-sectional points: the left bank, center, and right bank, each located at one-third intervals of the channel width. The appropriate propeller size was selected based on the water depth, with measurements taken at three vertical points: 0.2*h*, 0.6*h*, and 0.8*h* (where *h* represents the total water depth). The current meter was mounted on a measuring rod and positioned at each depth to record the propeller rotations over a 10 s interval. These measurements were repeated five times for each section, resulting in a total of 45 data points across the channel to ensure precise velocity profiling.

For the sediment concentration analysis, water samples were collected using bottle samplers at three depths (0.2*h*, 0.6*h*, and 0.8*h*) and at three cross-sectional positions (left, center, and right). The bottles were carefully submerged, facing the flow, to promote natural water and sediment intake without disturbing the process. The sampling was carried out with different intake gate openings to observe the sediment distribution across various flow conditions. This approach enabled an evaluation of both the vertical and lateral sediment distribution, supporting detailed analyses of the hydrodynamics and sediment transport.

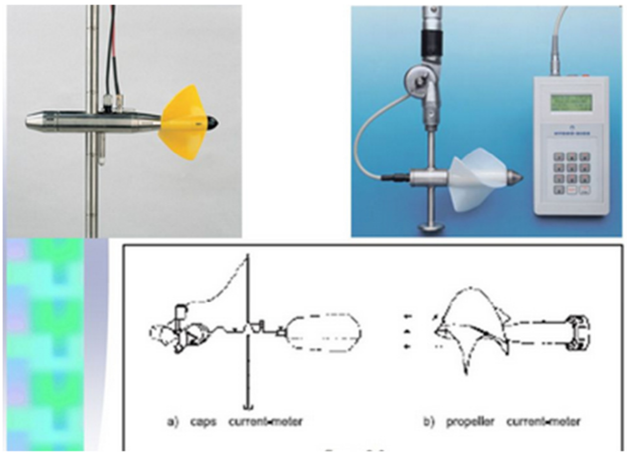

Fig. 2. Current meter and its parts.

The research was carried out through several systematic stages, beginning with data collection, followed by data processing, calculations, analysis, and discussion. During the preparation phase, channel cross-section drawings were collected through field observations as a reference for further analysis. In the execution phase, field instruments were used to measure the wetted cross-sectional area, flow velocity, and discharge. The velocity data were then converted into discharge values using hydraulic calculations to gain a better understanding of the flow characteristics.

Sediment concentration analysis was conducted in the laboratory using water samples collected from the field. Each sample (50 ml) was placed into a pre-weighed petri dish. The samples were then dried in an oven at 105°C for 24 h to evaporate the water, and the final weight was recorded. The sediment concentration was calculated by subtracting the initial weight from the final weight of the petri dish. This method provided accurate sediment measurements, which are essential for analyzing the sediment transport processes in the Saddang River at Benteng Weir.

C. Research Flow Chart

This research was carried out through a series of stages, starting with the preparation phase, which involved gathering channel cross-section data, defining the research parameters, and setting up the field equipment. The data collection phase included measuring the wetted cross-sectional area, flow velocity, and discharge, as well as collecting sediment samples at various depths and locations within the channel. The data were processed by converting the velocity into discharge, analyzing the sediment concentration in the laboratory, and applying hydraulic equations and models to validate the field measurements. The data analysis phase focused on evaluating variations in velocity, sediment transport patterns, and channel stability. Finally, the discussion and conclusion phase interpreted the findings, identified challenges, and provided technical recommendations to reinforce critical channel sections, thereby improving the long-term hydraulic efficiency and stability.

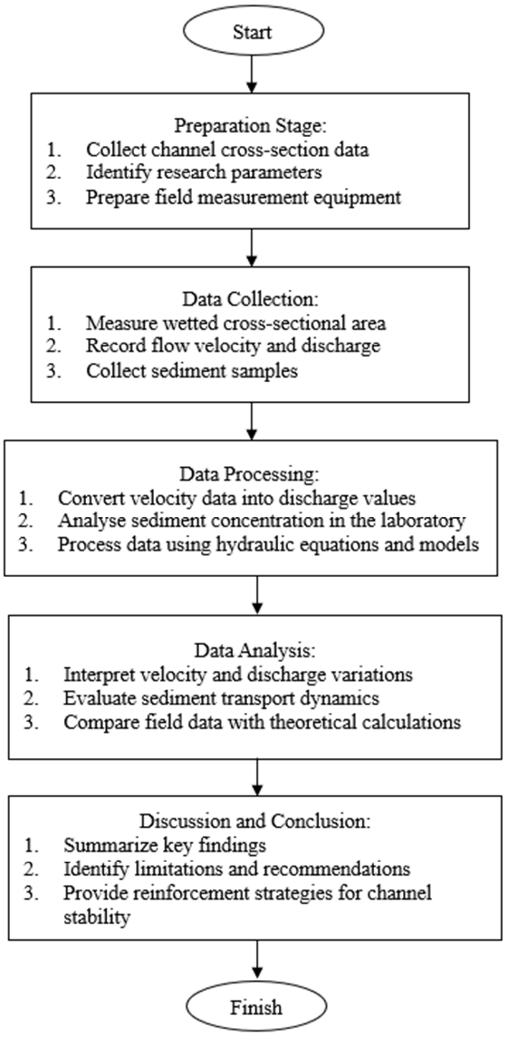

Fig. 3. Research flowchart.

III. RESULTS AND DISCUSSION

A. *Description of Research Result Data*

This study employs a quantitative approach, using direct field measurements at the sediment trap of Benteng Weir to gather data on the flow velocity and sediment concentration. Measurements were taken from October 25 to 27, 2024, to identify the sediment deposition patterns and hydraulic conditions. The location scheme provided in Figure 4 shows the measurement points and key site features. The data collected are used to analyze the sediment transport dynamics and evaluate the performance of the sediment trap. The results are expected to help optimize the sediment control and improve the long-term stability and function of the sediment trap weir.

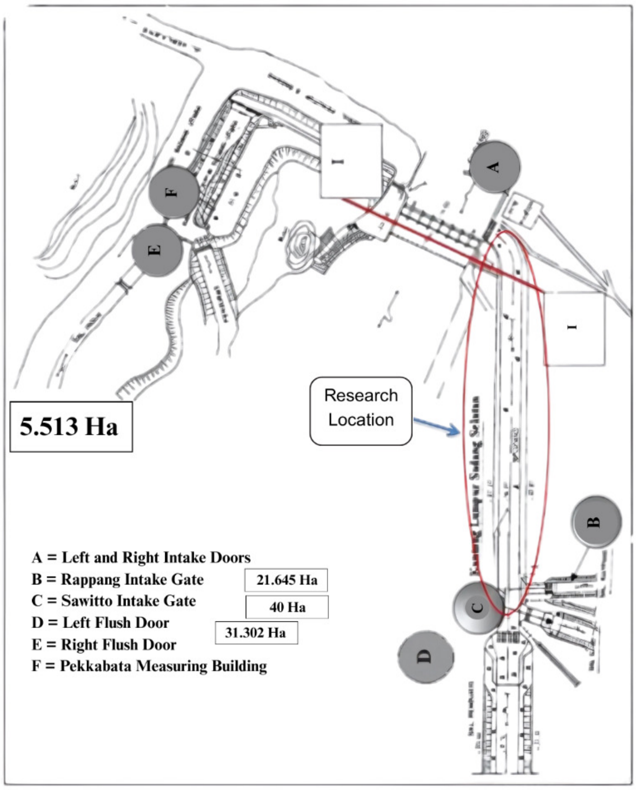

Fig. 4. Benteng Dam Plan.

B. *Description of the Results of the Mud Bag Research*

This study was conducted at the sediment trap of Benteng Weir, and the research findings are outlined as follows:

1) *Gate Opening Height and Water Surface Elevation*

Flow velocity measurements were taken with a current meter by adjusting the gate opening height. There are four different gate opening conditions, each corresponding to a different water surface elevation.

1. A gate opening height of 5.02 m corresponds to a water surface elevation of 21.03 m. Figure 5 shows the profile of the 5.02 m gate opening, providing a detailed view of the hydraulic conditions at this specific setting.

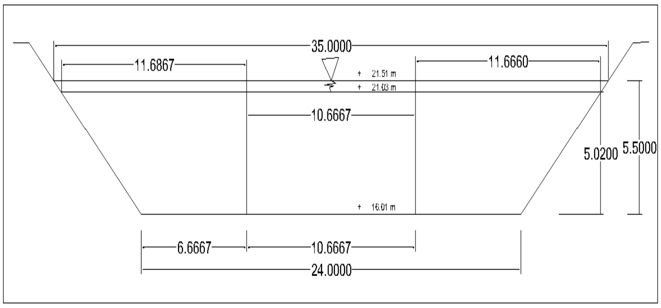

Fig. 5. Profile height of water gate opening 5.02 m.

2. A gate opening height of 4.00 m corresponds to a water surface elevation of +20.09 m. Figure 6 illustrates the profile of the 4.00 m gate opening, providing a detailed view of the hydraulic conditions in this specific context.

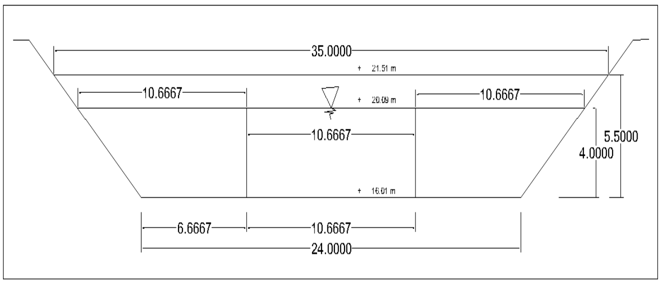

Fig. 6. Profile height of water gate opening 4.00 m.

3. A gate opening height of 2.08 m corresponds to a water surface elevation of 18.09 m. The profile of the 2.08 m gate opening is portrayed in Figure 7, which provides a detailed view of the hydraulic conditions in this specific context.

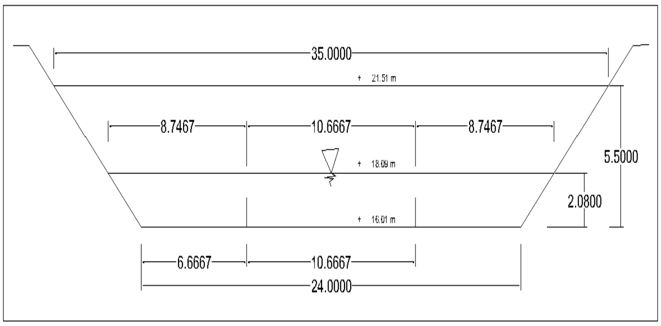

Fig. 7. Profile height of water gate opening 2.08 m.

4. A gate opening height of 1.12 m corresponds to a water surface elevation of 17.13 m. The profile of the 1.12 m gate opening shown in Figure 8 illustrates the hydraulic conditions at this specific setting.

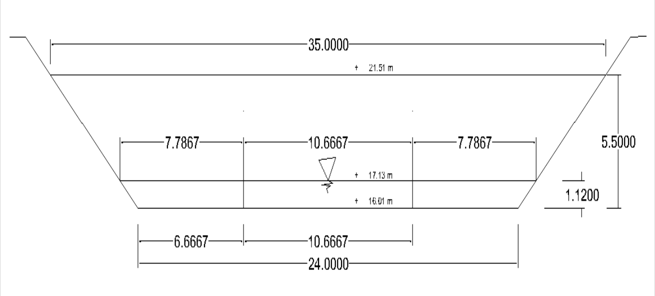

Fig. 8. Profile height of water gate opening 1.12 m.

The variations in the gate opening height and water surface elevation at Benteng Weir have a significant influence on the flow velocity and sediment transport dynamics within the sediment trap. Larger gate openings (5.02 m and 4.00 m) correspond to higher water surface elevations (21.03 m and 20.09 m, respectively), causing lower flow velocities and a reduced sediment transport capacity due to a decreased energy flow. Conversely, smaller gate openings (2.08 m and 1.12 m) correspond with lower water surface elevations (18.09 m and 17.13 m, respectively), which may lead to higher velocities and increased sediment resuspension, thus impacting the overall efficiency of the sediment deposition. These findings underscore the importance of optimal gate operation strategies in balancing the flow regulation and sediment management, thereby ensuring the long-term functionality and stability of Benteng Weir.

C. Flow Velocity (V)

The flow velocity (V) in the sediment trap channel was measured with a current meter. The initial velocity readings were in km/h and were then converted to m/s for consistent hydraulic analysis. The measured flow velocities at various vertical positions for each gate opening are presented in Table I, providing insights into the velocity distribution and its impact on the sediment transport within the channel.

TABLE I. FLOW VELOCITY IN MUD POCKET (V)

Rate at section i (R_{ai})	Depth	Door opening variations							
		H = 5.02 m		H = 4 m		H = 2.08 m		H = 1.12 m	
		Velocity (m/s)	Average (m/s)	Velocity (m/s)	Average (m/s)	Velocity (m/s)	Average (m/s)	Velocity (m/s)	Average (m/s)
P1. Left	0.2 H	1.28	1.22	1.08	1.09	0.93	0.96	0.37	0.36
P2. Left	0.6 H	1.31		1.16		1.02		0.43	
P3. Left	0.8 H	1.07		1.03		0.93		0.26	
P1. Middle	0.2 H	1.29	1.27	1.19	1.17	0.99	1.01	0.46	0.41
P2. Middle	0.6 H	1.34		1.22		1.10		0.49	
P3. Middle	0.8 H	1.18		1.10		0.93		0.27	
P1. Right	0.2 H	1.15	1.14	1.06	1.05	0.83	0.84	0.36	0.35
P2. Right	0.6 H	1.20		1.15		0.91		0.42	
P3. Right	0.8 H	1.08		0.95		0.77		0.27	

Based on the data listed in Table I, the flow velocity within the sluice channel varies significantly with changes in the sluice gate opening height. At the maximum opening gate (H = 5.02 m), the highest average velocity was recorded at the center of the channel, reaching 1.27 m/s, while the left and right sections measured 1.22 m/s and 1.14 m/s, respectively. When the opening gate decreased to H = 1.12 m, the average velocities dropped noticeably to 0.36 m/s on the left, 0.41 m/s in the center, and 0.35 m/s on the right. This trend aligns with basic hydraulic theory, which states that a smaller opening increases the flow resistance, thereby reducing the velocity. These observations support the findings in [12], where it was emphasized that the sluice gate configuration significantly influences the flow patterns and turbulence, ultimately affecting the sediment transport dynamics.

The variations in the flow velocity are directly connected to the sediment behavior within the channel. Larger gate openings allow for higher flow rates, promoting active sediment transport, while smaller openings result in reduced velocities that lead to sediment deposition. This phenomenon aligns with the studies that noted increased sedimentation under low-velocity conditions [13]. Additionally, authors in [14] highlighted that high-energy flow conditions can cause channel bed erosion, whereas lower energy flows typically lead to siltation and reduced channel capacity. Therefore, the proper regulation of sluice gate openings is essential for achieving a balanced sediment transport system, ensuring both hydraulic efficiency and the structural stability of the weir infrastructure [15].

D. Cross-Sectional Area

Based on field measurements, the cross-sectional area of each channel segment was identified. The channel cross-section was divided into three sections: one-third for the left bank, one-third for the middle section, and one-third for the right bank [16]. To find the cross-sectional area, the trapezoidal formula was applied to the left and right banks due to their sloping profiles, while the rectangular formula was applied to the middle section, which has a consistent shape [17]. This approach ensures an accurate representation of the hydraulic profile of the sluice channel, reflecting the actual geometry observed in the field. Determining the cross-sectional areas accurately is essential for a reliable flow analysis and sediment transport calculations [17]. The calculated values are summarized in Table II, which shows the cross-sectional areas for each section (A).

TABLE II. CROSS-SECTIONAL AREAS FOR EACH SECTION (A)

R_{ai}	Door opening variations			
	H = 5.02 m	H = 4 m	H = 2.08 m	H = 1.12 m
Left	46.02	34.67	16.03	8.09
Middle	53.55	42.67	22.19	11.95
Right	46.02	34.67	16.03	8.09
Total	145.59	112.00	54.25	28.14

The cross-sectional area of the sluice channel changes with the height of the sluice gate opening, as displayed in Table II. When the gate is fully open (H = 5.02 m), the total cross-sectional area is 145.59 m², including 53.55 m² in the central section and 46.02 m² on each side. As the gate opening decreases, the flow area significantly shrinks, with the smallest opening (H = 1.12 m) resulting in a total area of 28.14 m². This trend demonstrates the basic hydraulic principle that, under subcritical flow conditions, the flow area and discharge are directly proportional. The consistently larger area in the middle section is due to a reduced boundary friction, which allows for higher velocities compared to the side walls.

These observations align with the established literature, which shows that cross-sectional geometry and boundary conditions greatly influence the flow behavior [18]. Authors in [19] further emphasized that reduced gate openings change the velocity distribution and decrease the sediment transport efficiency. Therefore, the gate operation is a critical factor in regulating the discharge and sediment dynamics at Benteng Weir. Wider openings lead to higher discharge rates and increased sediment transport, but they also raise the risk of downstream erosion. Conversely, smaller openings restrict the discharge and may lead to sediment accumulation. These findings are in line with those of [20, 21], underscoring the importance of optimized gate control in maintaining the hydraulic efficiency and ensuring the long-term stability of the sluice infrastructure.

E. Flow Rate

The calculation of the water discharge in the mud pocket seeks to determine the amount of the vertical flow for each transverse direction section at every opening. Table III presents the flow discharge for each transverse direction section, and Figure 9 illustrates the relationship between the height of the door opening and the water discharge.

TABLE III. FLOW RATE OF EACH SECTION IN THE TRANSVERSAL DIRECTION

R_{ai}	Door opening variations			
	H = 5.02 m	H = 4 m	H = 2.08 m	H = 1.12 m
Left	56.24	37.69	15.35	2.88
Middle	68.13	49.94	22.31	4.87
Right	52.58	36.47	13.45	2.83
Total	176.95	124.09	51.11	10.58

According to Table III and Figure 9, the variation in the gate opening height affects the flow discharge in the sediment trap of the Benteng weir. The larger the gate opening height is, the greater is the water discharge through each transverse section of the channel. This results from the increased flow across the cross-sectional area, which allows a larger volume of water to pass through the gate. The highest discharge occurs at a gate opening height of 5.02 m, producing a total discharge of 176.95 m³/s, while the lowest discharge is recorded at an opening height of 1.12 m, with a total discharge of 10.58 m³/s.

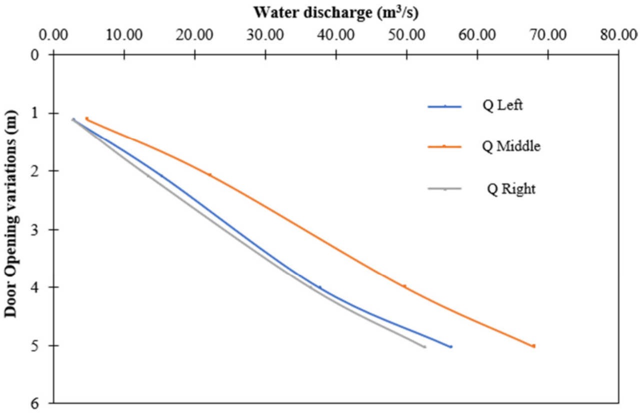

Fig. 9. Graph of the relationship between the door opening height and the water flow.

The distribution of the discharge across each transverse section shows that the middle section of the channel has a higher discharge than the left and right sections. This is clear from the discharge values for different opening variations, where the middle section consistently exhibits higher values than the edges. This difference is due to the flow velocity distribution, which tends to be greater in the middle of the channel. Similar results were reported in [22], where it was stated that the velocity profiles in the flow through openings increase in the middle section due to the distribution of fluid momentum.

The graph demonstrates that the relationship between the gate opening height and the water discharge exhibits a linear decreasing trend, where smaller gate openings result in a lower discharge. These findings align with those of [23], where it was stated that the water discharge through a sluice gate depends on the opening area and the difference in the water surface elevation. This study provides a deeper understanding of the discharge distribution patterns in the sediment trap, which can serve as a reference for planning and managing the sediment control infrastructure at Benteng weir.

Figure 9 depicts a trend where the sediment discharge increases as the gate opening height rises. This indicates that a bigger opening permits more water to flow, transporting a larger volume of sediment through the channel. Additionally, it is demonstrated that the water discharge measured in the transverse direction is the highest in the center section and decreases toward both edges of the channel. This pattern reflects the velocity and cross-sectional area distribution, where both the highest velocity and the largest cross-sectional area are located at the center of the channel. These findings are consistent with those of previous studies on flow dynamics, which have shown that the central part of a channel usually experiences higher flow rates due to more concentrated water movement and less friction compared to the edges.

Besides adjusting the intake gates, other flood mitigation methods—like retention basins, levee modifications, and controlled spillways—are frequently used to handle the excess water during flood events. Retention basins temporarily hold runoff and release it slowly, which helps reduce the peak discharge downstream. Although these basins are effective at managing the urban flooding and reducing the runoff pressure downstream, they require a substantial land area and may not be suitable for densely populated areas. Levee modifications, such as raising the elevation and adding setback levees, improve the containment capacity but may be expensive and disruptive to nearby land use. Controlled spillways are designed to safely divert the floodwater to designated areas, reducing the pressure on the main channels. However, their effectiveness depends on the accurate hydraulic design and sufficient land for overflow zones.

Compared to these alternatives, adjusting the intake gates provides a more flexible and localized method for the flood control, especially in existing hydraulic systems, like irrigation channels, reservoirs, and power plant inlets. Unlike the structural modifications, which typically require permanent changes and significant capital investment, gate adjustments can be made dynamically to respond to real-time hydrological conditions. This method allows operators to regulate the flow rates, adjust hydraulic pressure, and prevent upstream flooding without significant infrastructural modifications. Furthermore, when combined with predictive modeling and sediment management strategies, gate operations can serve a dual purpose: reducing the flood risk while controlling the sediment transport. While adjustments to the intake gates might not replace the large-scale flood mitigation infrastructure, they offer a cost-effective and adaptable solution that improves the overall flood management strategies when customized to specific site conditions.

IV. CONCLUSION

Based on the previous discussion, several conclusions can be drawn. The values of velocity, flow discharge, suspended sediment concentration, suspended sediment discharge, sedimentation efficiency, and flushing efficiency in the sediment pocket of the Benteng weir increase as the gate opening height rises. The sediment pocket of the Benteng weir remains highly effective in sedimentation, with an efficiency of 88%. During flushing, the shear stress surpasses the critical shear stress, allowing the sediment to be flushed entirely out without resettling. To optimize sedimentation, the gate should be opened to a height of 2.08 m, while for optimal flushing, it should be opened to a height of 4 m.

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