



Impact of Obstacle Blocks on Flow Parameters: A Flume-Based Study

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ABSTRACT

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Obstacle blocks in flume studies simulate natural or engineered resistance elements (e.g., boulders, vegetation, debris) to analyze their impact on hydrodynamic and river morphologic processes. These blocks alter flow patterns and energy dissipation, which are critical for applications in hydraulic engineering. This study aimed to analyze the effect of the number and arrangement of blocks inside the water flume on the hydraulic flow characteristics and water surface stability. The results showed that increasing the number of blocks leads to higher turbulence and energy consumption, which improves the water stability after obstacles. However, the irregular distribution causes significant local effects on the water flow. In terms of efficiency, it was found that small single blocks on both sides of the flume achieve the best balance between stability and efficiency, maintaining a low water surface depth in the backwaters, while multiple blocks (double/triple) reduce efficiency due to high turbulence. Statistical evaluation models also showed that the arrangement of cubic blocks on both sides only is the most accurate in predicting the flow characteristics (with a coefficient of determination $R^2 = 1.00$), while the arrangement including the bottom of the flume reduces accuracy due to high error values. These results demonstrate the significance of selecting a suitable arrangement of blocks according to the discharge rates for achieving high hydraulic performance and stable flow under controlled flow conditions.

1. INTRODUCTION

Flow in open channels is a common phenomenon in hydrodynamics. However, its flow characteristics in the presence of obstacle blocks, modeled as micro-roughness in the zone of low head flow, are relatively less explored. Numerous works have identified that adhering to the roughness classification, flow dynamics can be modeled into uniform flow region [1]. Arrangements of obstacle blocks play a critical role in controlling different mechanisms of particular phenomena. The complication of trying to relate these parameters with flow regions includes the non-linearity of the system due to flow phenomena. Obviously, due to such complexity, there is no analytical solution for estimating the creating cause from such a complex relationship of flow mechanisms.

The flume-based study is fundamental to understanding flow dynamics in open channels, especially in the presence of obstacles that affect flow parameters. It allows the accurate analysis of the effect of obstacles on the flow, which contributes to the classification of roughness and the phenomena associated with flow changes. Such modeling provides data necessary to understand the nonlinear relationships between different factors, which contributes to the development of more accurate models for analyzing the effect of obstacles on the flow.

Several studies were conducted to investigate the issues of the presence of obstacles in the flow of open channels.

AboulAtta et al. [2] conducted experimental work to enhance roughened stilling basins by using T-shaped roughness instead of cubic roughness. The study was performed in a hydraulic laboratory using a plexiglass, tilting flume with controlled upstream and downstream flow conditions. The T-shaped roughness was tested under five intensity levels and eight different lengths to determine the optimal configuration. Flow characteristics were analyzed for various gate openings and discharges, measuring hydraulic jump parameters and water surface profiles. Results were compared with a smooth bed to assess performance improvements. The study identified the optimal roughness intensity at about 12% and found that longer roughness lengths (up to 120 cm) were more effective in stabilizing the hydraulic jump and reducing jump length. The rough bed significantly decreased sequent depth (y_2) and jump length (L_j) compared to a smooth bed, improving flow control. Studies indicate that the blockage of water structures due to debris transport during floods leads to significant changes in their hydraulic efficiency, which features the importance of understanding the effect of obstructions on flow [3]. Imad and Hamad [4] performed laboratory research to analyze hydraulic characteristics, including energy dissipation and hydraulic jump reduction, using unconventional block types in stilling basins. A total of 240 runs were conducted, with 30 runs using triangular cut blocks ($\theta = 45^\circ$) to simulate a classical hydraulic jump with baffle blocks and end sills, while 25 runs were performed for different dissipation block configurations under various compound weir conditions. It

was found that a 60° V-notch compound weir with dissipation blocks effectively reduces flow energy (54.7%–55.4%). Triangular blocks (45°, 60°) minimized hydraulic jump length (L_j/Y_2 : 5.36–6.02). The recirculation zone ranged from 1.94 to 2.14 for a 60° triangular cut angle. The 60° and 90° V-notch with dissipation blocks showed the highest efficiency, especially at high discharges.

Pagliara and Kurdastani [5] investigated the effect of dams on the status of rock channels and concluded that the geometric shapes of the obstacles control the patterns of bottom erosion.

Müller et al. [6] presented a study examining how leaky barriers affect channel hydrodynamics, indicating that factors such as porosity, length, and structural design influence flow behavior. These barriers, primarily used for flood control, modify the surface water movement, reducing water velocity and mitigating downstream flood peaks. Flume experiments indicated that while the barriers altered flow patterns, their structural characteristics played a more significant role. The study shows the importance of thoughtful design to optimize hydrodynamic performance while minimizing ecological disturbance in natural flood management systems.

A study presented by Fuchsberger et al. [7] to simulate the interaction of fluids with immersed, moving solids, with the aim of understanding the interaction between fluid dynamics and the presence of obstacles within the flow path. A new numerical method was developed to model moving solid obstacles within a fluid medium using concepts from porous media theory, modifying the Navier-Stokes equations by adding a Darcy resistance term (Navier-Stokes-Brinkman). The RBVMS technique was also used to ensure numerical stability and represent turbulence. This method is computationally efficient and easy to integrate with finite element solutions, making it suitable for studying the effect of solids on flow. From an environmental perspective, planning for dams focuses primarily on the design of the outlets of these structures. Proper design of these structures is essential to meet the sustainability requirements of the surrounding ecosystem. Mohamed et al. [8] performed a study to analyze the effect of the length of the hydraulically generated calming basin, as well as the energy dissipation blocks, on the erosion depth, with the aim of determining the optimal performance of the stilling basin. To achieve this, an experimental study was conducted to investigate the effect of the dam blocks within the stilling basin on the erosion of the riverbed below the water structure. Several hydraulic parameters were included in the analysis and design process. The study presents an innovative approach to estimating the maximum erosion depth based on a nonlinear regression model.

A study by Zaffar and Hassan [9] was carried out to evaluate a set of hydraulic parameters, such as free surface area, flow depth, Froude number, vortex length, velocity, hydraulic jump efficiency, and turbulent kinetic energy, using the FLOW-3D numerical model before and after rehabilitation. The results showed that the old, calm basins were more consistent with previous studies, as clear linear relationships were observed between downstream water depth, Froude number, and vortex length. In contrast, the new basins exhibited different behavior, characterized by weak correlations between Froude number, water depth, and vortex length, higher velocities at the basin bottom, lower energy dissipation rates, and higher turbulent energy at the bottom. Recommendations: The study calls for additional hydraulic studies for a wider range of discharges and downstream water levels, and the use of

different turbulence models to analyze the hydraulic problems in the new basins.

Studied the hydraulic jump behavior within circular basins using baffle blocks. The results showed that these blocks effectively contribute to enhancing the stability of the jump site and improving its hydraulic properties, such as reducing the flow depth and increasing the relative energy loss [10]. Theoretical relationships were also developed to calculate the depth ratios and the forces acting due to the presence of obstacles, and a comparative analysis between the theoretical and experimental results confirmed good agreement. In their study have shown that hydraulic jumps are an effective means of dissipating excess kinetic energy beneath hydraulic structures such as inclined channels, spillways, and gates [11]. The performance of slackening basins is typically measured by energy dissipation efficiency and design economy. The use of corrugated or rough bottoms is an effective alternative to traditional smooth bottoms. These surface treatments increase shear stresses and improve energy dissipation efficiency while reducing jump length. This research direction intersects with the objective of the current study, which focuses on analyzing the effect of the placement and arrangement of artificial masses within the channel on flow parameters using a laboratory flow model, thereby enhancing flow stability and energy dissipation efficiency.

As performed by He et al. [12], a direct numerical simulation to explore the flow through an array of cylinders, observing the interactions between the wakes of individual elements. The arrangement was varied by adjusting the gap ratio, the array-to-element diameter ratio, and the incident flow angle (0°–30°). This study findings indicate that both the lift and drag coefficients can change significantly depending on the element arrangement. Additionally, the average drag coefficient and bulk velocity of individual cylinders can vary by up to 50% and a factor of 2, respectively. These effects are primarily due to variations in the flow and drag characteristics of individual cylinders within the array. The study identifies that arrangement effects are most noticeable in the intermediate range of flow blockage parameters, and reveals the importance of incorporating these effects into the prediction of bulk flow velocity. The findings offer a framework for describing and predicting flow characteristics in arrangements with varying configurations. Singh and Prasad [13] investigate turbulent flow dynamics in non-uniform open channels using a 3D Acoustic Doppler Velocimeter (ADV), focusing on subcritical flow conditions. experiments have investigated flow over porous and rough beds, focusing on sediment transport and turbulence behavior. Key parameters such as turbulence intensity, kinetic energy, and Reynolds shear stresses were analyzed from ADV measurements, aligning with theoretical frameworks derived from the Reynolds-Averaged Navier-Stokes (RANS) equations. These models predict vertical profiles of velocity and Reynolds stress, validated against empirical data to assess predictive accuracy. The influence of sediment grain size on mean flow properties was also examined, revealing that bed roughness significantly alters turbulence dynamics near the channel boundary. Particularly, higher density sand beds demonstrated enhanced turbulence intensities in both vertical and streamwise directions close to the bed, contrasting with smoother substrates. Variations in bed roughness were linked to differences (150–250%) in velocity triple products, which govern turbulent kinetic energy redistribution. Their findings feature the critical role of sediment type in shaping flow

structures and energy transfer mechanisms in open-channel turbulence. Albank and Khassaf [14] presents an experimental investigation to examine the impact of the design of a stepped channel on energy dissipation. Physical models of conventional stepped channels with varying slope angles (25°, 35°, and 45°) and step heights (45 and 90 mm) were tested. The study concluded that the energy dissipation rate is influenced by key factors such as the relative flow depth (y_c/h), the number of steps (N), and the channel slope. The results showed a significant increase in energy dissipation efficiency of approximately 4.6% when using steps with an end sill compared to flat steps, indicating the positive effect of obstacles in the flow path. These findings are directly relevant to the present research, focusing the role of incorporating obstacles (such as blocks) in changing flow characteristics and improving the performance of hydraulic structures.

Different from previous studies such as Müller et al. [6] that focused on semi-permeable barriers for environmental purposes, and Gül et al. [15] studied the effect of arrays of cylindrical elements on wake zones, this study features the use of solid cubical blocks arranged in various geometric configurations (across flow, on wall side, and bottom, with equal and non-equal spacing) within a low-head flow, and the analysis of their effect on flow stability, energy efficiency, and hydraulic jump length.

This study investigates the impact of geometric arrangements and the number of cuboidal blocks on flow parameters and hydraulic behavior within a flume-based

experimental setup, aiming to characterize how variations influence the flow dynamics characteristics, water surface stability, and resistance to improve the hydraulic efficiency of low head flow in open channels. The innovation of this study is in analyzing the effect of block shapes and geometric arrangement on flow stability and energy dissipation in low-head flume flow, and in developing a high-accuracy predictive model with a new interpretation of negative energy efficiency values.

2. MATERIALS AND METHODS

2.1 Experimental setup

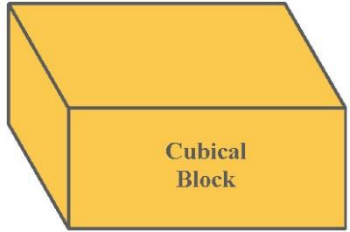
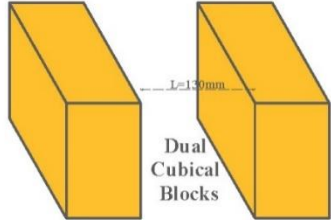
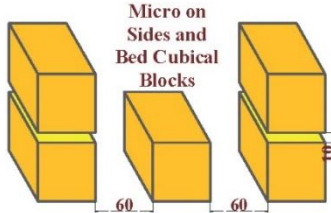
Experiments were carried out in a rectangular flume within the hydraulic laboratory at the University of Babylon, College of Engineering, Department of Civil Engineering. The flume length is 10 m and has a cross-section of 0.3 m in width and 0.45 m in height of type (S6-Tilting flume with zero slope). It featured toughened glass walls and a stainless-steel floor. Two portable carriages equipped with three ultrasonic water surface gauges were installed on brass rails along the top edges of the channel, as shown in Figure 1.

Three different models of wooden cubes were fabricated and prepared for use as laboratory models in experiments. Table 1 presents the detailed dimensions and configurations for cuboidal blocks.



Figure 1. Flume and measurement device setup

Table 1. Dimensions and configurations for block models

Block Description	Set No./Number of Blocks	Dimensions per Block (in mm)	Geometric Shape
Single Cross Cuboidal Blocks	set# 1: 1 set# 2: 2 set# 3: 3	Length = 130 Width = 300 Height = 130	
Double on Two Side Cuboidal Block	set# 1: 2 set# 2: 4 set# 3: 6	Length = 130 Width = 85 Height = 130	
Single Micro on Two Side and Bed Cuboidal Blocks	set# 1: 5 set# 2: 10 set# 3: 15	Length = 60 Width = 60 Height = 60	

2.2 Methodology for conducting the experimental work

- **Block model setup:** position the block models on the flume bed at the specified locations according to the planned sequence of experiments.
- **Pre-test calibration:** measure the baseline for the elevations at selected points along the flume using ultrasonic water level sensors prior to initiating the pump, ensuring meters are calibrated to zero.
- **Initial flow operation:** Operate the flume pump at the lowest discharge rate ($Q = 6.9$ Liter/sec) via the ultrasonic flow-meter control panel. Monitor the system until the outflow stabilizes and water surface fluctuations reach equilibrium.
- **Data collection:** Record the reading of the ultrasonic water level meter (Model: QDY70-D) at upstream and downstream positions relative to the blocks. Simultaneously, measure the hydraulic jump dimensions.
- **Incremental flow adjustments:** Repeat steps 1–4 with progressively higher discharge rates (13.2 liter/sec and 18.5 liter/sec) to complete all trials for each block configuration of the same design.
- Conduct the entire procedure sequentially for each additional block type under investigation.

The flow was calibrated using the volumetric method. A series of runs were conducted to collect a specific volume of water, measure the time required, and compare these runs with the ultrasonic flow-meter (Model: HGLS-2000B wall mounted) records. The results showed high agreement, and the results were adopted in all experiments.

In addition, the accuracy of the measuring devices used was reviewed, as follows: Ultrasonic water level meter: ± 0.5 F.S accuracy. Ultrasonic flowmeter: $\pm 1.5\%$ accuracy. Two replicate runs were conducted for each case to ensure stability and minimize the effect of instantaneous flow fluctuations.

The experiments included three block geometries, each tested with four arrangements (single, double, triple-equal and unequal). For each, three discharge values were applied, totaling 36 experiments. Only one run replicate was performed for each geometry and discharge condition to confirm measurement consistency. A semi-randomized design was used to different block and discharges.

3. RESULTS AND DISCUSSION

3.1 Effect of geometric configurations of blocks on water surface patterns

Effects of geometric configurations of obstacle blocks on the patterns of a water flow were analyzed experimentally in the experimental setup. Figures 2-4 show the variations of water surface depths for different block shapes and arrangements corresponding to various rates of flow in the case of cuboidal blocks that are installed along flume width.

The results show the effect of flow rate, number of blocks, and their arrangement on the variation of the water surface depth. As the discharge increases from $Q = 6.9$ liter/s to $Q = 18.5$ liter/sec, the hydraulic turbulence at the block locations increases, resulting in a sharp drop in depth immediately after the blocks, followed by a faster rise of the level due to the increase in hydraulic momentum. In Figure 2, double blocks lead to a deeper drop compared to single blocks, especially at higher discharge, while in Figure 3, the distribution of three equal spaced blocks yields a regular oscillatory pattern that reveals overlapping hydraulic effects. From Figure 4, the non-equal arrangement of triple blocks, produce irregular turbulence where the depth heights and depths vary, making the flow more complex and less stable. Regarding the block arrangement, the even distribution provides a regular

distribution of energy losses, which reduces sharp changes in water depth, while the uneven distribution leads to variable turbulence where some areas experience higher energy losses, affecting the regularity and strength of the flow. These changes directly affect the hydraulic efficiency of the system, as uniform mass distribution improves energy transfer and reduces hydraulic loss, while irregular distribution can lead to greater turbulence and higher energy loss, which reduces flow efficiency and affects the performance of the hydraulic channel. The fluctuations in the water surface depth for different types of blocks and their arrangements, for various flow rates in the case of cubic blocks installed along the channel are shown in Figures 5-7.

Figure 5 shows that using double cubic blocks on both sides of the channel compared by a single block increases the hydraulic effect, resulting in a rise in the water depth immediately after the installation site, followed by an evident decrease before the flow stabilizes again. This indicates that the presence of double blocks increases the local changes in pressure and flow compared to the single arrangement. From Figure 6, it is noted that adding three evenly spaced cubic blocks results in a regular increase in the water depth with relatively irregular crests appearing along the flow axis. This

pattern reflects the presence of interferences between the hydraulic effects of each block, resulting in a more regular turbulence compared to the double arrangement. While, from Figure 7 the irregular distribution of the triple blocks results in irregular changes in the water level. More complex crests and declines appear along the channel, referring to a nonlinear effect of hydraulic interference between the blocks. This indicates that the no-equal distribution creates irregularity in the distribution of hydraulic energy and increases the variability of turbulence. Overall, it is observed that higher flow rate (Q) leads to a greater increase in the depth of the water surface after the obstacles, which increases the hydraulic effect of the blocks especially at high flows. This shows that the number of blocks, their arrangement, and the distance between them play a critical role in the flow stability. In general, these results confirm that the design of channels equipped with longitudinal cubic blocks requires careful study of the positions and arrangement of the blocks to ensure hydraulic stability, reduce energy loss, and ensure flow efficiency. Figures 8-10 shows a variation in the behavior of the surface of the water based on different types of micro blocks and various flows along the flume.

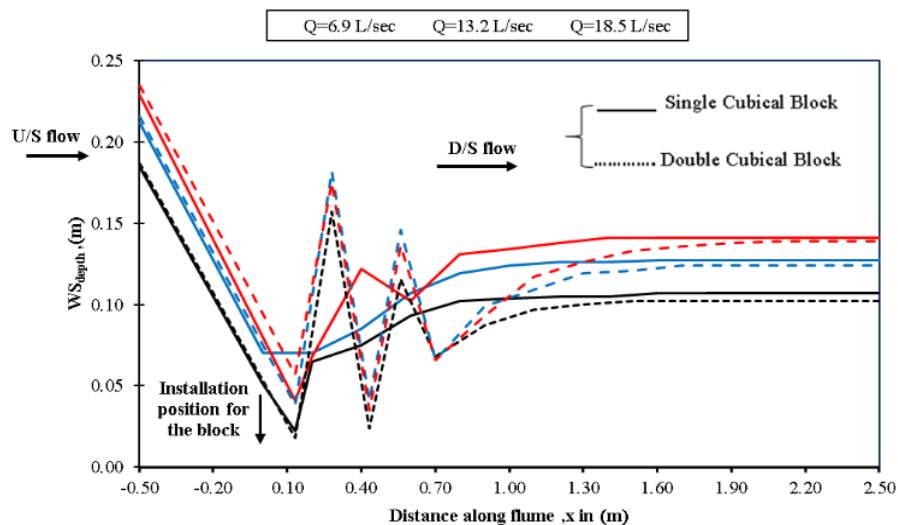


Figure 2. Comparison of water surface depth over the flume longitudinal axis for single and double across cuboidal blocks

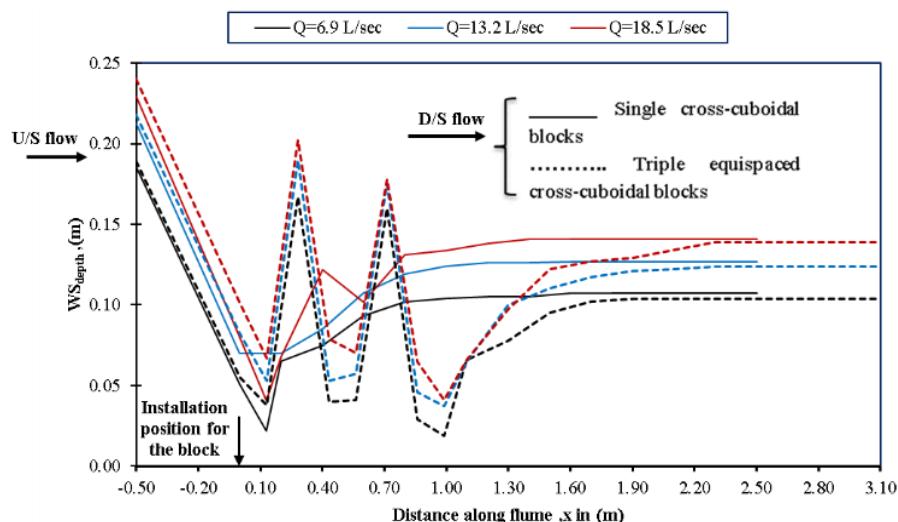


Figure 3. Comparison of water surface depth over the flume longitudinal axis for single and triple equal spaced across-cuboidal blocks

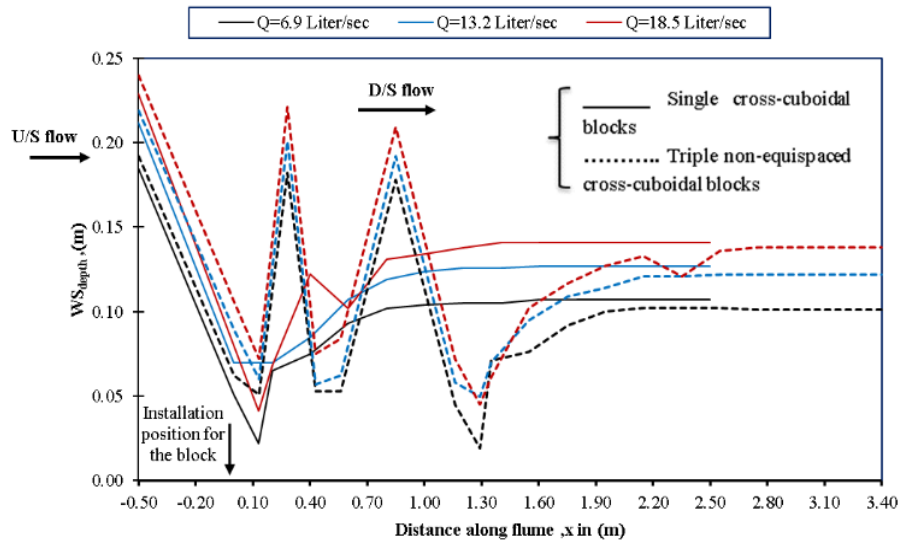


Figure 4. Comparison of water surface depth over the flume longitudinal axis for single and triple non-equal spaced across-cuboidal blocks

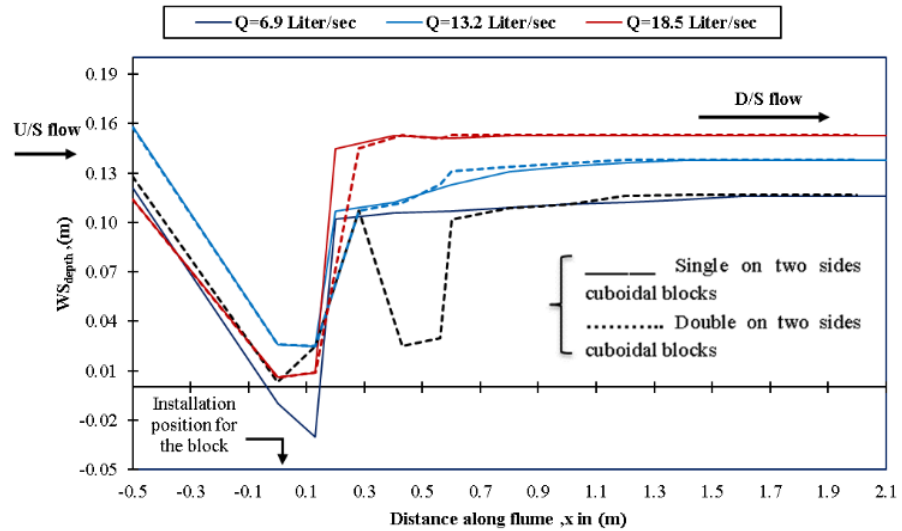


Figure 5. Comparison of water surface depth over the flume longitudinal axis for single and double longitudinal cuboidal blocks

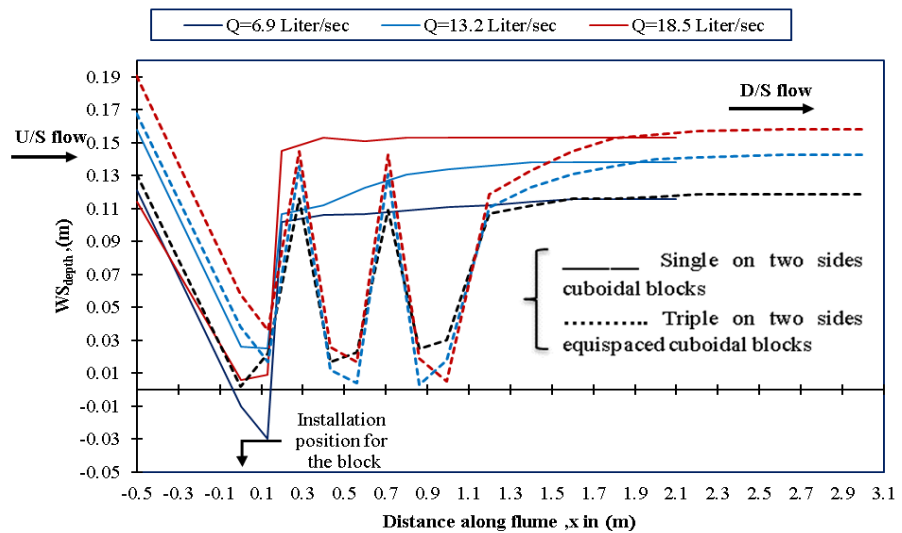


Figure 6. Comparison of water surface depth over the flume longitudinal axis for single and triple equal-spaced cuboidal blocks

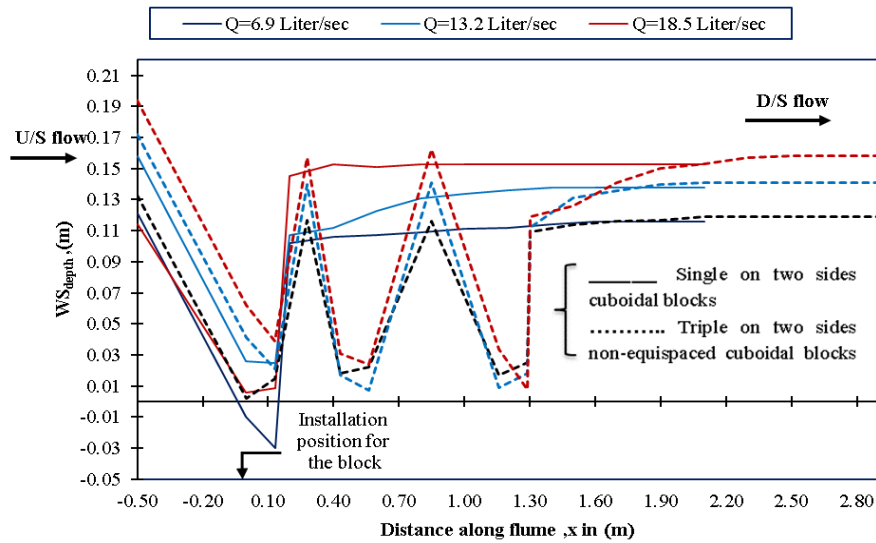


Figure 7. Comparison of water surface depth over the flume longitudinal axis for single and triple non-equal spaced cuboidal blocks

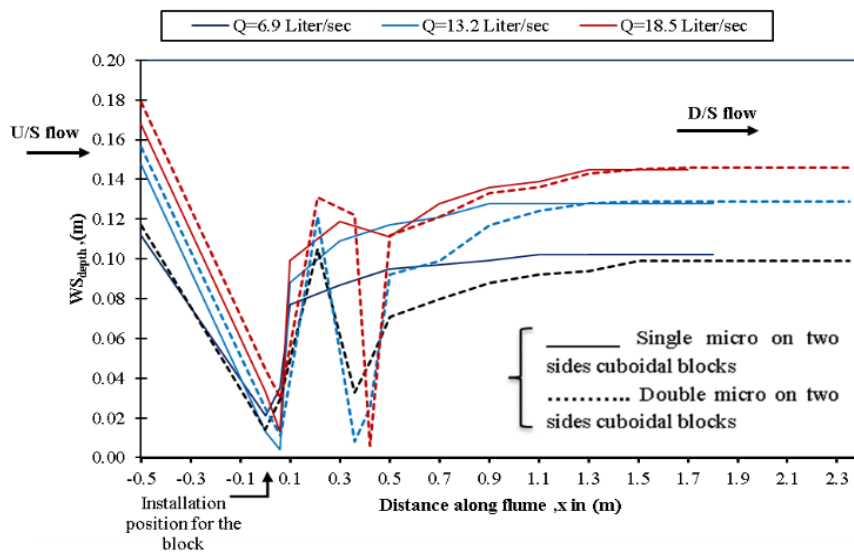


Figure 8. Comparison of water surface depth over the flume longitudinal axis for single and double on two side micro cuboidal blocks

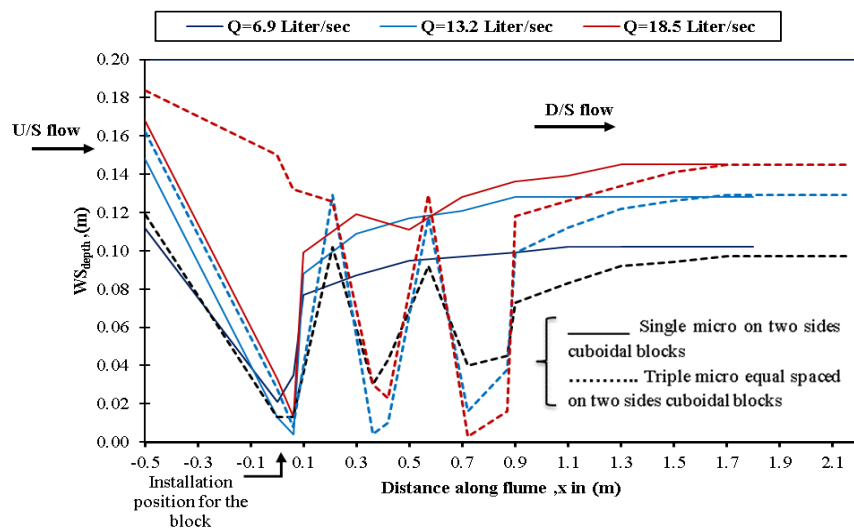


Figure 9. Comparison of water surface level over the flume longitudinal axis for single and triple equal spaced two side micro cuboidal blocks

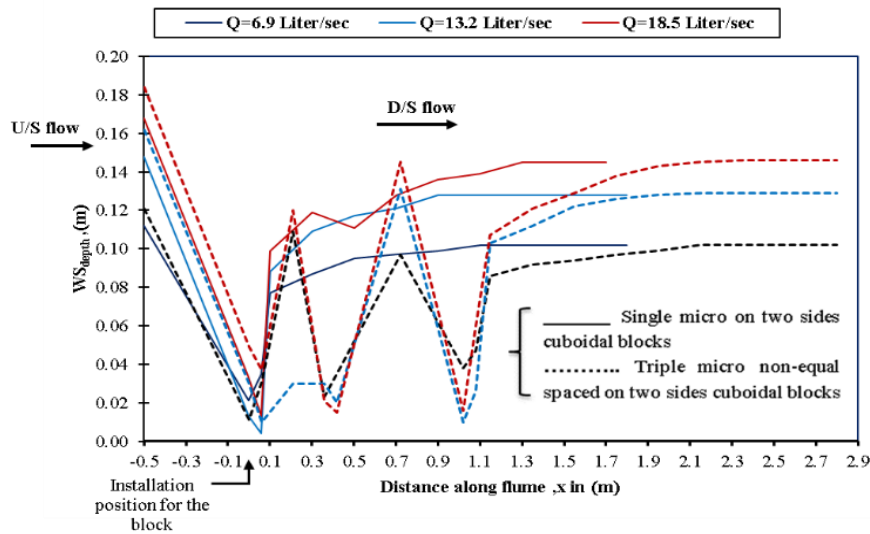


Figure 10. Comparison of water surface depth over the flume longitudinal axis for single and triple non-equal spaced two side micro cuboidal blocks

According to Figure 8, it appears that the single cubic blocks contribute to better stability for the depth of the surface of the water, where a fixed level is reached more quickly compared to other blocks, especially in higher flows ($Q = 18.5$ Liters/sec). On the other hand, double micro blocks show a more significant disturbance in the flow of water, which leads to fluctuations in the depth of water, especially for case of high flows. Figure 9 shows the effect of the triple groups of micro blocks spaced equally on the sides of the flume, where a significant turbulence of the water flow occurs with noticeable fluctuations in the depth of the surface of the water, indicating an increase in the flow resistance and irregular distribution of depth along the flume. As for Figure 10, it appears that the non-equal spaced micro blocks result in more intense flow disturbances, especially in high flows, which leads to clear fluctuations in the depth of the surface of the water, which indicates that this type of block may be less hydraulic efficient compared to other types.

Many studies confirm that the presence of partial or complete blockages in channels, such as geometrically distributed obstructions, directly affects the height of standing water and velocity distribution, especially when the slope angle and blockage ratio change. A study by Miranzadeh et al. [16] conducted an experimental study that has shown the accumulation of wood debris in front of culverts under unstable flow conditions leads to blockage, especially during the hydrographic recession phase, causing hydraulic and structural failure. The results indicated that circular culverts are more susceptible to blockage than box culverts. Zayed [17] showed that increasing the blockage ratio from 0.20 to 1.00 causes a non-linear increase in backwater rise of up to 13 times, with a simultaneous increase in flow turbulence and surface depression depth, which is consistent with this research findings on the effect of increasing the number of cubic blocks on turbulence generation and energy consumption. These findings highlight the importance of studying the effect of obstructive objects on flow, which aligns with the current research objective of evaluating the effect of roughness masses on the suction forces in open channels. These findings support the importance of studying the geometric configuration of blocks in improving flow stability and reducing the risk of flooding resulting from changing hydraulic patterns.

Table 2. Percentage of energy dissipation efficiency ($\%E_R$) for various arrangements of blocks over different flow rates

Flow Rate Blocks Type and Arrangement	$\%E_R$		
	Q = 6.9 (Liter/sec)	Q = 13.2 (Liter/sec)	Q = 18.5 (Liter/sec)
Single cross cuboidal block.	43.82	44.49	39.28
Double cross equal-spaced cuboidal blocks.	59.83	42.37	22.67
Triple cross equal-spaced cuboidal blocks.	43.95	35.49	30.23
Triple cross non-equal spaced cuboidal blocks.	47.95	43.64	43.62
Single on two side cuboidal block.	-0.19*	0.11	25.31
Double on two side cuboidal block.	-1.03*	4.62	5.78
Triple on two side equal-spaced cuboidal block.	-5.91*	-1.94*	9.09
Triple on two side non-equal spaced cuboidal block.	5.03	-9.36*	0.44
Single micro on two side and bed cuboidal blocks.	-53.09*	-24.72*	-12.79*
Double micro on two side and bed cuboidal blocks.	-68.7*	-48.27*	-33.82*
Triple micro on two side and bed equal spaced cuboidal blocks.	-88*	-56.27*	-14.63*
Triple micro on two side and bed non-equal spaced cuboidal blocks.	-82.79*	-49.83*	-30.14*

* Negative values refer change in the specific energy distribution of (E_2) than (E_1).

3.2 Effect on energy distribution efficiency

The percentage of energy dissipation efficiency ($\%E_R$) can be expressed as [4]:

$$\%ER = \left(1 - \frac{E_2}{E_1}\right) \times 100\% \quad (1)$$

where, E_1 , and E_2 are the specific energy for upstream and downstream flow relative to the blocks (m). Table 2 gives the percentage of energy dissipation efficiency (%ER) for various configurations of blocks over different rates of flow.

Table 2 shows the relationship between block arrangements and energy dissipation efficiency (%ER) for three flow rates. It is evident that equal-spaced configurations, particularly the double cross cuboidal blocks, provide higher energy dissipation efficiency at lower discharges (6.9 L/s), indicating more uniform resistance and stable energy loss. However, some configurations yielded negative %ER values, where the specific energy downstream (E_2) exceeded the upstream energy (E_1). This does not imply an actual increase in energy but is attributed to local increases in water surface depth due to flow slowing and backwater effects in low-head flume. These values show a redistribution of hydraulic energy, mainly as increased potential energy downstream. While such effects might be useful in controlled applications regulating flow in irrigation channels, they must be interpreted carefully. The results reveal the significant role of geometric arrangement in forming energy behavior, but further validation is needed before applying these findings to real-world systems influenced by sediment transport, vegetation, and higher variability.

3.3 Effect on the relative length of the hydraulic jump

The relative length of hydraulic jump (L_j/y_0) for different arrangements of blocks over various rates of flow are given in Table 3.

The results in Table 3 show that the hydraulic jump length (L_j/y_0) is significantly affected by the flow rate and the type and arrangement of blocks. When the flow rate increases from 6.9 Liter/sec to 18.5 Liter/sec, hydraulic jumps generally increase, indicating that increasing the kinetic energy of water leads to longer jumps when faced with changes in depth. The analysis also shows a significant variation in jump length based on block type, with composite blocks, such as "triple cross equal-spaced cuboidal blocks" contributing to longer jump lengths compared to single blocks, reflecting the role of geometric design in improving flow performance. Furthermore, the arrangement of blocks plays a critical role in flow behavior. Blocks arranged in a spaced or complex manner increase jump length, while close arrangements may reduce it. These arrangements affect fluid dynamics by changing the distribution of kinetic energy and pressure to ensure their efficiency in water flows.

The results of this study apply to the design and improvement of the performance of low-head open channels, such as irrigation canals, by controlling flow stability. The results showed that the equally spaced arrangement of blocks, especially lateral, reduces water depth fluctuations, which reduces the erosion of the bottom and sides in unlined earthen canals. The results also showed that energy dissipation efficiency was increased in double across blocks, as they improved energy dissipation efficiency by more than 50% at low discharges, which reduces the need for energy-dissipation structures. Also, shortened the hydraulic jump, as the studied arrangements significantly reduce the length of the hydraulic jump, which enables the use of these arrangements within a limited length at the entrances of structures. The results provided flexibility in distribution according to discharge, as the study showed that selecting the appropriate block type and arrangement should be based on the design discharge, which

provides the engineering design according to different hydraulic conditions.

Table 3. Relative length of hydraulic jump (L_j/y_0) for different arrangements of blocks over different flow rates

Flow Rate Blocks Type and Arrangement	L_j/y_0		
	Q = 6.9 (Liter/sec)	Q = 13.2 (Liter/sec)	Q = 18.5 (Liter/sec)
Single cross cuboidal block.	6.486	5.66	5.24
Double cross equal-spaced cuboidal blocks.	4.278	4.63	5.106
Triple cross equal-spaced cuboidal blocks.	4.233	5.894	5.00
Triple cross non-equal spaced cuboidal blocks.	4.167	3.653	5.833
Single on two side cuboidal block.	12.14	8.665	10.526
Double on two side cuboidal block.	6.555	7.375	4.439
Triple on two side equal-spaced cuboidal block.	9.229	8.333	6.283
Triple on two side non-equal spaced cuboidal block.	6.083	1.90	3.008
Single micro on two side and bed cuboidal blocks.	9.286	6.014	7.976
Double micro on two side and bed cuboidal blocks.	9.231	7.244	7.43
Triple micro on two side and bed equal spaced cuboidal blocks.	6.975	5.432	4.783
Triple micro on two side and bed non-equal spaced cuboidal blocks.	8.843	6.914	7.174

3.4 Prediction of empirical relationships

The hydraulic of flow in the horizontal flume is affected by different parameters such as the flow rates, fluid properties and boundary roughness conditions:

$$f(Q, B, H_b, L_b, N_b, y_0, y_1, L_j, \rho, \mu, g) \quad (2)$$

where, Q is the flow rate in the flume [$\text{m}^3\text{sec}^{-1}$], B is the flume width [m], H_b is the height of the block [m], L_b is the length of the block [m], N_b is the number of blocks in the flume, y_0 and y_1 are the flow depth in the upstream and downstream directions of the flow around blocks, respectively [m], L_j is the length of hydraulic jump [m], and ρ , μ , and g are the density of water [kgL^{-3}], the viscosity of fluid [$\text{kgm}^{-1}\text{sec}^{-1}$] and the gravitational acceleration [9.803 msec^{-2}].

Applying dimensional analysis to identify the dimensionless groups that relate the influencing parameters in the investigated problem.

According to the Buckingham π theorem, it is possible to form (n-k) independent dimensionless groups (π groups). Where n is the number of variables, and k is the fundamental dimensions. For this problem, $n = 11$, and $k = 3$. Thus, the dimensionless groups (π -groups = $11-3 = 8$). The general form for each π_i is:

$$\pi_i = Q^{a_1} B^{a_2} H_b^{a_3} L_b^{a_4} N_b^{a_5} y_0^{a_6} y_1^{a_7} L_j^{a_8} \rho^{a_9} \mu^{a_{10}} g^{a_{11}} \quad (3)$$

where, the exponents a_1 to a_{11} must be determined so that the dimensions of each π_i -group equal to 1. The derived dimensionless groups are:

$$F(\pi_1, \pi_2, \pi_3, \dots, \pi_8) = 0 \quad (4)$$

However, the general form of the resulting dimensionless groups are:

$$F\left(\frac{Q}{BH_b^2\sqrt{g}}, \frac{\rho L_j^3}{\mu^2\sqrt{g^3}}, \frac{\mu^2 g}{\rho L_b^2}, \frac{y_0}{L_b}, \frac{y_1}{L_b}, \frac{L_b}{B}, \frac{L_b}{B}, N_b, \frac{y_0 L_b}{H_b^2}\right) = 0 \quad (5)$$

In which π_1 is a Froude number scaled by block width, π_2 is the association between the viscous and gravitational forces acting on the flow, particularly relating to the length of the hydraulic jump, π_3 is the effect of viscosity and gravity on flow regarding the resistance to flow around obstacles, π_4 and π_5 are relative upstream and downstream flow depths, π_6 is the geometric ratio of obstacle length to channel width, π_7 is the blockage density, and π_8 is the block influence number.

In the framework of hydrodynamic analysis to improve, the performance of water flow under low-head conditions, this study presented an empirical models based on the obstacle

blocks, where parametric relationships were derived that correlate hydraulic efficiency parameters such as flow efficiency, frictional resistance, and the dimensions and arrangement of blocks. These relationships were developed through quantitative analysis using multiple nonlinear regression analysis models using IBM SPSS Statistics 27 software.

$$\frac{y_1}{y_0} = f_1\left(Fr_0, Re_0, \frac{L_b}{B}, \sigma_b\right) \quad (6)$$

where, (y_1/y_0) is the sequent depth ratio, Fr_0 and Re_0 are the Froude and Reynolds numbers related to the downstream flow over blocks in the flume, and σ_b is the is the density of roughness blocks, in which:

$$\sigma_b = N_b \frac{y_0 L_b}{H_b^2}$$

$$\frac{y_1}{y_0} = \alpha_0 + \alpha_1 Fr_0^{\alpha_2} Re_0^{\alpha_3} \left(\frac{L_b}{B}\right)^{\alpha_4} \sigma_b^{\alpha_5} \quad (7)$$

Table 4 estimates the regression parameters for Eq. (7) for all types of blocks and their arrangements investigated in the present study.

Table 4. Parameter estimates for regression parameters of Eq. (7), corresponding to each type of block

Blocks Type and Arrangement*	Eq. (7)
Cross flow cuboidal blocks	$\frac{y_1}{y_0} = 0.106(Fr_0)^{-0.057} (Re_0)^{0.015} \left(\frac{L_b}{B}\right)^{-0.462} (\sigma_b)^{0.405}$
On two side cuboidal block	$\frac{y_1}{y_0} = 2.217(Fr_0)^{0.26} (Re_0)^{0.013} \left(\frac{L_b}{B}\right)^{0.342} (\sigma_b)^{-0.316}$
Micro on two side and bed cuboidal blocks	$\frac{y_1}{y_0} = 1.605(Fr_0)^{-0.135} (Re_0)^{-0.111} \left(\frac{L_b}{B}\right)^{-0.228} (\sigma_b)^{0.111}$

* For double and triple arrangements, only the equal-spaced ones were considered.

The empirical equation (Eq. (7)) fits the flume-based data and were evaluated by considering the following statistical matrices; the coefficient of determination (R^2):

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (8)$$

where y_i and $\hat{y}_i$ are the measured and predicted value for i observation, and $\bar{y}$ is the average of measured values. The Root Mean Square Error (RMSE) is a commonly used measure of the difference between predicted and observed values in regression. It highlights the size of errors, with greater importance given to large errors due to the squaring process.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (9)$$

The Standard Error of Estimation (SEE) for multiple nonlinear regression models that is quantifies the average deviation between the observed values and the predicted values generated by the nonlinear model.

$$SEE = \sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n - k}} \quad (10)$$

where, n and k are the number of observations, and number of estimated parameters in the prediction model, respectively. Table 5 gives the values of evaluation metrics for prediction models based on ANOVA tests.

Table 5. Statistical evaluation metrics for prediction models

Blocks Type and Arrangement*	Evaluation Criteria		
	R ²	RMSE	SEE
Cross flow cuboidal blocks	0.9936	0.002	0.007
On two side cuboidal block	0.9997	0.111	0.012
Micro on two side and bed cuboidal blocks	0.8870	0.062	0.185

The statistical evaluation results in Table 5 showed difference in the performance of the predictive models. The cross flow cuboidal blocks model achieving a near-perfect coefficient of determination ($R^2 = 99.36\%$) with small prediction errors (RMSE = 0.002, SEE = 0.007), revealing its ability to explain almost all the variance in the data and its high reliability. The on two side cuboidal blocks model showed a discrepancy, achieving a perfect coefficient of determination ($R^2 = 99.97\%$), but with non-zero errors (RMSE = 0.111, SEE = 0.012), although the model produced a very high coefficient of determination, this result show the well-controlled conditions of the flume experiments, low-dispersion conditions, within a limited range of discharges and variables. Further validation is recommended for broader field

applications where natural variability may reduce model precision. The Micro blocks model performed the less ($R^2 = 0.887$), with RMSE = 0.062, SEE = 0.185, due to the lack of comprehensiveness of the explanatory variables or the complexity of the equation versus the size of the data, which makes it less efficient in practical applications.

As a comparative summary, several recent studies provide evidence on the influence of the geometric arrangement of obstacles in waterways, improving our understanding of the present research findings. Kumcu and Ispir [18] validated that varying the size and spacing of energy dissipating blocks significantly influences sluice gate efficiency and surface turbulence, supporting this study's observation that the geometric arrangement of blocks affects energy dissipation and flow surface stability. Djunur et al. [19] confirmed through experimental and numerical modeling that transverse dissipator arrays improve energy dissipation in chute channels by over 40%, aligning with this study result that equal-spaced transverse blocks yield the highest %ER at low discharges. Similarly, Kumcu and Ispir [20] found that baffle blocks placed with consistent spacing in spillway launch channels lead to improved energy dissipation and reduced hydraulic jump length, findings that complement the reduction in L_j/y_0 observed in equal spacing arrangements in the present study. The predictive model developed by Miranzadeh et al. [16] also showed excellent accuracy ($R^2 > 0.98$) when applied to dissipater layout prediction, validating the approach of using nonlinear regression, as adopted in the present empirical model ($R^2 = 0.9997$). Finally, promising for field-scale applications, suggesting a practical solution to balance hydraulic efficiency, structural applicability, and low-cost viability of maintenance in low-head flow systems [21]. These results provide a scientific basis for irrigation and drainage infrastructure, where energy dissipation and flow control are essential.

4. CONCLUSIONS

- The number of blocks and their arrangement within the flume significantly affects the water surface depth. Increasing the discharge enhances the initial decline of the level, while using a larger number of blocks leads to more turbulence, which enhances energy consumption and achieves greater stability of the water after passing obstacles. Uniformly distributing blocks provides a more regular response, while irregular distribution leads to more evident local effects on the water flow.
- Effect of blocks on hydraulic flow efficiency: Increased number or non-equal spaced distribution of blocks increases hydraulic resistance and increases water surface fluctuations, while equal spaced arrangement maintains stable flow. High discharge rate increases the depth behind obstacles, which requires designing channels based on discharge expectations to improve efficiency. Small single blocks achieve the best balance between stability and efficiency, while multiple blocks (double/triple) reduce efficiency due to severe turbulence.
- The micro-single blocks on the flume sides are appears to be better as they contribute to maintaining a low and stable water surface level, especially in the backwater area.
- The block arrangements are scalable for field use, especially in rectangular channels, allowing efficient

installation without affecting flow or maintenance. Their simplicity and cost-effectiveness make them suitable for irrigation systems. Lateral and micro-blocks also improve flow stability and energy distribution, enhancing eco-hydraulic performance in agricultural open channels.

- Statistical evaluation models showed that the on two side cuboidal block arrangement was the most accurate in predicting flow characteristics, achieving a coefficient of determination ($R^2 = 0.9997$), indicating a perfect agreement between the predicted and measured values. While, the Micro on two side and bed cuboidal blocks arrangement was the least accurate, with a relatively low coefficient of determination ($R^2 = 0.887$) and the highest error values (RMSE and SEE). This highlights the importance of choosing the block arrangement to achieve more accurate and efficient results in hydraulic system design.
- It is recommended that the study be expanded in the future to include irregular sections and variable discharges, with the application of statistical analyses such as ANOVA to verify the significance of differences between arrangements, in addition to field verification of the optimal configurations in real irrigation environments.

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