AQUA

Water Infrastructure, Ecosystems and Society

AQUA — Water Infrastructure, Ecosystems and Society Vol 72 No 8, 1539 doi: 10.2166/aqua.2023.074

Application of meta-heuristic methods in the optimization of geometrical sections in trapezoidal channels in jump energy loss

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ABSTRACT

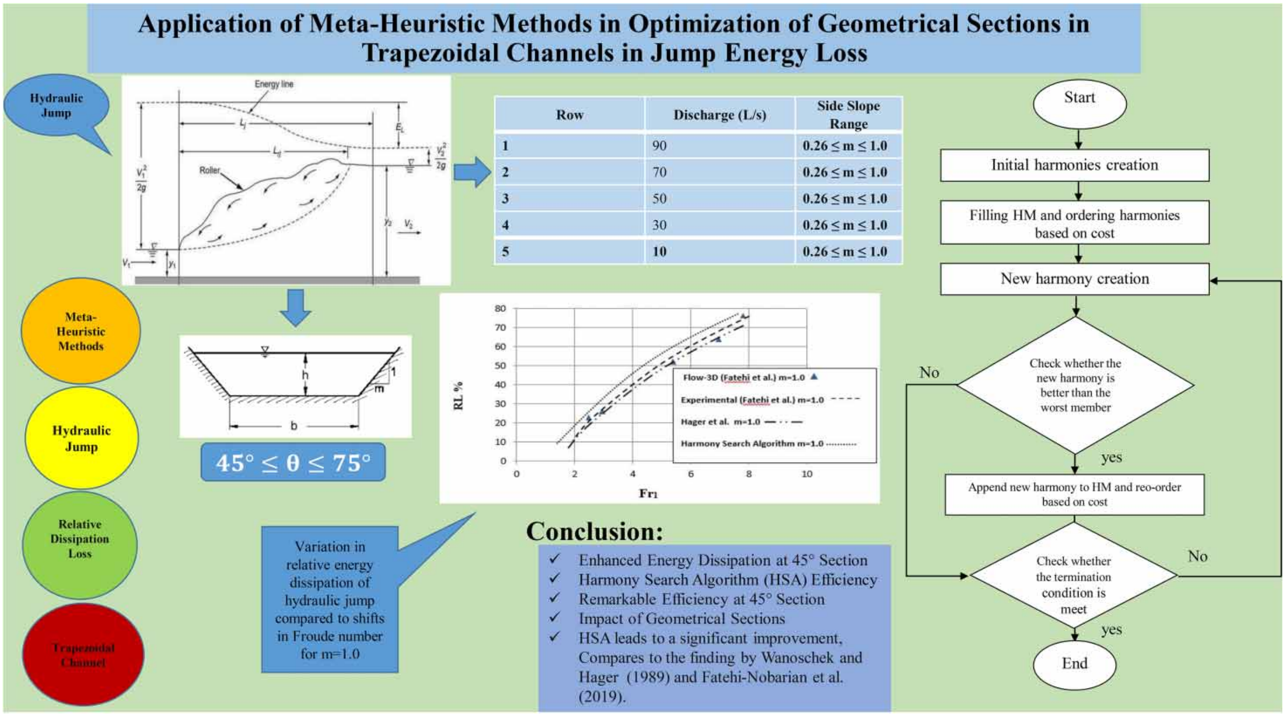
Hydraulic jump is of fast altering flow type, within which a critical flow transforms into a subcritical flow, and such alteration occurs within a relatively short path of the channel. In the present study, the impact of lateral angles of trapezoidal channel walls in the continuous form on the relative loss of hydraulic jump energy is investigated. For this purpose, the meta-heuristic harmony search algorithm is used for declaring the continuous lateral angles within the range of 45°–75°. With regard to the hydraulic definition for the hydraulic jump phenomenon, the harmony search algorithm, which is widely used for optimization and continuous problems, is considered as a simple concept of a useful algorithm. The results demonstrated the high efficiency of harmony search in the optimization of hydraulic problems. The highest value of jump energy loss up to 81% was recorded for the angle of 45°, implying the high efficiency of this section. As can be clearly seen in the results, the amount of destructive energy loss of hydraulic jump in the meta-heuristic algorithm is significantly higher than other previous methods.

Key words: hydraulic jump, meta-heuristic methods, relative dissipation loss, trapezoidal channel

HIGHLIGHTS

- In the present study, the impact of lateral angles of trapezoidal channel walls in the continuous form on the relative loss of hydraulic jump energy is investigated. For this purpose, the meta-heuristic harmony search algorithm is used for declaring the continuous lateral angles with the range of 45°–75°.
- Continuously assuming trapezoidal channel angles in this research has been one of the most impressive functions of this algorithm.
- At the angle of 45 degrees, the highest amount of hydraulic jump energy loss has been shown compared to other responses obtained from the algorithm.

GRAPHICAL ABSTRACT



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Row	Discharge (L/s)	Side Slope Range
1	90	$0.26 \leq m \leq 1.0$
2	70	$0.26 \leq m \leq 1.0$
3	50	$0.26 \leq m \leq 1.0$
4	30	$0.26 \leq m \leq 1.0$
5	10	$0.26 \leq m \leq 1.0$

$45° \leq \theta \leq 75°$

Variation in relative energy dissipation of hydraulic jump compared to shifts in Froude number for m=1.0

Conclusion:

- ✓ Enhanced Energy Dissipation at 45° Section
- ✓ Harmony Search Algorithm (HSA) Efficiency
- ✓ Remarkable Efficiency at 45° Section
- ✓ Impact of Geometrical Sections
- ✓ HSA leads to a significant improvement, Compares to the finding by Wanoschek and Hager (1989) and Fatehi-Nobarian et al. (2019).

NOMENCLATURE

b	Base width (m)
Q	Discharge (L/s)
y_1	First depth of the hydraulic jump (m)
y_2	Secondary depth of the hydraulic jump (m)
m	Cotangent of the side slope
Fr_2	Froude number before the hydraulic jump (–)
E_1	Energy loss before the hydraulic jump (m)
E_2	Energy loss after the hydraulic jump (m)
ΔE	$E_1 - E_2 = E_\mathrm{L}$
g	Acceleration of gravity (m/s^2)
V_1	Velocity of flow before the hydraulic jump (m/s)
V_2	Velocity of flow after the hydraulic jump (m/s)
R_L	Relative energy loss (%)

INTRODUCTION

According to the findings of the previous studies, it can be inferred that the majority of this research focused on the hydraulic jump phenomenon within the rectangular channels for understanding the jump characteristics. The hydraulic jump is generally defined as the flow mode transformation from critical state to subcritical state, during which significant energy dissipation is expected and the flow depth mitigates considerably within a relatively short distance. Fatehi-Nobarian *et al.* (2022) conducted a study on semicircular channels entitled 'Investigation of the Effect of Velocity on Secondary Currents in Semicircular Channels on Hydraulic Jump Parameters'. The modeling results showed that the velocity of the cells of the secondary currents in the horizontal direction (perpendicular to the axis of flow) (X) was greater in the semicircular sections with a radius of 0.3 m. Figure 1 depicts the general structure of a hydraulic jump within a horizontal channel. Omid *et al.* (2007) have carried out research on energy loss induced by the hydraulic jump, and they numerically studied the various trapezoidal sections in terms of jump and energy loss. Among the studies on the hydraulic jump phenomenon, we can refer to studies conducted by Chanson (2009) on the

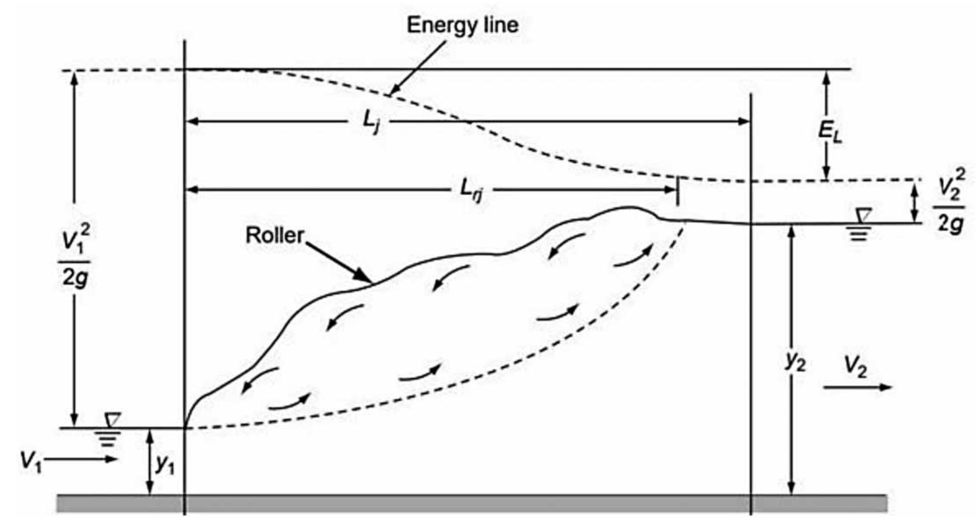


Figure 1 | General structure of the hydraulic jump within a horizontal channel.

classic hydraulic jump and Wanoschek & Hager (1989) and Muhsun (2012) on the hydraulic jump in the trapezoidal sections. The results of the aforementioned experimental studies on a trapezoidal flume (channel) with a wall slope of 45° and numbers range from 5.5 to 15. It was evident that the hydraulic jump in the channel with trapezoidal sections exhibited a different behavior compared to that of the rectangular channel and focused on the characteristics of the trapezoidal channel and they employed the Newton Raphson method for cross-sectional momentum requirements of these channels. They found that the non-rectangular sections exhibited high efficiency in energy dissipation. In a numerical study on the behavior of trapezoidal channels during the hydraulic jump, Fatehi-Nobarian *et al.* (2018) determined the proper geometrical section based on the Renormalization Group (RNG) turbulence model for the secondary currents within the channels. Kim *et al.* (2015) carried out a study on the hydraulic jump and investigated the associated properties regarding the energy depreciation at the downstream of a sliding gate. Javan & Eghbalzadeh (2013) reported their findings for the submerged hydraulic jump using a turbulence model ($k - \varepsilon$). Gualtieri & Chanson (2010) studied the impact of Froude number on the air bubbles developed in the hydraulic jump and they concluded that the presence of the air bubbles during the hydraulic jump in the jump rolling part may play an important role in energy depreciation. During the past few years, a new method has been added to those optimization techniques inspired by natural phenomena like genetic algorithms. The harmony search algorithm (HSA)-based optimization algorithm is a novel, powerful optimization technique. Hassanvand *et al.* (2019) have used multi-criteria decision-making for selecting the spillway type and optimizing dimensions by applying the harmony search algorithm. Geem (2006) used the optimal cost design of water distribution networks based on a harmony search. Geem (2009) has studied the music-inspired harmony search algorithm, theory and applications. Houichi *et al.* (2013) have studied the length of a hydraulic jump in the U-shaped channel by the Artificial Neural Network (ANN) method. Abbaspour *et al.* (2013) have estimated the hydraulic jump on a corrugated bed using ANNs and genetic programming, and finally they concluded that the proposed ANN models are much more accurate than the GP models. Azimi *et al.* (2018) have used the neuro-fuzzy inference system–firefly algorithm for the estimation of hydraulic jump length on rough channels. Geem *et al.* (2001) investigated HSA. In this paper, two test systems of the Economic Load Dispatch (ELD) problems are solved by adopting the Cuckoo Search (CS) algorithm. A comparison of obtained simulation results by using the CS algorithm is carried out against six other swarm intelligence algorithms: Particle Swarm Optimization, Shuffled Frog Leaping Algorithm, Bacterial Foraging Optimization, Artificial Bee Colony, Harmony Search, and Firefly Algorithm. Fatehi-Nobarian *et al.* (2019) have experimentally researched trapezoidal channels and the results obtained from the comparison of experimental measurements and numerical models of the rate of secondary currents in different Froude numbers demonstrated that there exists an opposite relationship between the secondary velocity in the direction perpendicular to the axis of flows (V_x) and the velocity in a direction perpendicular to the flow level (V_z) in trapezoidal channels. Moreover, at a 45° angle, there has been a remarkable energy loss during the hydraulic jump. The ratio of the increase in the secondary current velocity in the X direction in Froude number 10 of 45° angle is higher than that of two other sections, which is equal to 71%, compared to the 75° angle in numerical models, and in Froude number 9, it was 91% during experimental tests. Then, the secondary current velocity in the Z direction for Froude number 2 of 75° angle is higher than that of two other sections, which is 88%, compared to the 45° angle in numerical models, and in Froude number 1.5, it was equal to 74.5% for experimental tests. The results of a metaheuristic investigation by Mahdavi-Meymand & Sulisz (2022) indicate that the meta-heuristic algorithms substantially improve the performance of Support Vector Regression (SVR). The results show that the integrative methods, Support Vector Regression-Multi Tracker Optimization Algorithm (SVR-MTOA), Support Vector Regression-Particle Swarm Optimization (SVR-PSO), and Support Vector Regression-Differential Evolution (SVR-DE), are more accurate than the Multilayer Perceptron Neural Network (MLPNN) and the Multiple Linear Regression (MLR). On average, the integrative methods provide 39.63% more accurate results than the MLPNN and 79.34% more accurate results than the MLR. The average Root Mean Square Error (RMSE) and R^2 for the integrative methods are 0.0054 m and 0.977, respectively. Among all integrative methods, the SVR-MTOA yields the best results, with $RMSE = 0.0044$ m and $R^2 = 0.986$. Wang *et al.* (2022) researched the Artificial Intelligence algorithm. In this study, we proposed a novel approach to improve centrifugal pump performance with regard to the pump head, pump efficiency, and power. Firstly, to establish constraints, an optimal numerical model accounted for factors such as pump efficiency and the head was considered. The pump was designed, and an Artificial Intelligence algorithmic approach was applied to the pump before performing experiments. Singh & Roy (2023) have investigated energy dissipation in hydraulic jumps. The experiments showed that the energy of the supercritical flows can be dissipated effectively by using perforated screens. The difference in energy dissipation between the upstream and downstream of the screen was more significant than the energy dissipation caused by classical hydraulic jumps. Comparing the results of the present study with the previous research, it was found that the energy loss in the case of the present study was more than the previous research. The relative energy loss in the present study was found to vary from 74 to 94%. The value of the Froude number downstream of the screen, F_2, varied from 1.1 to 1.81, with an average value of 1.35. The tailwater deficit parameter, D, varied from 0.66 to 0.90. Laishram *et al.* (2022) have investigated the hydraulic jump. The experimentation was performed in a channel flume with a rectangular cross-section (16 m long, 0.6 m wide, and 0.8 m deep) in the Hydraulics Laboratory, Department of Civil Engineering, NIT, Manipur. A sluice gate and a radial gate are used in the channel to generate a hydraulic jump at the downstream of the flow. The characteristics of hydraulic jumps, such as length of jump, upstream and downstream head, velocity, sequent depth ratio, and amount of energy dissipated were measured with different heights of gate opening and flow rate. The results show that the radial gate is much safer for the structure and dissipates more energy, and the control of the flow is much easier as compared to the sluice gate and can be considered as an appropriate model for dissipating energy. Benabdesselam *et al.* (2022) have researched hydraulic jumps in a straight rectangular compound channel. In this paper, the general regression neural network (GRNN) was applied to predict the basic characteristics of hydraulic jumps in a straight rectangular compound channel: (i) the sequent depth ratios, (ii) the relative energy losses, and (iii) the relative lengths. Experiments were carried out with three different values of the ratio between the main channel width and the flood plain one (W_y). The W_y values were: (1/4, 1/3, and 1/2). For each W_y ratio, several values of the inflow Froude number were considered according to the five inflow ratio depths' (W_z) values (0.167, 0.200, 0.253, 0.287, and 0.333) between the first sequent depth and the main channel one. The predicted values in the testing stages using the GRNN followed the experimental ones with a correlation coefficient (R) of 0.990 for the sequent depth ratios, 0.982 for relative energy losses, and 0.873 for the relative lengths of hydraulic jumps. The best models have been selected among several input configurations for each of three considered characteristics of the jump. In this paper, the energy depreciation in the hydraulic jump of the trapezoidal channels with continuous lateral wall angles ranging from 45° to 75° is investigated using one of the new meta-heuristic approaches, so-called HSA, which was able to outline the relative energy dissipation in the hydraulic jump within the trapezoidal channel for the continuous angles ranging from 45° to 75°. The novelty of this research can be justified by the research gap on the application of this algorithm in solving hydraulic problems. One of the innovations of the meta-heuristic optimization method with the continuous method in channels, which is used in this research, is the investigation of the full range of side wall angles in a trapezoidal channel. In this sense, all the side angles in a trapezoidal channel have been found to have much more accurate results than the previous methods, and in the old optimization methods, only a few specified angles were examined, which definitely did not have more accurate results. In general, the method used in this research can be used in spillways in dams and also can be used on the outer edges of coastal piers.

Meta-heuristic method

Harmony search is a meta-heuristic method used for optimizing hydraulic structures. It was developed in 2001 and is one of the newest and simplest meta-heuristic methods. The algorithm is inspired by the simultaneous playing of music and is a desirable method for routing in the sensor network. It is a powerful algorithm with excellent exploitation capabilities, and it can find solutions to optimization problems.

The meta-heuristic methods use the information obtained from the former point as the guidance for selecting the next point(s). These methods are known as the optimization algorithms that seek to establish a balance between the diversification in the search space and results intensification. These methods are capable of solving various problems, regardless of the good behavior of the objective function or whether the search space is discrete or continuous.

Evolutionary algorithms

All algorithms involve a search mechanism, and their emergence philosophy is related to the likelihood of several solutions for the optimization problem, dimension magnitude, and discrete of the search space since there is a probability of the fact that the optimization problem may possess several locally or globally optimal solutions. Figure 2 presents the locally and globally optimal points (Fatehi-Nobarian *et al.* 2022).

This algorithm is known as a music-inspired harmony search algorithm. Indeed, the main purpose of harmony search is to find a relation between the musical notes and the optimal solution for a difficult engineering problem. This algorithm was proposed by Geem *et al.* (2001). An HS algorithm is inspired from the search mechanism used for reaching a full harmony in the music. That is, a musician attempts to generate thoroughly harmonic music free from any deficiency. The quality, beauty, and the elegance of musical instruments are intrinsically determined by the pitch (sound frequency), resonance (sound quality), and amplitude (sound loudness).

Steps of harmony search algorithm

Using harmony memory, the initial acceptable solutions are generated. Indeed, the harmony memory is a matrix encompassing our harmony which is outlined by Equation (1). Each harmony is regarded as a vector including the decision variables of the optimization problem. Until the desired number, the harmonies are created and stored in the harmony memory during the initial step of the algorithm.

$$\mathrm{HM} = \begin{bmatrix} \mathrm{Position}_{1,1} & \cdots & \mathrm{Position}_{1,\mathrm{nvar}} \\ \vdots & \ddots & \vdots \\ \mathrm{Position}_{\mathrm{HMS},1} & \cdots & \mathrm{Position}_{\mathrm{HMS},\mathrm{nvar}} \end{bmatrix} \tag{1}$$

where nvar represents the variable count and IMS denotes the number of primary harmonies. The harmony memory consideration rate (HMCR) controls the solutions of the new harmonies against the initial solutions. This coefficient

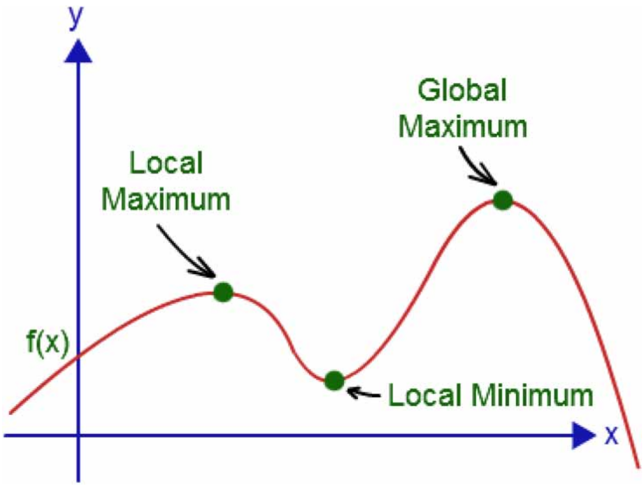


Figure 2 | Locally and globally optimal points of function.

determines the citation likelihood of the harmony memory.

$$0.0 < \mathrm{HMCR} < 1.0 \tag{2}$$

The closer the value of this coefficient is to 1, the better the answer will be. The concentration power on the former solutions increases and the reduction in this coefficient leads to an increase in the search power within the search space. This algorithm consists of five phases and all phases of the harmony search, from start to the end, are presented by a flowchart in Figure 3.

In the present research, the lateral angle of the trapezoidal channel is taken into account as the continuous variable, while the flow discharge is considered as a variable, and Table 1 presents the associated properties and calculation order.

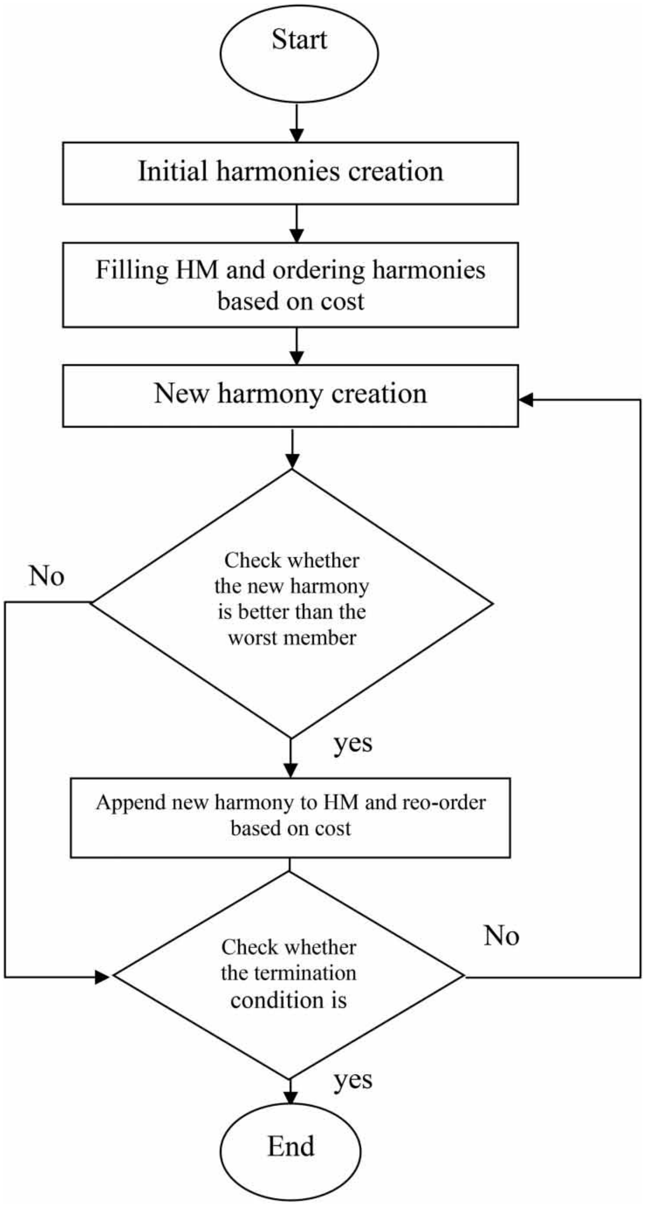


Figure 3 | General flowchart of the harmony search algorithm.

Table 1 | Flow discharge order used in the present study

Row	Discharge (L/s)	Side slope range
1	90	$0.26 \leq m \leq 1.0$
2	70	$0.26 \leq m \leq 1.0$
3	50	$0.26 \leq m \leq 1.0$
4	30	$0.26 \leq m \leq 1.0$
5	10	$0.26 \leq m \leq 1.0$

As seen in the flow chart, if a new harmony is better than the worst member, the new harmony will be appended to the memory, and the order is updated, until the moment that the terminating condition is met; otherwise, it returns to the phase, which is responsible for creating a new harmony and such a cycle continues.

Governing equations of relative energy dissipation

To determine the relative energy dissipation of the hydraulic jump within trapezoidal channels, it is feasible to use energy relations. This analysis is done by considering the uniform flow and the prismatic channel between the two sections where the beginning section is the start point of the hydraulic jump and the end section is known as the shallow depth of the hydraulic jump. Generally, it is worth noting that the use of an energy relationship is suggested when the amount of energy loss between the two sections is equal to or greater than zero. However, due to the limitations of the execution phase and equipment in the laboratory, it is not possible to use many lateral angles for the channels. Equation (3) yields the energy dissipation of jump (ΔE) along the hydraulic jump.

$$\Delta E = E_l = E_1 - E_2 = \left(Y_1 + \frac{V_1^2}{2g}\right) - \left(Y_2 + \frac{V_2^2}{2g}\right) \tag{3}$$

where V_1 and V_2 refer to the flow velocity within the channel before and after the hydraulic jump, respectively. While g denotes the gravitational acceleration, and y_1 and y_2 are conjunctive depths linked to the section #1 and section #2, respectively, which is written as Equation (4):

$$E_L = Y_1 - Y_2 + \frac{F_{r1}^2}{2} D_1 \left[1 - \left(\frac{A_1}{A_2}\right)^2\right] \tag{4}$$

where A_1 and A_2 are the cross-sections of the flow in section #1 and section #2, respectively. Fr_1 is the Froude number of the flow for section #1; starting section of the hydraulic jump. D_1 denotes the hydraulic depth of flow, which is obtained from Equation (5). Finally, E_L represents the energy difference of the flow between two sections. In Equation (5), T_1 is the flow level width in the trapezoidal channel for section #1.

$$D_1 = \frac{A_1}{T_1} \tag{5}$$

The relative energy dissipation of flow is obtained from Equation (6).

$$R_L = \frac{Y_1 - Y_2 + \frac{F_{r1}^2 D_1}{2}\left[1 - \left(\frac{A_1}{A_2}\right)^2\right]}{Y_1 + \frac{F_{r1}^2 D_1}{2}} \tag{6}$$

As seen, the relative energy dissipation for a hydraulic jump is dependent on parameters such as Froude number, flow cross-section, and conjunctive depths. Of course, it should be noted that the value of flow cross-section for the trapezoidal channels alters along with changes in the lateral angle of the channel wall.

RESULTS AND DISCUSSION

With regard to the preceding studies on the trapezoidal channel properties in dealing with phenomena, like hydraulic jump (1), it can be stated that the variation in the lateral angle of the trapezoidal channel wall plays an important role in push energy dissipation, and these shifts are highly limited in the experimental studies. Due to the limitations of the execution phase and the equipment in the laboratory, it is not possible to use many lateral angles for the channels. This means that the researchers cannot test or experiment with many different angles for the channels due to the limitations of the laboratory equipment. It should be noted that the m parameter represents the lateral angle of the trapezoidal channel (Figure 4).

Side slope range

From a hydraulic consideration perspective, the trapezoidal channels are cost-effective and more practical, compared to the other channels; as a result, the side slope of the trapezoidal channel is determined based on the soil type and vegetation. Hence, the side slope of the buried channels is considered to be steeper than that of the channels deployed on the embankment. For huge and highly deep channels, the side slope of the section associated with the free board can be considered steeper than that of the underwater area. The side slope of the coated channels is usually steeper than the non-coated channels.

Therefore, this is one of the most important problems related to the trapezoidal channels deserving in-depth study using the meta-heuristic approach like the harmony search optimization algorithm. So far, such an algorithm is not applied to the hydraulic and fluid mechanic field for optimization purposes.

$$m = \frac{1}{\tan\theta} \tag{7}$$

where m is side slope of the channel wall.

The lateral angle range for the trapezoidal channel wall in this research follows the following inequality:

$$45^\circ \leq \theta \leq 75^\circ$$

As noted, all angles between 45° and 75° are scrutinized, that is, the continuous distance of angles is taken into account, while the experimental or numerical studies are merely capable of using a limited number of the angles, which may result in constrained results. The continuous feature of the lateral angles boosts the energy field efficiency of the hydraulic jump, which is relative to the various flow discharges. In this research, five stream discharges, as presented in Table 1, are used.

As seen in Table 1, the angle in the range of 45°–75° for the side wall of the channel and all discharge rates are studied.

The geometrical properties of the channel are presented in Table 2.

Generally, an optimal model is characterized by three sections as below:

(1) Objective function
(2) Constraints

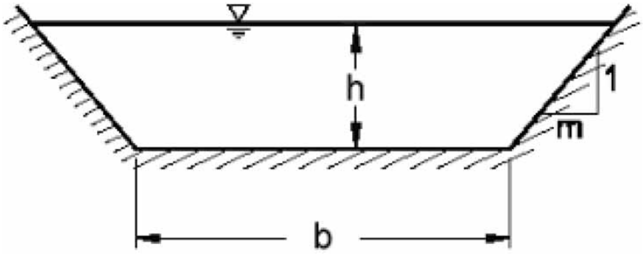


Figure 4 | Schematic of the trapezoidal channel incorporating the lateral angle.

Table 2 | Geometrical properties of the study channel

Section type	Width of channel bottom (m)	Water height in the channel (m)
$0.26 \leq m \leq 1.0$	0.2	0.45

(3) Decision-making variables

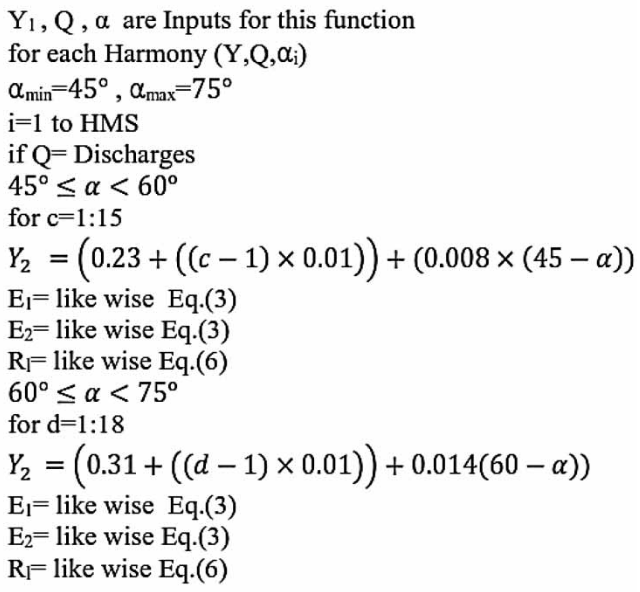
The pseudocode for the implemented algorithm is presented in Figure 5 for the proper perception of the coding phases. It is worth noting that the entire coding using MATLAB programming language consisted of 260 lines.

In the present research, the coding phase considers the aforementioned sections. The harmony development is realized in two modes based on the HMCR probability using the HM components and the HMCR probability using random numbers.

The entire optimized space for the desired range is stored as an output with the title of 'Hyper Memory,' and the best results are stored with the title of 'Output,' which are applied to curves of relative energy dissipation of hydraulic jump relative to the variation in the channel geometrical section for various discharge rates. The algorithm results are presented in Figures 6–10.

The reason for the breakdown of the energy loss graph in the range of 60° from the hydraulic channel was because the calculation process of the algorithm was based on the continuous method, and usually the algorithm reviews the best answers in the range between the two banks of minimum and maximum. For this reason, a break in the trend of the chart can be seen in this range, but there has been no change in the overall trend of the result. As can be clearly seen in the results, the amount of destructive energy loss of hydraulic jump in the meta-heuristic algorithm is significantly higher than other previous methods. Therefore, the effectiveness of this method in examining macroscopic hydraulic problems is much higher and this method can be considered a better alternative to previous numerical methods. As can be seen in Figures 6–10, the slope of the hydraulic jump energy drop line was much higher at angles of 45°, and this energy drop was directly related to the Froude number, that is, the higher the Froude number, the greater the drop. With regard to the presented curves, it can be deduced that the horizontal axis of the variation curve for the lateral angle of the channel wall ranging from 45° to 75° is continuous and the vertical axis of the relative energy dissipation in the hydraulic jump is per percent. In the curve of Figure 6 for the discharge rate of 90 L/s, the maximum relative energy dissipation of jump with a value of 81% is attributed to the 45° section, which is considered as the highest relative energy dissipation.

Of course, for discharge rates of 70, 50, 30, and 10 L/s, the amount of energy loss during hydraulic jump is equal to 71.3, 53, 20, and 9%, respectively, which implies that the energy loss for trapezoidal sections with more open lateral walls is much



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$Y_1$ , Q , $\alpha$ are Inputs for this function
for each Harmony (Y,Q,$\alpha_i$)
$\alpha_{min}$=45° , $\alpha_{max}$=75°
i=1 to HMS
if Q= Discharges
$45° \leq \alpha < 60°$
for c=1:15
$Y_2 = \left(0.23 + ((c-1) \times 0.01)\right) + (0.008 \times (45 - \alpha))$
$E_1$= like wise Eq.(3)
$E_2$= like wise Eq.(3)
$R_l$= like wise Eq.(6)
$60° \leq \alpha < 75°$
for d=1:18
$Y_2 = \left(0.31 + ((d-1) \times 0.01)\right) + 0.014(60 - \alpha))$
$E_1$= like wise Eq.(3)
$E_2$= like wise Eq.(3)
$R_l$= like wise Eq.(6)
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Figure 5 | Pseudocode for geometrical section optimization in trapezoidal channels.

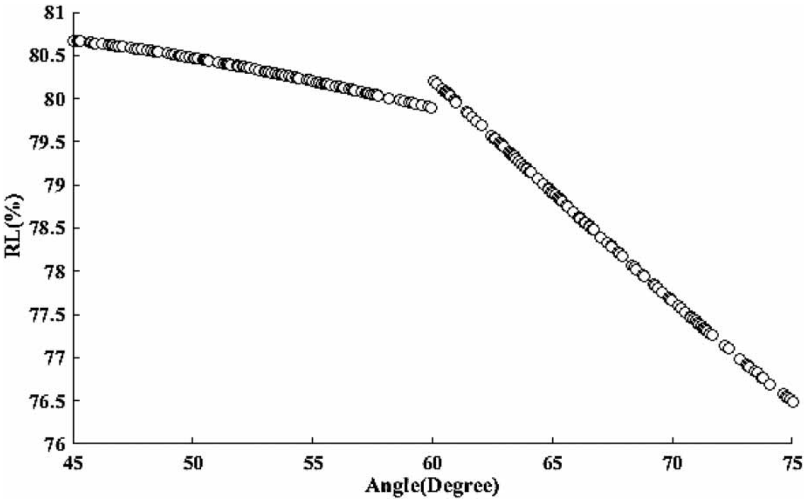

Figure 6 | Changes in the relative energy dissipation of the hydraulic jump relative to the continuous lateral angle for 90 L/s discharge.

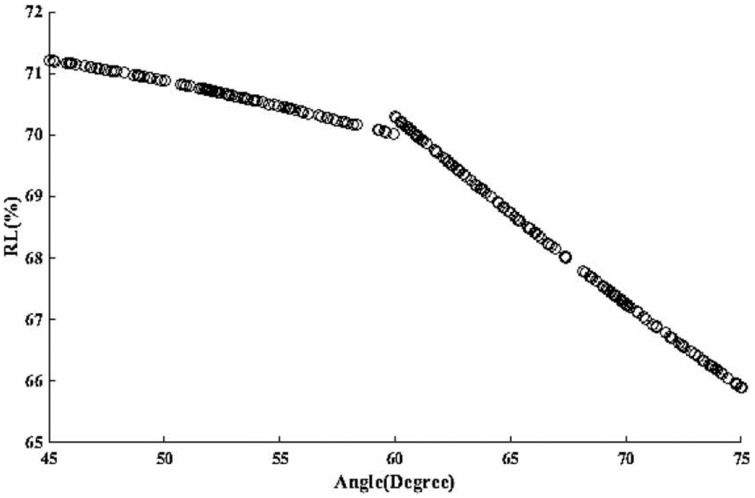

Figure 7 | Changes in the relative energy dissipation of the hydraulic jump relative to the continuous lateral angle for 70 L/s discharge.

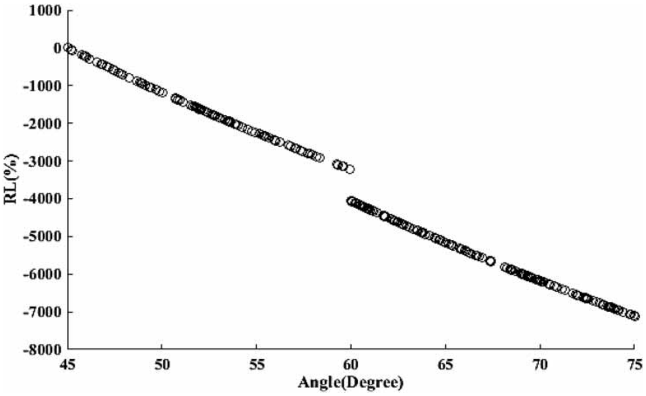

Figure 8 | Changes in the relative energy dissipation of the hydraulic jump relative to the continuous lateral angle for 50 L/s discharge.

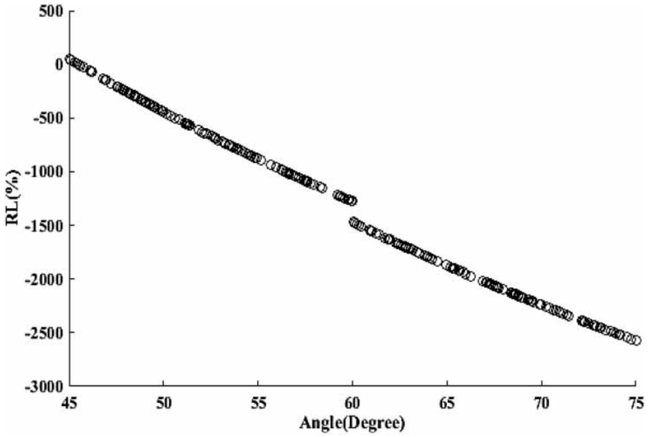

Figure 9 | Changes in the relative energy dissipation of the hydraulic jump relative to the continuous lateral angle for 30 L/s discharge.

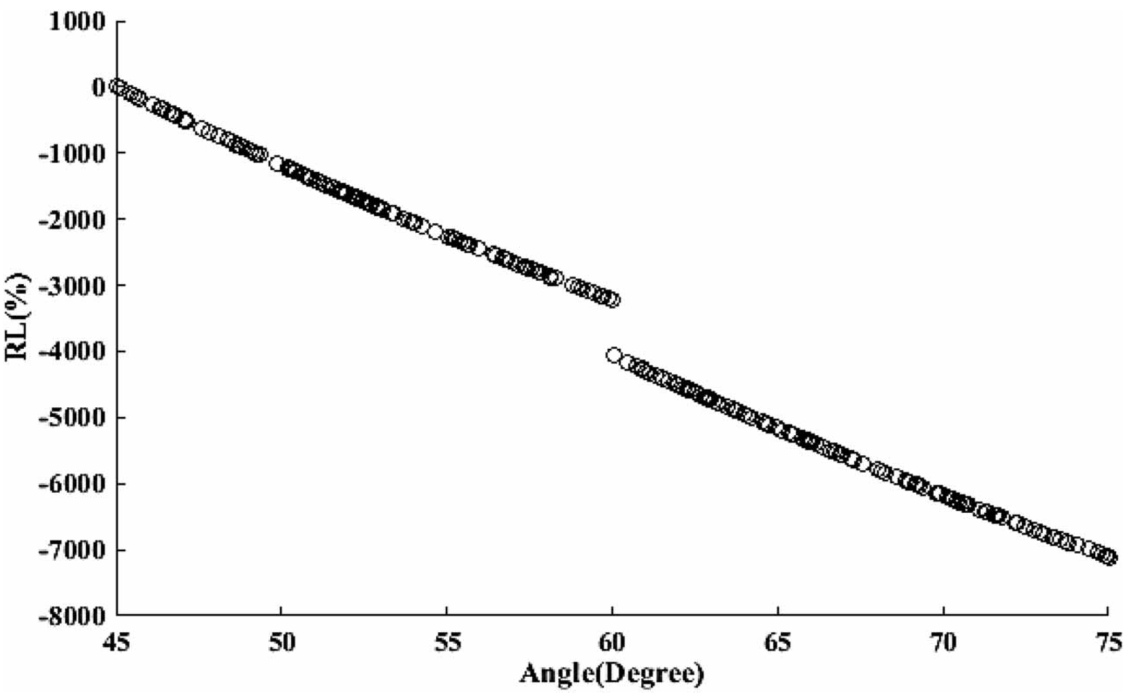

Figure 10 | Changes in the relative energy dissipation of the hydraulic jump relative to the continuous lateral angle for 10 L/s discharge.

more than that of trapezoidal sections with more vertical walls. Before the complete comparison of the results of this research with the previous research, which is shown in Figure 11, first, an explanatory and thematic comparison between the research conducted in this field with the results of the current research has been made, which is given in Table 3. To study the lateral angles of the wall of trapezoidal channels continuously (angle infinity) in the algorithm used in this research, Figure 11 illustrates a proper comparison of this research with previous research.

For more proper validation of the results obtained from the optimization algorithm, these results are compared with that of the previous studies (Figure 11).

Normally, in the investigation of energy loss in trapezoidal channels, the experimental results of Wanoschek and Hager for an angle of 45° are considered as a benchmark, and the same process has been done in this research, and apart from that, the results of the algorithm with the experimental results of Fathi-Nobarian *et al.* have been evaluated. With regard to the results

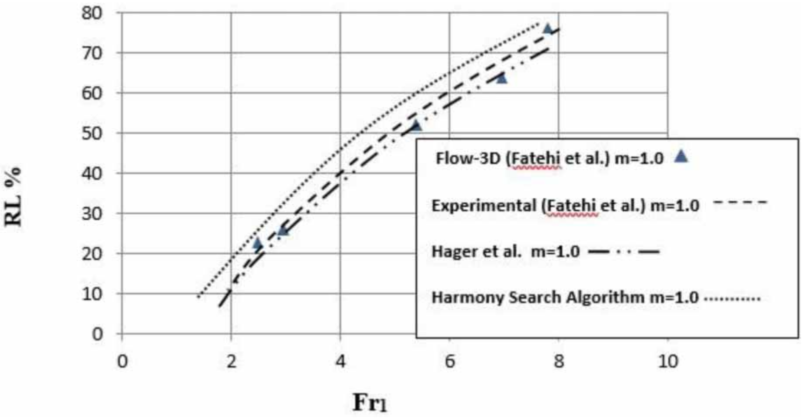

Figure 11 | Variation in the relative energy dissipation of the hydraulic jump compared to shifts in the Froude number for $m = 1.0$.

Table 3 | Comprehensible comparison of the results with previous researches

Row	Research's report	Description	Results
1	Fatehi-Nobarian *et al.* (2019)	It has been done in trapezoidal channels with a 45° side wall, experimentally on the hydraulic jump	In Froude number 4, 40% of hydraulic jump energy has been reduced. And the same process has continued with the increase in the Froude number.
2	Wanoschek & Hager (1989)	It has been done in trapezoidal channels with a 45° side wall, experimentally on the hydraulic jump	In Froude number 4, 36% of hydraulic jump energy has been reduced.
3	Present study	The influence of the changes of the (continuous) side angles of the trapezoidal channels.	In Froude number 4, 47% of hydraulic jump energy has been reduced. And the same process has continued with the increase in the Froude number.
4	Fatehi-Nobarian *et al.* (2022)	The influence of the geometric cross-section of the semicircular on the energy loss of the jump has been done.	With the increase of Froude number, the energy loss of hydraulic jump has increased.
5	Kim *et al.* (2015)	The hydraulic jump and energy dissipation in the classic section have been done.	With the increase in the length of the jump, the energy loss of the hydraulic jump has also increased.

of Wanoschek & Hager (1989) for the 45° section, the comparison and validation are accomplished for a section of $m = 1.0$ between the experimental results of Fatehi-Nobarian *et al.* (2019) and the numerical results derived from Flow-3D software for the Froude number in the range of 1.7–9. Accordingly, the results obtained by the HS algorithm indicate 6% increase, compared to that of experimental results presented by Fatehi-Nobarian *et al.* (2019). The results derived from the harmony search algorithm are consistent with experimental results obtained by Wanoschek & Hager (1989) and Fatehi-Nobarian *et al.* (2019), which refers to the fact that the proposed method exhibited a desirable performance.

CONCLUSION

The limitations of the performed method are only for classic sections, because in rectangular sections there is no side angles for the channel walls, while the potential field of the method used in this research is its ability to be expanded for all channels whose side walls have an angle. It is variable or has radial adjustments for circular geometric sections, because nowadays most of the flow channels in dams and upstream plains are designed from trapezoidal sections. With regard to the results, it can be concluded that the behavior of trapezoidal channels using various side slopes is different from the channels with non-trapezoidal sections. The trapezoidal channels with the wall slope of 45° exhibited a better behavior.

1. At the 45° section, the flow moves slowly near the surface and is directed toward the side walls due to the formation of the rolling zone at the bottom. The flow can include higher air due to the adequate opening in the wall at an angle of 45°, leading to relative energy dissipation in the hydraulic jump for these sections, even for higher discharge rates.
2. Compared to the preceding numerical studies, the results obtained for geometrical section optimization of the trapezoidal channels using the harmony search algorithm ascertained the efficiency of HSA.
3. For a discharge rate of 90 L/s, the highest relative energy dissipation (81.6%) in the hydraulic jump is attained at the 45° section, which demonstrated the considerable efficiency of these sections.
4. For other geometrical sections of the channel, the following results are obtained for discharge rates of 70, 50, 30, and 10 L/s, and the relative energy dissipation in jump was equal to 71.3, 53, 20, and 9%, respectively, implying that the higher side slope (m) of the trapezoidal channel leads to a higher increase in energy dissipation.
5. The present optimization results were compared to previous research, and it was found that there is a 6 and 10% increase relative to the experimental research conducted by Wanoschek & Hager (1989) and Fatehi-Nobarian *et al.* (2019), and the results of Flow-3D. These values indicate a desirable agreement between the results and the validation, all of which refer to the efficiency of harmony search algorithm for studying the relative energy dissipation in the hydraulic jump phenomenon.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abbaspour, A., Farsadizadeh, D. & Ghorbani, M. A. 2013 Estimation of hydraulic jump on corrugated bed using artificial neural networks and genetic programming. *Water Science and Engineering* **6** (2), 189–198.

Azimi, H., Bonakdari, H., Ebtehaj, I. & Michelson, D. G. 2018 A combined adaptive neuro-fuzzy inference system–firefly algorithm model for predicting the roller length of a hydraulic jump on a rough channel bed. *Neural Computing and Applications* **29** (6), 249–258.

Benabdesselam, A., Houichi, L. & Achour, B. 2022 GRNN-based models for hydraulic jumps in a straight rectangular compound channel. *Modeling Earth Systems and Environment* **8** (2), 1787–1798.

Chanson, H. 2009 Current knowledge in hydraulic jumps and related phenomena. A survey of experimental results. *European Journal of Mechanics-B/Fluids* **28** (2), 191–210.

Fatehi-Nobarian, B., Hajikandi, H., Hassanzadeh, Y. & Jamali, S. 2018 Numerical modeling investigation of secondary current cells in trapezoidal channels and their effect on hydraulic jump's properties. *Journal of Dam and Hydroelectric Powerplant* **5** (17), 25–38.

Fatehi-Nobarian, B., Hajikandi, H., Hassanzadeh, Y. & Jamali, S. 2019 Experimental and analytical investigation of secondary current cells effects on hydraulic jump characteristics in trapezoidal channels. *Tecnología y ciencias del agua* **10** (3), 190–218.

Fatehi-Nobarian, B., Panahi, R. & Nourani, V. 2022 Investigation of the effect of velocity on secondary currents in semicircular channels on hydraulic jump parameters. *Iranian Journal of Science and Technology, Transactions of Civil Engineering* **46** (4), 3351–3359.

Geem, Z. W. 2006 Optimal cost design of water distribution networks using harmony search. *Engineering Optimization* **38** (03), 259–277.

Geem, Z. W. 2009 *Music-Inspired Harmony Search Algorithm, Theory and Applications*. Springer-Verlag, Berlin, Germany.

Geem, Z. W., Kim, J. H. & Loganathan, G. V. 2001 A new heuristic optimization algorithm: harmony search. *Simulation* **76** (2), 60–68.

Gualtieri, C. & Chanson, H. 2010 Effect of Froude number on bubble clustering in a hydraulic jump. *Journal of Hydraulic Research* **48** (4), 504–508.

Hassanvand, M. R., Karami, H. & Mousavi, S. F. 2019 Use of multi-criteria decision-making for selecting spillway type and optimizing dimensions by applying the harmony search algorithm: Qeshlagh Dam case study. *Lakes & Reservoirs: Research & Management* **24** (1), 66–75.

Houichi, L., Dechemi, N., Heddam, S. & Achour, B. 2013 An evaluation of ANN methods for estimating the lengths of hydraulic jumps in U-shaped channel. *Journal of Hydroinformatics* **15** (1), 147–154.

Javan, M. & Eghbalzadeh, A. 2013 2D numerical simulation of submerged hydraulic jumps. *Applied Mathematical Modelling* **37** (10–11), 6661–6669.

Kim, Y., Choi, G., Park, H. & Byeon, S. 2015 Hydraulic jump and energy dissipation with sluice gate. *Water* **7** (9), 5115–5133.

Laishram, K., Devi, T. T. & Singh, N. B. 2022 Experimental comparison of hydraulic jump characteristics and energy dissipation between sluice gate and radial gate. In: *Innovative Trends in Hydrological and Environmental Systems: Select Proceedings of ITHES 2021*. (Dikshit, A. K., Narasimhan, B., Kumar, B. & Patel, A. K., eds). Springer Nature Singapore, Singapore, pp. 207–218.

Mahdavi-Meymand, A. & Sulisz, W. 2022 Simulation of energy dissipation downstream of labyrinth weirs by applying support vector regression integrated with meta-heuristic algorithms. *Journal of Hydro-Environment Research* **40**, 91–101.

Muhsun, S. S. 2012 Characteristics of the hydraulic jump in trapezoidal channel section. *Journal of Environmental Studies [JES]* **9**, 53–63.

Omid, M. H., Esmaeeli Varaki, M. & Narayanan, R. 2007 Gradually expanding hydraulic jump in a trapezoidal channel. *Journal of Hydraulic Research* **45** (4), 512–518.

Singh, U. K. & Roy, P. 2023 Energy dissipation in hydraulic jumps using triple screen layers. *Applied Water Science* **13** (1), 17.

Wang, C. N., Yang, F. C., Nguyen, V. T. T. & Vo, N. T. 2022 CFD analysis and optimum design for a centrifugal pump using an effectively artificial intelligent algorithm. *Micromachines* **13** (8), 1208.

Wanoschek, R. & Hager, W. H. 1989 Hydraulic jump in trapezoidal channel. *Journal of Hydraulic Research* **27** (3), 429–446.

First received 24 March 2023; accepted in revised form 10 July 2023. Available online 21 July 2023