The Hydraulic Jump Formed Downstream a Stepped Gabion Weir: An Experimental Study

Ali Mekki Al-Fawzy1,*1, Kadhim Naief Al-Taee2, Fadhil Mohammed Al-Mohammed3, and Ali Hassan Hommadi4

1Directorate of Water Resources in Kerbala City, State Commission on Operation of Irrigation and Drainage Projects, Ministry of Water Resources, Iraq
E-mail:ali_alfawzy85@yahoo.com
2College of Engineering, University of Babylon, Iraq
E-mail: altaee_kadhim@yahoo.com
3Kerbala Technical Institute, Al-Furat Al-Awsat Technical University, Iraq
E-mail: fnhmjme@yahoo.com
4Al-Hindyiah Barrage Project -Babylon, State Commission of Dams, Ministry of Water Resources, Iraq - E-mail: alihassan197950@yahoo.com
* Corresponding author: Directorate of Water Resources in Kerbala City, State Commission on Operation of Irrigation and Drainage Projects, Ministry of Water Resources, Iraq. Tel: +9647723715510.

Abstract. The current study focus on the effect of using stepped gabion weir in a laboratory channel on the hydraulic jump distance which form at its toe. A series of 175 operation tests and 25 laboratory experiments were conducted by using a laboratory flume 10 m long, 0.3 m wide, and 0.5 m deep. The tested gabions had different five lengths 0.72 m, 0.84 m, 0.96 m, 1.08 m, and 1.20 m respectively, and the material used to fill the gabions was natural quarry mono graded gravel in five different sample sizes of diameters ranged between (09.5-14.0) mm, (14.0-19.0) mm, (19.0-25.0) mm, (25.0-37.5) mm, and (37.5-50.0) mm. The operation flow rate values ranged between 2.33*10^-3 to 50.00*10^-3 m³/s/m. Dimensional analysis was used to generate dimensionless parameters, and correlated them using the Buckingham Pi-Theorem. The results of this study showed that the hydraulic jump distance increases by increasing the flow rate value, but increasing the values of both of the gravel sample used and the total length of the weir have an undular effect on the hydraulic jump distance.

Keywords: dimensional analysis; gabions; hydraulic jump; hydraulic models; stepped gabion weirs.
1. Introduction

Occurrence of hydraulic jumps in open channels take many forms according to the nature of channel, the tested hydraulic structure, and the target study. Generally, this phenomenon can be defined as a transformation of flow state from high-velocity, super-critical flow to low-velocity, sub-critical flow (Abady and Akhtari, 2018; Abbas et al. 2018; Abbaspour et al. 2013; Abbaspour et al. 2019; Al-Fawzy et al. 2020; Anandraj, 2012; De Padova et al. 2018; Fisher et al. 2018; Gavhane et al. 2017; Ghose et al. 2019; Jafar, 2016; Maatooq et al. 2013; Movahed et al. 2018; Palermo and Pagliara, 2018; Torkamanzad et al. 2019; and Yousefi et al. 2018). The hydraulic jump characteristics have been studied to explain and comprehend a lot of problems related to the management of water resources. (Abady and Akhtari, 2018) performed a numerical simulation of the hydraulic jump in divergence rectangular sections, and compared the laboratory results with that made using Flow-3D program and some standard turbulence models to evaluate the effect of vertical and curved blocks on the specification of hydraulic jump, whereas the study results showed that creating of vertical blocks reduces the length of the jump as much as 17.64%, and in case of curved blocks the jump reduces to 35.29%. (Habib, 2013) carried out an experimental study to investigate the effect of relative pipe diameter on the characteristics of the free hydraulic jump that formed downstream a weir controlled by a sluice gate, by comparing the hydraulic characteristics of the jump using a weir with circular openings and weir without openings, and using the dimensional analysis for developing theoretical model to predict the relative depth of water and relative energy loss of the hydraulic jump. (Maatooq et al.2013) proposed a treatment for the hydraulic jump formation in Diyala weir structure, whereas the scour occurs due to the position of the jump because its subsequent depth is higher than exist tail water depth, by present a suitable stilling basin or use of weir with low height at the end of the basin to ensure stability of the jump. While (Jafar, 2016) used a flow partitioning structure, FPS, downstream a sluice gate to raise the tail water level to move the jump into a closer distance from the gate's outlet. He found that using this structure increases the tail water level due friction resistance, and force the hydraulic jump back toward the gate. (Fisher et al. 2018) tried to control the hydraulic jump using the electro-magnetic force in a liquid metal flow, whereas this force could be generated using electrical currents and magnetic fields injected externally to control the jump. They found that applying this force has a repeated and predicted impact on the hydraulic jump, and could be useful in solving future practical problems related to it. (De Padova et al. 2018) modeled the smooth particle hydrodynamics of the hydraulic jump at an abrupt drop. The results of this modeling showed that particularly both of the vorticity, the turbulent kinetic energy fields, the velocity of flow, depths of water, and pressure spectra downstream of the jump can computed and analyzed. (Abbas et al. 2018) investigated the characteristics of the hydraulic jump on smooth adverse slope in three different states without appurtenances, and they illustrated that the jump length ratio was reduced by 22.1%. (Yousefi et al. 2018) tried to estimate the hydraulic jump length in a rectangular channel, and propose roughness for the used stilling basin. From their study they found that all the upstream and downstream water depths, upstream Froude number, and bed roughness are independent variables affect the hydraulic jump formation, and accordingly the jump length reduces as the stilling basin roughness increases. Also, (Ghose et al. 2019) tested the hydraulic jump formation in a laboratory flume has inclination, and they illustrated that the jump length dimensionless parameter depend significantly on the bad of the channel. (Abbaspour et al. 2019) investigated the operation of porous screens in super-critical flow condition experimentally, by installing them on two reverse slopes to evaluate the losses of energy of flow. Their investigation showed that the distance of screen from the hydraulic jump toe has insignificant effect on the energy dissipation. (Ljubičić et al. 2018) proposed the use of reverse slope stilling basin with stepped chutes instead of smooth chutes to study the characteristics of flow aeration, energy dissipation and the hydraulic jump, whereas they found that the proposed state has a better agreement with the experimental data, as compared with standard state, and useful in primary design. (Jalil, 2018) modeled the hydraulic jump that generated partially on a sloped apron, using multi-slope bed to generate the hydraulic jump at different locations by controlling the tail water depth. Results of study showed that the energy exchange process depends on the Froude number and the location of the hydraulic jump. The main purpose of this study is to investigate the effect of use the stepped shape of gabion weir on the distance of hydraulic jump experimentally.
2. The laboratory work

The experimental works conducted at the hydraulic laboratory of College of Engineering, University of Babylon in Iraq. The laboratory has a tilting flume of 10 m length, 0.3 m width and 0.5 m depth. The bed of flume was fabricated from iron plates and the flume side walls were made of anti-crush glass supported by stainless steel bars. The tested physical models have total lengths of 0.72, 0.84, 0.96, 1.08, and 1.20 m, and these models are assigned as SGW.A, (Stepped Gabion Weir A), SGW.B, SGW.C, SGW.D, and SGW.E respectively. Figure 1 shows the sketch of general shape of the tested gabion weirs. All physical models have constant cross-section width of 0.3 m and maximum weir height of 0.4 m. Table 1 shows the dimensions of the models used in this study, whereas h1, h2, and h3 present the effective distance of step height, L1, L2, and L3 are divided according to maximum weir length which is equal to 1.20 m; where L1 has a percentage of 33.3% of the maximum weir length, L2 has a percentage of 16.7% of the maximum weir length, and L3 has a percentage of 10% of the maximum weir length, for SGW.A, and the percentage of L3 increases accumulatively by 10% of maximum weir length with every physical model tested according to their alphabetical arrangement above. All the tested models were installed at distance of 4 m from the beginning of the flume. The gravel samples used as filling material for the weir models were five mono-sized gravel samples with diameters ranged between (9.5-14.0), (14.0-19.0), (19.0-25.0), (25.0-37.5), and (37.5-50.0) mm, and numbered as GS.I, (gravel sample number I), GS.II, GS.III, GS.IV, and GS.V respectively. The frame of the weirs was made of thin steel plate bars, covered by a wire mesh, and fixed inside the flume by silicone glue. A photo of SGW.B with GS.III is shown in Figure 2. A centrifugal pump having a capacity of 40 l/s was used to deliver flow to the flume. Two movable carriages with point gages were mounted on brass rail at the top of flume sides, which have accuracy of 0.1 mm to measure the depths of water. The first was located at the upstream side of the weir to measure the upstream water depth at equal distances starting from 0.0 m to 1.0 m before the weir during the single test run. The second was at the downstream side of the weir to measure the downstream water depths before and after the hydraulic jump location during the single test run. The total number of test runs was 175, and their flow rate values were varied between 2.33*10^-3 - 50.00*10^-3 m3/s/m.

![Figure 1. The sketch of the general shape stepped gravel gabion weir tested in this study.](image)
Table 1. Details of step dimensions for all steps of the tested gabion weir.

| Stepped gabion weir | Step dimensions | 1st step dimensions | 2nd step dimensions | 3rd step dimensions |
|---------------------|----------------|---------------------|---------------------|---------------------|
|                     |                | h1 cm               | L1 cm               | h2 cm               | L2 cm               | h3 cm               | L3 cm               |
| A                   |                | 15                  | 40                  | 15                  | 20                  | 10                  | 12                  |
| B                   |                | 15                  | 40                  | 15                  | 20                  | 10                  | 24                  |
| C                   |                | 15                  | 40                  | 15                  | 20                  | 10                  | 36                  |
| D                   |                | 15                  | 40                  | 15                  | 20                  | 10                  | 48                  |
| E                   |                | 15                  | 40                  | 15                  | 20                  | 10                  | 60                  |

Figure 2. Stepped gabion weir B with gravel sample number III.

3. Theoretical background and dimensional analysis

Generally, the relationships which combine multi-components can be represented in many different ways as the direct relations or (x-y) relation, empirical equations, standard formulas, or correlated by using the dimensional analysis (e.g. Abbas et al. 2018; Abbaspour et al. 2013; Abbaspour et al. 2019; Abozeid et al. 2010; Al-Fawzy et al. 2020; Anandraj, 2012; Dhahir and Mohammed-Hasan, 2017; Habib, 2013; Jafar, 2016; Jalut and El-Baaja, 2014; Ljubičić et al. 2018; Movahed et al. 2018; Obaed et al. 2016; and Sharif and Kabiri-Samani, 2018). In this study, the geometric and hydraulic components of the stepped gabion weir upon which the hydraulic jump distance may depend can by as:

\[ DHJ = f_1(q, d_G, L_3, L, \rho_w, g) \] (1)

whereas DHJ is the hydraulic jump distance formed at the weir toe (m), q is the unit discharge or flow rate, (m³/s/m), d_G is the possible diameter of the used gravel sample (mm), L_3 is the third step length of the weir (m), L is the total length of the weir (m), \( \rho_w \) is water mass density (kg/m³), and g is the gravitational acceleration (m/s²).

The Buckingham Pi – Theorem is an effective method used for representing of relationships of components functionally in dimensionless form (e.g. Abbas et al. 2018; Abbaspour et al. 2013; Abbaspour et al. 2019; Abozeid et al. 2010; Al-Fawzy et al. 2020; Dhahir and Mohammed-Hasan, 2017;
Habib, 2013; Jafar, 2016; Movahed et al. 2018; Sharif and Kabiri-Samani, 2018; Torkamanzad et al. 2019; and Yousefi et al. 2018). Thus, the general equation of the hydraulic jump by the other components, within the limitations of this study, can be expressed dimensionally as follows:

\[
\text{DHJ} = f_1 \left( \frac{\text{Component 1}}{\text{The same chosen component}}, \frac{\text{Component 2}}{\text{The same chosen component}}, \frac{\text{Component 3}}{\text{The same chosen component}}, \ldots, \text{etc} \right)
\]

Where the chosen component is one of the components in the right side of equation (1), that chosen for specific study, and components 1, 2, 3, …, etc are other components on the same side of the chosen one.

4. Results and discussion

4.1 Effect of discharge on the hydraulic jump distance

The relationship between the discharge and the distance of the hydraulic jump has been represented by using of the direct mode, the x-y relationship, (Al-Fawzy et al. 2020), (Jafar, 2016), (Jalut and El-Baaja, 2014), and (Obaed et al. 2016). The figures 3, 4, 5, 6, and 7 show the drawn relationship between the discharge and the hydraulic jump distance.

**Figure 3.** The discharge-hydraulic jump distance relationships for all gravel samples used with SGW.A.

**Figure 4.** The discharge-hydraulic jump distance relationships for all gravel samples used with SGW.B.
In these figures, the equation of trend lines that represent this relationship varies between the exponential and power forms.

\[ DHJ = c_1 e^{c_2 q} \]  \hspace{1cm} (3)

\[ DHJ = c_3 q^{c_4} \]  \hspace{1cm} (4)

whereas \( c_1, c_2, c_3 \) and \( c_4 \) are constants, and table 2 presents their values. The larger value of discharge listed in table 2 represent the maximum, and safe value of discharge recorded for every series of test runs of a specified physical model and gravel sample, taking into consideration prevention of water from pass over the flume sided walls, and keeping the hydraulic jump at a safe distance about 0.75 m from the flume end. Generally, for the figures 3, 4, 5, 6, and 7 the hydraulic jump distance increases as the discharge value increases, and the proportion is direct.
4.2 Effect of the gravel sample on the hydraulic jump distance

The figures 3-7, in each figure it's obvious that there is no clear effect of increasing the diameter of the used gravel sample on the hydraulic jump distance at low values of discharge. This leads to the possibility of use any available material within the limitations of this study in field works, whereas the water flow through the pores of gravel particles in laminar state, and there is no formation of hydraulic jump in most of case. However, increasing of discharge value, this behavior transforms to an undular effect on the distance of the hydraulic jump. Also, using the dimensional analysis after combining the data of the figures 3-7, and draw the relationship between the parameters \( \left( \frac{DHJ}{d_G} \right) \) and \( \left( \frac{q}{d_G^{0.5}} \right) \) as shown in figure 8, where every single trend line represent a gravel sample used with all physical models, gives the same result of undulation. From figure 8 it is clear that the smallest gravel samples may be useful in detention of water, but it pushes the hydraulic jump away from the weir toe, while the largest
samples of gravel do the opposite behavior by making the hydraulic jump come closer, whereas it makes the weir downstream portion behave as a stilling basin and reduce the length of the formed hydraulic jump. Furthermore, the accuracy of equation of trend line reduces with increasing the diameter of the used gravel sample due dispersion in their data, and the equation of these trend lines varies between the exponential and power forms too. Equations (5) and (6) may be used for design purposes.

\[
\frac{DHJ}{d_G} = c_5 e^{c_6 \left( \frac{q}{q_{G0.5}} \right)^{0.75}} \tag{5}
\]

\[
\frac{DHJ}{d_G} = c_7 \left( \frac{q}{q_{G0.5}} \right)^{c_8} \tag{6}
\]

Whereas \(c_5, c_6, c_7\) and \(c_8\) are constants, and table 3 presents their values.

![Figure 8. The gravel sample-hydraulic jump distance non-dimensional relationship.](image)

| SGW | GS | c5  | c6  | c7  | c8  | R²    |
|-----|----|-----|-----|-----|-----|-------|
| All | I  | -   | -   | 23567 | 2.769 | 0.810 |
| All | II | -   | -   | 01718 | 2.005 | 0.858 |
| All | III | 0.014 | 151.30 | -   | -   | 0.781 |
| All | IV | 0.029 | 098.84 | -   | -   | 0.518 |
| All | V  | 0.169 | 054.47 | -   | -   | 0.318 |

4.3 Effect of the gabion total length on the hydraulic jump distance

To view the effect of weir length on the hydraulic jump distance, two values of applied discharges, minimum \(2.33 \times 10^{-3}\) m³/s/m and \(12.00 \times 10^{-3}\) m³/s/m, were used for comparison purposes as shown in table 4. From this table it's clear that the gabion total length has slight effect on the hydraulic jump distance, and this result was verified by using of dimensional analysis to draw the relationship between
the parameters \( \frac{DHJ}{L} \) and \( \frac{q^{0.5} \cdot L^{1.5}}{L} \) as shown in figure 9. Whereas the smallest lengths may be beneficial in dissipating the energy of flow more than reducing the hydraulic jump length, while the largest values of \( L_3 \) works as a part of stilling basin. Furthermore, the accuracy of trend line equation reduces with increasing diameter of the used gravel sample due to the clear dispersion of data, and the equation of these trend lines varied between the exponential and power forms too. Equations (5) and (6) probably used for design purposes.

\[
\frac{DHJ}{L} = c_9 e^{c_{10}(\frac{q}{\sqrt[3]{q \cdot L^{1.5}}})} \quad (7)
\]

\[
\frac{DHJ}{L} = c_{11}(\frac{q}{\sqrt[3]{q \cdot L^{1.5}}})^{c_{12}} \quad (8)
\]

Whereas \( c_9, c_{10}, c_{11} \) and \( c_{12} \) are constants, and table 5 shows their values.

![Figure 9. The gabion length-hydraulic jump distance non-dimensional relationship.](image)

| GS | Applied discharges * \(10^{-3}\) (m³/s/m) | Distance of hydraulic jump (m) |
|----|---------------------------------|-----------------------------|
|    | Physical models                  | SGW:A          | SGW:B          | SGW:C          | SGW:D          | SGW:E          |
| I  | 2.33                            | 0.00            | 0.00            | 0.00            | 0.00            | 0.00            |
|    | 12.00                           | 0.20            | 0.12            | 0.26            | 0.43            | 0.11            |
| II | 2.33                            | 0.00            | 0.00            | 0.00            | 0.00            | 0.00            |
|    | 12.00                           | 0.17            | 0.19            | 0.32            | 0.60            | 0.05            |
| III| 2.33                            | 0.00            | 0.00            | 0.00            | 0.00            | 0.00            |
|    | 12.00                           | 0.08            | 0.48            | 0.07            | 0.22            | 0.12            |
| IV | 2.33                            | 0.00            | 0.00            | 0.00            | 0.00            | 0.00            |
|    | 12.00                           | 0.09            | 0.18            | 0.09            | 0.16            | 0.06            |
| V  | 2.33                            | 0.00            | 0.00            | 0.00            | 0.00            | 0.00            |
|    | 12.00                           | 0.09            | 0.07            | 0.05            | 0.03            | 0.00            |

**Table 4.** Values of distance of hydraulic jump at 2.33*10^{-3} and 12.00*10^{-3} m³/s/m applied discharges.

*Applied discharges are in m³/s/m.*
Using multi-linear regression for the data set to correlate the dependent and independent components (e.g. Abbas et al. 2018; Al-Fawzy et al. 2020; Dhahir and Mohammed-Hasan, 2017; Jalil, 2018; Sharif and Kabiri-Samani, 2018; Torkaman zad et al. 2019; and Yousefi et al. 2018), 60% of data were used in regression process, (data recorded of test runs of the 1st, 3rd, and 5th total lengths of the weir), and 40% of data were used in verification of the resulted equation, (data recorded of test runs of 2nd and 4th total lengths of the weir). After many trials, equation (2) can be re-written as,

\[
DHJ_{\text{Calculated}} = 0.467 \left( DHJ_{\text{Measured}} \right)^{0.61} \quad R^2 = 0.82
\]

Equations (10) and (11) express this relationship,

\[
\frac{\left( \frac{DHJ}{L} \right)^{0.005}}{0.005} = (0.8267) + 0.1668 \times \left( \frac{q}{q_{0.5} + L_{1.5}} \right)^{0.1} + 0.0716 \times \left( \frac{L}{L} \right)^{0.05} + 3044.4112 \times \left( \frac{d}{L} \right)^{0.1} \quad R^2 = 0.67
\]

According to these figures, an acceptable agreement has been achieved between the values. Both values of hydraulic jump distance, calculated and measured, has a percentage of errors, that was calculated for this study by equation (12) with an average value of -49.1%. May be this value becomes better and more accurate if a separation has been made between the data of through flow and the over flow.

\[
E\% = \frac{(DHJ_{\text{Calculated}} - DHJ_{\text{Measured}})}{DHJ_{\text{Calculated}}} \quad (12)
\]
5. Conclusions
The current study aimed to investigate how the distance of hydraulic jump affected by placing a stepped gabion weir of three steps in a rectangular Laboratory channel. Relationships between components were made either directly or in non-dimensions’ style, while the regression process was used to correlate all components. Within the limitations of this study, it can have concluded that:

- The hydraulic jump distance increases by increasing the discharge.
- The hydraulic jump distance behaves undular with increasing both the diameter of the used gravel sample and the total length of the weir.
- The formulated dimensionless equation to combine all components of the current study has $R^2$ equal to 0.67.
- The calculated-measured relationship of the hydraulic jump distance has been drawn and the fitness equations were with $R^2$ equal to 0.82 and 0.73 respectively.
- The percentage of errors was -49.1% for the relationship between the calculated and measured distance of hydraulic jump.

Acknowledgements
A great full thanks and gratitude for all people who have a share in supporting and completing this work, and specially for the technical team, and their leader in fluid laboratory of college of engineering in Babylon university.

References
[1] Abady, Kh., & Akhtari, A. (2018). Effect of vertical and curved blocks on hydraulic jump characteristic in diverging rectangular sections with Flow-3D software. *Modares Civil Engineering Journal*, 17, 6, 269-279.
[2] Abbas, A. S., Alwash, H., & Mahmood, A. A. (2018). Experimental study of hydraulic jump in adverse stilling basin at smooth bed. *Diyala Journal of Engineering Sciences*, 11, 3, 7-13.
[3] 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 Journal, 6, 2, 189-198.

[4] Abbaspour, A., Taghavianpour, T., & Arvanaghi, H. (2019). Experimental study of the hydraulic jump on reverse bed with porous screens. Applied Water Science, https://doi.org/10.1007/s13201-019-1032-7.

[5] Abozeid, G., Mohamed, H. I., & Shehata, S. M. (2010). Hydraulics of clear overfall weirs with bottom openings. Journal of Engineering Sciences, Assiut University, 38, 1, 19-28.

[6] Al-Fawzy, A. M., Al-Mohammed, F. M., & Alwan, H. H. (2020). Energy dissipation in Gabion Weirs. IOP Conference Series: Material Sciences and Engineering, 671, 012068, 1-12.

[7] Anandraj, A. (2012). Investigational study on self aeration characteristics of hydraulic jump. Journal of Mechanical and Civil Engineering, 4, 2, 27-31.

[8] De Padova, D., Mossa, M., & Sibilla, S. (2018). SPH numerical investigation of the characteristics of an oscillating hydraulic jump at an abrupt drop. Journal of hydrodynamics, 30, 1, 106-113.

[9] Dhahir, F. M., & Mohammed-Hasan, A. M. (2017). Using of hydraulic jump characteristics as criterion for energy dissipation in rectangular gabion weir. International Journal of Advanced Research, 5, 7, 268-276.

[10] Fisher, A. E., Kolemen, E., & Hvasta, M. G. (2018). Experimental demonstration of hydraulic jump control in liquid metal channel flow using Lorentz force. Physics and Fluids Journal, 30, 6, 067104, 1-9.

[11] Gavhane, A. T., Sathe, N. J., Hinge, G. A. & Jain, S. S. (2017). Studies on design of hydraulic jump type stilling basin in laboratory for Gunjawani dam, Maharashtra, India. Journal of water resources engineering and management, 4, 3, 15-22.

[12] Ghose, D. K., Mandal, P., & Samantaray, S. (2019). Experimental study of hydraulic jumps in an inclined rectangular flume. Pertanika Journal of Science and Technology, 27, 1, 397-407.

[13] Habib, A. A. (2013). Effect of weir opening on hydraulic jump characteristics d. s. of the weir. Minia Journal of Engineering and Technology, 32, 1, 49-61.

[14] Jafar, M. S. (2016). The friction resistance effect of the hydraulic jump location and energy dissipation, a laboratory study. Kufa Journal of Engineering, 7, 2, 90-103.

[15] Jalil, Sh. A. (2018). Modeling of Hydraulic Jump Generated Partially on Sloping Apron. Journal of University of Babylon, Engineering Sciences, 26, 1, 81-93.

[16] Jalut, Q. H., & El-Baaja, N. F. (2014). Experimental study for energy dissipation using stilling basin with one and two consecutive drops. Diyala Journal of Engineering Sciences, 7, 2, 61-82.

[17] Ljubičić, R., Zindović, B., Vojt, P., Pavlović, D., Kapor, R., & Savić, L. (2018). Hydraulic Jumps in Adverse-Slope Stillling Basins for Stepped Spillways. WATER, Hydraulics-Setion, 10, 460-477.

[18] Maatooq, J. S., Al.Adili, A. Sh., & Sameen, S. S. (2013). Relevant problems of a hydraulic jump at Diyala weir and the proposed remedy. Eng. and Tech. Journal, University of Technology, 31, A, 2504-2512.
[19] Movahed, S. A. M., Mozaffari, J., Davood-Magami, D., & Akbari, M. (2018). A semi-Analytical equation to estimate hydraulic jump length. *Periodica Polytechnica Civil Engineering*, 62, 4, 1001-1006.

[20] Obaed, I. H., Al-Salim, N. H. A., & Al-Fatlawy. Th. J. M. (2016). Experimental study for hydraulic characteristics of flow over compound regular notches. *Journal of Babylon University, Engineering Sciences*, 24, 1, 38-55.

[21] Palermo, M. & Pagliara, S. (2018). Semi-theoretical approach for energy dissipation estimation at hydraulic jumps in rough sloped channels. *Journal of Hydraulic Research*, 56, 786-795.

[22] Sharif, M., & Kabiri-Samani, A. (2018). Flow regimes at grid drop-type dissipators caused by changes in tail-water depth. *Journal of Hydraulic Research*, 56, 1-12.

[23] Torkamanzad, N., Dalir, A. H., Salmasi, F., & Abbaspour, A. (2019). Hydraulic jump below abrupt asymmetric expanding stilling basin on rough bed. *Water*, doi:10.3390/w11091756

[24] Yousefi, F., Mozaffari, J., & Movahed, S. A. M. (2018). Developing a hydraulic jump length model on horizontal rough beds. *Journal of the South African Institution of Civil Engineering*, 61, 3, 2-6.