Properties of Flow through and over Gravel Basket Weir

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Submission date:- 15/5/2019	Acceptance date:- 27/6/2019	Publication date:- 4/8/2019

Abstract

Construction of gravel basket weir in waterways causes water accumulation in front of this porous structure less than solid weir. In the present study the upstream flow depth, water surface profile and discharge coefficient are investigated through laboratory experiments. Four different weir lengths (15, 20, 25 and 30 cm) and four different degrees of gravel coarseness (1.13, 1.58, 2.19 and 2.27) are studied. Accordingly, sixteen models are tested under different free flow conditions. Analysis of the results show that in "through flow" regime the increase in weir length raises the generated upstream depth for all coarseness degrees by 30% while coarseness lowers the depth by 28%. In "transition flow", however, doubling the length increases the flow depth by 7%, but increasing coarseness from 1.13 to 2.72 cm mean diameter causes 7% reduction in flow depth. The "overflow" regime begins to appear when the depth to length ratio equals 0.75 for long weir, and about 1.54 for shortest weir. A comparison between gravel basket weir and corresponding solid weir indicates that average depth reduction is 7.5% for coarseness of 1.13 cm and 9% for coarseness of 2.72 cm. Mathematical models for water depth prediction for the three flow regimes are presented. For "overflow" an empirical formula is proposed to estimate the coefficient of discharge with acceptable accuracy.

Key words: gravel basket; gabion weir; material coarseness; weir length; flow regime; free flow.

Introduction

Flow in channels and streams serve humans in different ways. While the floods cause damage, controlling the flood wave and managing wave propagation is an economical human interest. Flow management and control in natural streams is accomplished by constructing hydraulic structures [1]. Creating obstruction in stream flow such as weirs or implementing dams is a successful way in watershed management and at the same time they can force the occurrence of critical depth which is essential in flow measurement [2].

Construction of gravel basket weirs, also known as gabion weirs, in the streams enhances water aeration and improves the life environment for fish habitat. This weir type, as its name suggests, is constructed from natural materials and does not have negative effects on the living creatures in the water, unlike solid weirs that are constructed from synthetic materials. Consequently, the gravel basket weir is environmentally friendly and has attracted the researchers increasingly. Northcote and Klasserisn [3] studied the effect of v-shaped gabion weir on the enhancement of salmonid production, it was concluded that gabions improve rearing habitat. Mohamed [4] conducted experiments on three different mean sizes of gravel in gabion under free and submerged conditions of flow, and observed two flow regimes one through the gabion body and the second over the crest surface, it was also shown that water depth accumulated upstream is less than that caused by broad-weir of the same dimension. Stepped gabion weir is a stable structure having good resistance to water loads and efficient in dissipating flow energy, it also may safe 10 - 30% on stilling basin length [5]. This conclusion has been proved by Salmasi *et al.* [6] by comparison of energy dissipation using decision tree technique to classify the parameters affecting energy dissipation. It was shown that porosity does not have essential effect on energy dissipation, and the slope has no effect. Nazari *et al.*[7] have investigated the problem of floor scouring downstream gabion step weir by changing the discharge, slope and aggregate size. They showed that there is an increase in erosion depth with increase of discharge and slope of steps while there is a decrease in the erosion depth with the increase of aggregate size and tail water depth. Wüthrich and Chanson [8] studied the air-water flow over stepped gabion and how it is associated with smaller rates of energy dissipation compared to impervious smooth stepped falls, it was shown that seepage through pores modifies the cavity flow and bubble count rate by causing larger velocities at downstream part of the stepped gabion fall especially in skimming regime flow. Wuthrich and Chanson [9] studied the aeration efficiency of stone stepped gabion and indicated that it can be increased by flattening the steps with impervious material. Fadhil and Saad [10] studied the "through flow" and "transient flow" regimes by using three different average gravel diameters, the study concluded that the upstream depth of water increases with the decrease of gravel size for the same length of gabion, and also the depth increases with the increase of gabion length for the same gravel size. Velázquez and Ventura [11] studied the flow through gravel basket weir and reported that the stone shape and size have direct effect on sediment retention during flooding in catchment area, the bigger rocks size allows to pass more amount of soil particles and the angled rocks shape have large influence on percentage sediment retaining. Saad and Fattouh [12] investigated the weir with openings and how it tends to lift upward the maximum velocity from the channel bed, and that the number of openings decreases the length of hydraulic jump downstream the weir. Gunjalli *et al.* [13] studied perforated weir in different shapes and areas and indicated that the head is less than that generated from solid one, and the best effective shape in lowering head is the rectangle.

The present investigation aims to study the effects of the gravel size and the weir length on the flow properties, flow regimes and discharge capacity of the gravel basket weir under free flow conditions.

Theoretical Background

Three regime of flow could happen when gravel-weir constructed in stream. If the discharge is sufficient, water will flow over the top surface of the weir causing “overflow”, this regime is similar to the flow over solid broad-crested weir but with additional flow through its body. However, when the discharge is not so enough, it will flow only through its porous structure. In this case, it will only pass through the front face forming what is known as "through flow" or penetrating from the front side and top surface generating what is called "transition flow" regime. For the purpose of illustration, Figure (1) presents a definition sketch for these flow cases of the gravel basket weir.

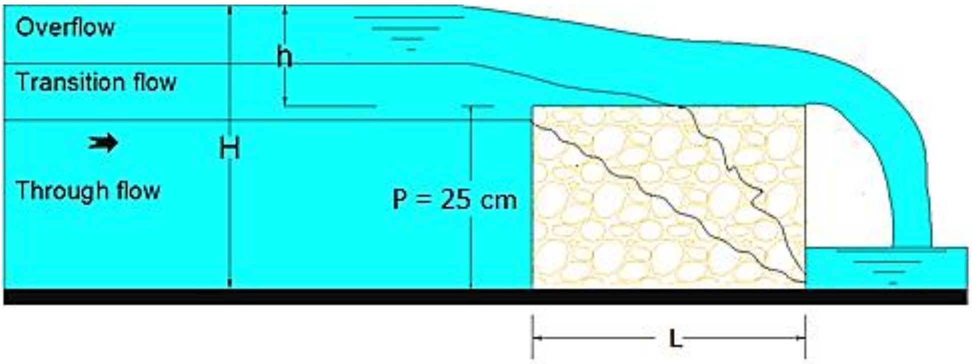

Figure (1) Definition sketch for the flow cases of the gravel basket weir.

In the "overflow" regime, the state of flow is affected by the following parameters: total upstream flow depth (H), the crest-referenced head (h), the porosity presented by material coarseness (dm), length of the weir (L), height of the weir (P), width of the weir (B) and physical properties of water. These parameters reflect the flow discharge and can be expressed as:

$$Q = f(H, P, , h, d_m, B, L, g, \rho, \mu) \quad ....(1)$$

Where g is acceleration due to gravity; ρ is fluid density; and μ is fluid dynamic viscosity.

Following the transformation of Mohamed (2010), the non-dimensional functional equation can be written as:

$$\frac{Q}{\sqrt{g}\, B\, H^{1.5}} = f\left(\frac{Q\rho}{B\mu}, \frac{h}{P}, \frac{h}{L}, \frac{dm}{L}\right) \quad ....(2)$$

The dependent variable in Equation (2) is the coefficient of discharge and the first independent variable is Reynolds number. The dimensionless equationmay berewritten as:

$$C = f\left(Log(\text{Re}), \frac{h}{P}, \frac{h}{L}, \frac{dm}{L}\right) \quad ....(3)$$

Experimental Work

The experimental work has been carried on in the Hydraulic Laboratory of the College of Engineering at the University of Duhok. A glass-sided flume of 5 m working length, 0.3 m wide and 0.45 m deep is used in the investigation. A total number of sixteen weirs is tested. The weirs have a height of 25 cm and four different lengths: 15, 20, 25 and 30 cm. The sizes of the weirs are decided depending on the size of the flume which is used in the laboratory work. For stability reasons, practical construction rules for such weirs are based on the value of minimum structure length which must be more than half its height for the structure to be safe and resist thrusts exerted by water [14].

As to the material of the weirs, early literatures and practices state that stone sizes between 15 and 30 cm in diameter are generally used for constructing gabion weir up to 4 m high. This gives a percentage of 1/10 to 1/25 of the weir height [14]. For the present work, sieved gravel of four mean sizes: 1.13, 1.58, 2.19, and 2.72 cm diameter are used to construct the weirs, as shown in Figure (2). The dimensions and porosity of the gravel basket weirsare detailed in Table (1). Sixteen different flow rates are applied on every model to cover the observation of the three flow regimes. The water surface profile along the center of the channel is measured for each flow rate by Vernier point gauges of 0.01 mm accuracy.

Figure (2) Gravel basket weirstested in the laboratory flume.

Table (1) Dimensions and porosity of the tested gravel basket weirs

Model No.	Weir length L (cm)	Weir height P (cm)	Gravel size dm (mm)	Porosity
1 - 4	15	25	1.13 , 1.58, 2.19, 2.72	33%, 34% , 36%, 38%
5 - 8	20	25	1.13 , 1.58, 2.19, 2.72	33%, 34% , 36%, 38%
9 - 12	25	25	1.13 , 1.58, 2.19, 2.72	33%, 34% , 36%, 38%
13 - 16	30	25	1.13 , 1.58, 2.19, 2.72	33%, 34% , 36%, 38%

Results and Discussion

Constructing gravel basket weirs across streams accumulate water for many purposes. The level of water surface in front of these structures depends on the incoming discharge, structural dimensions and material coarseness. When the structure height is constant, the length will affect the depth of water in front of the weir. In general, two regimes of flow pass the body of gravel basket and a third regime passes over its top surface. The first one is "through flow" which occurs only in contact with the front face of the structure passing through voids.The second is “transition flow” which moves through voids from the front face and crest without free falling. The third regime is "overflow" occurring when that over falling water starts to appear from the downstream edge. Figure (3) shows the three regions corresponding to the level of the upstream water. It can be noticed that the increase of water depth in front of structure is rapid as the discharge increases for the "through flow" regime and the increases is less than that in the other two regimes.

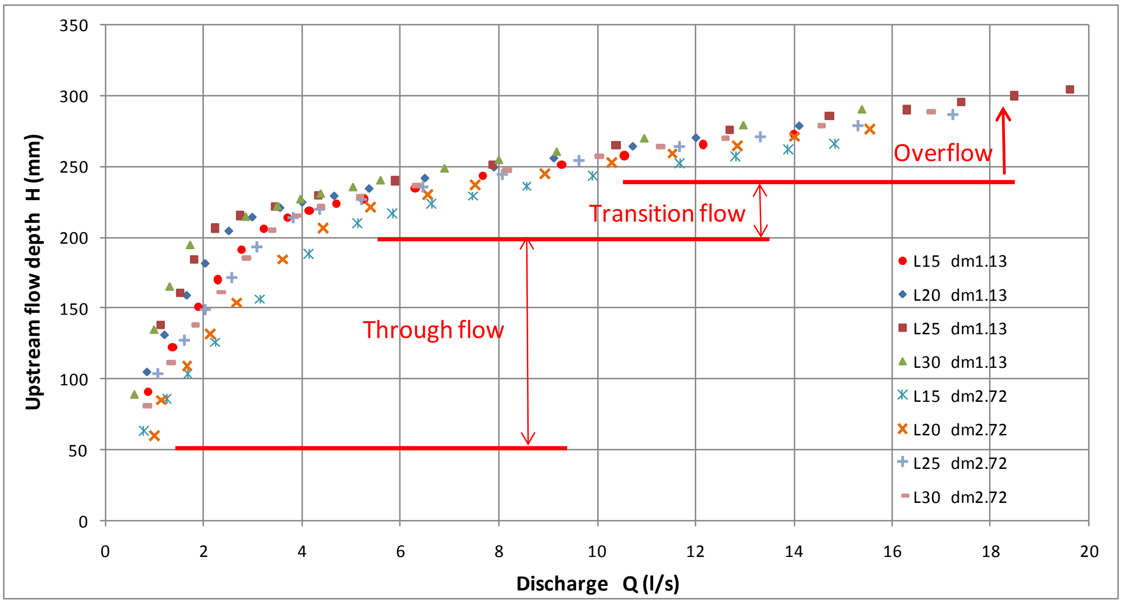

Figure (3) Regimes of flow and variation of depth with rateinflow.

Figure (3) also shows the effect of gravel basket length and the coarseness of materials on the depth of flow and its rate of increasing. In "through flow" the effect of structure length and material coarseness is very clear due to their high influence on the flow discharge.

The change in the upstream water depth with the change in structure length and gravel size is illustrated in Figure (4), which shows that H increases as L increases and decreases as dm increases. The increase of H due to the increase in gravel basket length twice is 30%, and the reduction in H is 28% as a result of the increase in material coarseness from 1.13 to 2.72 cm (i.e., porosity increasing from 33% to 38%).

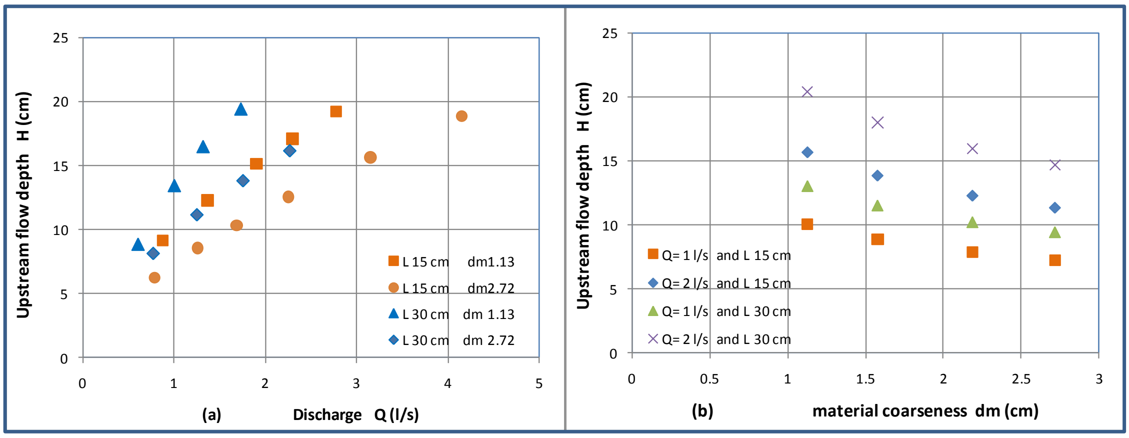

Figure (4) Depth of "through flow" variation with weir length and material coarseness.

For "through flow",the experimental data of Q, L and dmare correlated to Happlying nonlinear regression analysis. A mathematical model for predicting the depth of water in front of porous structures is found as:

$$H_{(cm)} = 3.753\ Q_{(l/s)}^{0.648} L_{(cm)}^{0.379} dm_{(cm)}^{-0.370} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4) \qquad R^2 = 0.974$$

When the flow rate is enough to generate a depth of water exceeding the weir height, then a creeping flow on the top surface appears and a change in the rate of variation between depth and discharge starts to reflect the properties of this "transition flow". The new flow properties are the effect of the increasing area of the wet surface. To clarify the relation between the generated depth and incoming discharge, Figure (5a) shows that for constant L, increasing dm reduces H. Figure (5b) shows the increasing effect of L on the increase of H. The experimental results show that the average reduction in H is 7% due to the increase of gravel size from dm = 1.13 cm to dm = 2.72 cm (i.e., porosity change from 33% to 38%). The average increase in H is 7% due to the increase of L from 15 cm to 30 cm. The correlation between variables in Equation (1) and nonlinear regression generates a mathematical model for the prediction of the upstream flow depth as:

$$H_{(cm)} = 12.932\, Q_{(l/s)}^{0.194} L_{(cm)}^{0.094} dm_{(cm)}^{-0.081} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(5)\; R^2 = 0.911$$

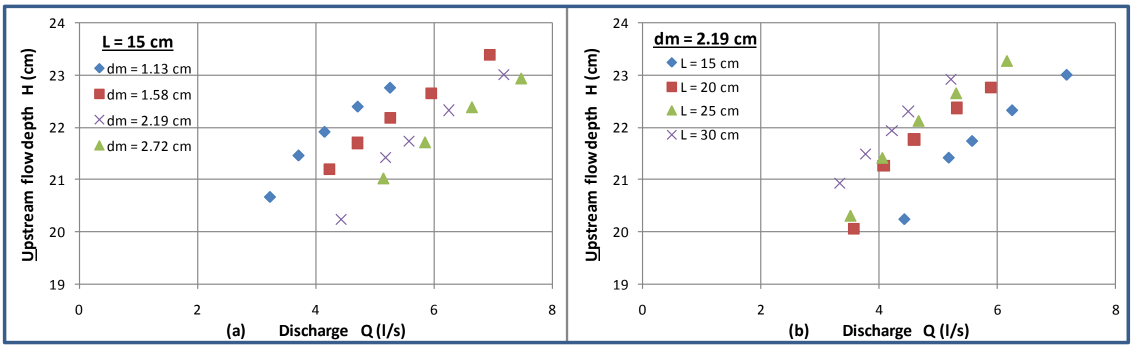

Figure (5) "Transition flow" depth variation with rate of flow

Observation for the upstream water depth show that “overflow” takesplace when H/L is 1.54 for L =15 cm, and 0.75 for L =30 cm, or when h/L is 0.26 for L =15 cm, and 0.13 for L =30 cm. Figure (6) shows the variation of the flow rate versus the values of H/L and h/L. In overall,this flow regime generates at average value of 1.15 for H/L and 0.2 for h/L depending on the material coarseness.

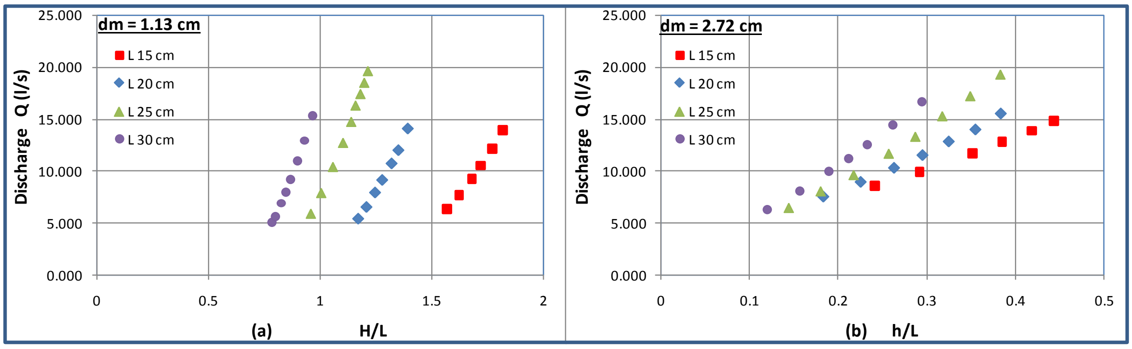

Figure (6) Variation of "overflow” discharge with the relative upstream depths.

When the regime of flow is overflow it looks like a solid broad-crested weir flow but with parts of flow moving through the porous material reducing the upstream depth of water. An equation suggested by Lakshmana Rao cited in Subramanya [15] has been used to calculate equivalent depth for the experimental discharge data. This equivalent depth has been used to make performance comparison between gravel basket weir and a solid weir of the same dimensions. The calculated depth and the measured onesare shown in Figure (7). Visual inspection shows the effect of material coarseness on the reduction in flow depth for the same discharge. Due to the increase in length from 15 cm to 30 cm, the relative decrease of flow depth compared to broad weir is found to be from 5% to 8% for dm =1.13 cm, and from 7% to 11% for dm =2.72 cm.

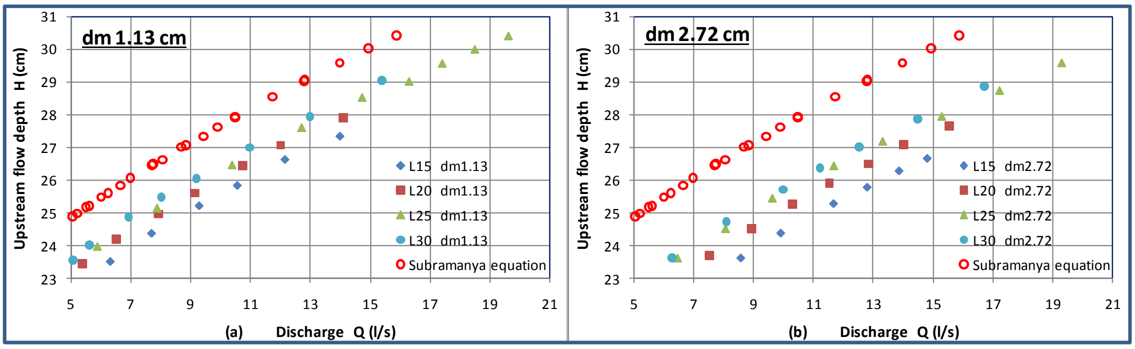

Figure (7) Depth variation with discharge in gravel basket and Subramanya broad weir equation.

A comparison between the discharge of solid broad weir and that of gravel weiris done by calculating the advantage in discharge of aggregate to solid discharge. The calculated results indicated that the relative discharge increase for L = 15 cm and 30 cm is between 38% and 23%, respectively, when dm = 1.13 cm, and is between 50% and 33% when dm = 2.72 cm. Figure (8) shows the values of the coefficient of discharge $C = (Q/(\sqrt{g}BH^{1.5})$ decreasing with increasing thevalues of coarseness-depth ratios (dm/H) and (dm/h). In addition, it can be noted that for a particular value of (dm/H) or (dm/h), the value of C increases with the decrease of L, this increasing trend is more notable when dm = 2.72 cm.

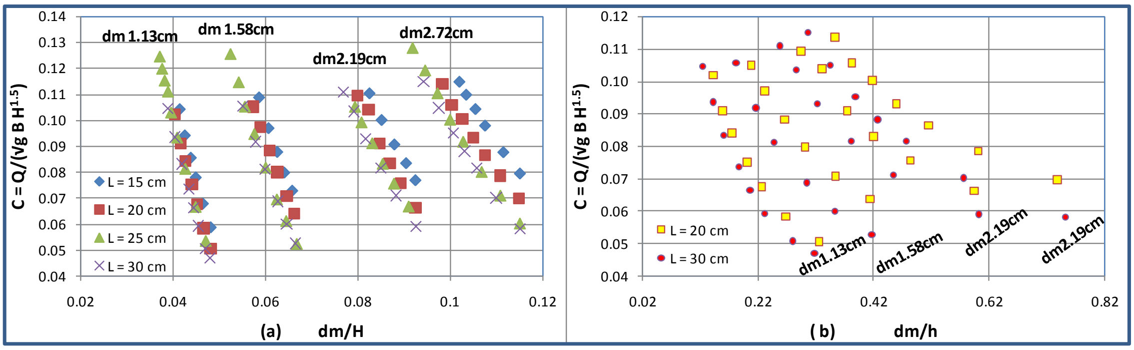

Figure (8) Variation of C and (dm/H) and (dm/h) for different weir length.

A prediction model for the flow depth in front of gravel weirs from the values of Q, L and dm is found by nonlinear regression as:

$$H_{(cm)} = 13.40\, Q_{(l/s)}^{0.200} L_{(cm)}^{0.070} dm_{(cm)}^{-0.042} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6) R^2 = 0.990$$

Multi-linear regression analysis is employed for "overflow" to get mathematical model for predicting flow depth as:

$$\frac{H}{P} = 0.602\, Log(Re) - 0.792 \frac{d_m}{L} - 1.365 \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots (7) R^2 = 0.977$$

The experimental data are correlated to the coefficient of discharge (C). The correlation shows that the highest Pearson coefficient are 0.885, 0.832 and 0.247 for the parameters (H/P), (h/L) and (dm/L),respectively. A mathematical model is found by utilizing multi-linear regression with the standard error of 0.00209060:

$$C = 0.191\frac{h}{P} + 0.035\frac{h}{L} + 0.196\frac{d_m}{L} - 0.002 \quad \dots\dots\dots\dots\dots\dots\dots\dots (8) \qquad R^2 = 0.989$$

Conclusion

The length and gravel coarseness have direct effect on the performance of gravel basket weir. From analysis of experimental data and laboratory observations, the following findings may be concluded within thelimitations of the present work:

1- The increase in gravel basket length to twice, raises the flow depth by 30% in "through flow", while the increase of gravel coarseness lowers flow depth by 28%.

2- The increase in gravel basket length to twice raises the average flow depth by 7% in "transition flow", while the increase of gravel coarseness from 1.13 to 2.72 cm lowers the flow depth by 7%.

3- The "overflow" regime begins when the average value of H/L equals 1.54 for the 15 cm long weir, and 0.75 for the 30 cm long weir.

4- In "overflow" regime, the average decrease in flow depth compared to solid weir is 7.5% for the 1.13 cm gravel size, and 9% for the 2.72 cm gravel size.

5- Mathematical models are proposed to estimate the flow depth in "through flow", "transition flow" and "overflow "with reasonable accuracy.

6- An empirical formula is presented to estimate the coefficient of discharge in terms of H/P, h/L and dm/L.

7- All the gravel weirs are able to pass higher discharges, compared to solid weirs.

Conflicts of Interest

The author declares that they have no conflicts of interest.

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خصائص الجريان فوق وخلال هدارات سلال الحصى

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الخـــــلاصة:

يؤدي إنشاء هدارات من سلال الحصى في المجاري المائية إلى تراكم المياه أمام هذه المشأت المسامية، ويكون فيها منسوب المياه أقل من تلك التي تتجمع مقدمة الهدارات الصلبة. تتضمن هذه الدراسة، تقديرعمق الماء المتجمع امام هذه الهدارات مع قياس شكل السطح الحر للجريان والتنبؤ بقيمة معامل التصريف من خلال التجارب المختبرية. كما تمت دراسة أربعة أطوال مختلفة من الهدارات (15 ، 20 ، 25 و 30 سم) وأربع خشونات مختلفة من الحصى (1.13 ، 1.58 ، 2.19 و 2.27). وفقًا لذلك، فقد تم اختبارستة عشر نموذجاً في ظروف مختلفة من التدفق الحر. أظهرتحليل نتائج نظام الجريان "التدفق النافذ" أن الزيادة في عرض السد تسبب في زيادة عمق الماء المتجمع امام الهدارات ولجميع درجات الخشونة بنسبة 30٪ بينما تقلل الخشونة من العمق بنسبة 28٪. وفي "التدفق الانتقالي"، يؤدي مضاعفة الطول إلى زيادة عمق التدفق بنسبة 7٪، بينما تؤدي زيادة الخشونة من 1.13 إلى 2.72 سم في انخفاض عمق الجريان بنسبة 7٪. يبدأ نظام "التدفق الفائض" بالظهورعندما تساوي نسبة عمق الماء إلى عرض السد حوالي 0.75 للعرض الكبير و1.54 للعرض القليل. تشير المقارنة بين هدارات سلال الحصى والهدارات الصلبة إلى أن متوسط تقليل عمق الماء هو 7.5٪ للصلابة البالغة 1.13 سم و9٪ للصلابة البالغة 2.72 سم. تم اقتراح نماذج رياضية للتنبؤ بعمق المياه لأنظمة التدفق الثلاثة، أما بالنسبة لنظام "التدفق الفائض"، فقد اقتُرِحَت صيغة تجريبية لتقدير معامل التصريف بدقة مقبولة.

الكلمات الدالة: سلة الحصى؛ هدارات حجرية؛ خشونة المواد؛ عرض السد؛ نظام التدفق؛ التدفق الحر.