Applied Water Science (2021) 11:16
https://doi.org/10.1007/s13201-020-01342-9

ORIGINAL ARTICLE

Discharge coefficient of flow over Al-Shalalat stepped weir on Al-Khusr River

Azza N. Altalib[1]

Received: 19 October 2020 / Accepted: 10 December 2020 / Published online: 14 January 2021

Abstract

Many hydraulic structures are constructed in an open channel according to the purposes and the nature of the region. Weir is one of these structures which is used for discharge measurements as well as rising water depth in irrigation channels. According to the crest, there are two different shapes: sharp and broad crested weir. A stepped weir is constructed to reduce scour that happened downstream. There are different studies dealt with discharge coefficient, energy dissipation, and other hydraulic characteristics for flow over the weir. In this study, the coefficient of discharge for the Al-Shalalat stepped weir on the Al-Khusr River has been evaluated. The discharge coefficient equation is predicted, and the result values are compared with previous studies. The percentage error for the predicted discharge equation presented in this study compared with previous studies does not exceed 10%.

Keywords Broad crested weir · Stepped weir · Discharge coefficient · Al-Khusr River

Abbreviations

- S_r Surface runoff depth of rainstorm
- A Catchment area upstream stepped weir
- b Width of the stepped weir
- C_d Coefficient of discharge
- H Water head above stepped weir
- W Width of the crest at the top
- P The total height of the stepped weir
- Q Discharge over the stepped weir
- R_a Accumulated rain depth for the individual rainstorm

Introduction

The open channels and stepped weirs were used more than 3000 years ago. At the time of the Assyrians, the oldest dams and stepped weirs were built on the Khusr River in Iraq since the year 694 BC and the weir was designed for supplying water to the Assyrian city of Nineveh. The gradient (stepped) is used in many applications of hydraulic structures such as stepped waterways (irrigation channels) and water supply systems for cities, spillways, and stepped weirs, where the benefit lies in dissipating the high flow energy and thus protecting the waterways from scouring in addition to reducing the requirements of the stilling basin downstream hydraulic structure. The stepped weir also leads to control of water quality through high ventilation, besides, to reduce the capacity of vortices, and thus, the stepped structures are safer than others, Nasiralla Al-Talib and Abd Al-Majeed Hayawi (2009).

Many studies dealt with stepped weir experimentally and theoretically. The studies Reeve et al. (2019), Shahheydari et al. (2015), Patil and Jadhav (2017), Krisnayanti and Sholichin (2015), Ali and Yousif (2019), Mohammed (2009a, b, 2012) and Krisnayanti and Dermawan (2014) dealt with hydraulic characteristics of flow over stepped weir and discharge coefficient in these types of weirs, and the relative error does not exceed 10%. There are deferent studies dealt with energy dissipation of flow over stepped weir such as Ashoor and Riazi (2019), Parsaie et al. (2016), Chatila and Jurdi (2004), Altalib et al. (2019), Jahad et al. (2016), Felder and Chanson (2011), Krisnayantia et al. (2016) and Chanson (1995). The energy dissipation can improve using stepped weir, and this dissipation reached 20%.

Gandhi and Mishra (2016) submitted a review on stepped spillways and the effect of baffle blocks on energy dissipation and conclude that using baffles can reduce the length of the stilling basin. Guenther et al. (2013) studied the possibility of using stepped spillway as flow aeration and found that

✉ Azza N. Altalib
a.altalib@uomosul.edu.iq

[1] Dams and Water Resources Engineering Department, College of Engineering, University of Mosul, Mosul, Iraq

the slope 26.6° gives the best results on flow aeration and energy dissipation. In this paper, coefficient of discharge for Al-Shalalat broad crested stepped weir on Al-Khusr River studied, evaluated, equation predicted, and compared with previous studies.

Description of Al-Khusr River

Al-Khusr River is one of the seasonal tributaries that flow into the left side of the Tigris River near the center of the city of Mosul, where this river feeds from the lands and mountains to the north and northeast of Mosul. The boundaries of the basin of the course are confined between Mosul, Maqloub Mountain, and the Ain Sefni Road in the east, the Sheikhan Mountains, and Al-Qosh in the north, the Mosul Al-Qush Road in the west and the Tigris River in the south. Rain constitutes one of its most important water sources, especially the winter and spring seasons. As well as, the spring water is a major source in feeding the river with water (Younis 2012).

The geographical location of the Khusr River basin

According to one of the studies that dealt with the Khusr River basin using Geographic Information System (GIS), the river basin is confined between longitude (24.75°–43.04°) and (43.25°–46.06°) east and between latitudes (36.30°–44.74°) and (36.49°–16.95°) north. (Younis 2012). A steep slope in its upper section characterizes the Khusr River basin, as it consists of high mountainous lands in the far north and northeast of it, and reaches a height of 1233 m above the sea surface. Then, the feeding basin extends in undulating lands sloping to the south and its slope gradually decreases until it reaches its lowest level at the estuary, which is 215 m in its confluence area with the Tigris River near the city center, as the area of this basin reaches 836 km^2 (Tawfiq 2013).

The importance of the location of the Khusr River basin geographically lies, in that it is located in a region separating the mountains from one side and between the plains and valleys on the other hand. This site naturally contributed to providing a natural source of water for many of the areas that the plains and valleys that are fed by rain and springs water pass through (Younis 2012). Figures 1 and 2 show the location of the Khusr River and the surrounding lands and front and side view of the stepped weir.

Find the dimensions of the stepped weir

The dimensions of stepped weir are found using field measurements and tested using Google Maps, the total length of the stepped weir (from field measurements) is 100 m and total weir height is 2.65 m. The location of weir is between (N 43°11′ E 36°27′) and (N 43°12′ E 36°27′) as shown in Fig. 3.

Using the QGIS program, 3.4.2, a set of points along the edge of the crest and at the upstream and downstream of the stepped weir were chosen for the purpose of identifying levels as shown in Fig. 4.

Table 1 shows the levels of stepped weir using the QGIS 3.4.2 program.

From the above values, it can be found the height of the stepped weir is 2.65 m, 254.5–251.85 = 2.65 m.

The number of steps and the dimensions of each step are shown in Figs. 5 and 6.

Results and discussion

Discharge measurement

To calculate the discharge overstepped weir an empirical equation adopted from previous studies dealt with depth surface runoff and daily rainstorms (Saadallah 2014):

$$S_r = 0.00015\, R_a^{2.664}, \quad \text{for } R_a \geq 9\,\text{mm} \tag{1}$$

where S_r: surface runoff depth for rainstorm (mm), and R_a: accumulated rain depth for individual rainstorm (mm) from Mosul weather station (N 43° 09′ E 36° 19′) which is 20 km from the weir.

Using daily data on rain depth accumulated for the individual rainstorm for the period (2000–2018) from the Mosul weather station, to calculate the discharge over the stepped weir as the following equation:

$$Q = S_r * A \tag{2}$$

where Q: discharge over the stepped weir (m^3/s), and A: catchment area upstream stepped weir which is taken as 696 km^2 (Saadallah 2014).

The theoretical discharge can be found using the following equation (Radecki-Pawlik et al. 2017):

$$Q = 1.704 * b * H^{3/2} \tag{3}$$

where b: width of stepped weir equal 100 m, and H: water head above stepped weir (m).

To ensure that the weir is broad crested weir, we use the following equation (Varshney et al. 1978):

$$W \geq (1.5 - 3)H \tag{4}$$

where W: width of the crest at the top which is found 1 m.

The data applied on Eq. (4) show that 96.6% checked that the stepped weir is broad crested weir. The relation between water head and discharge is shown in Fig. 7.

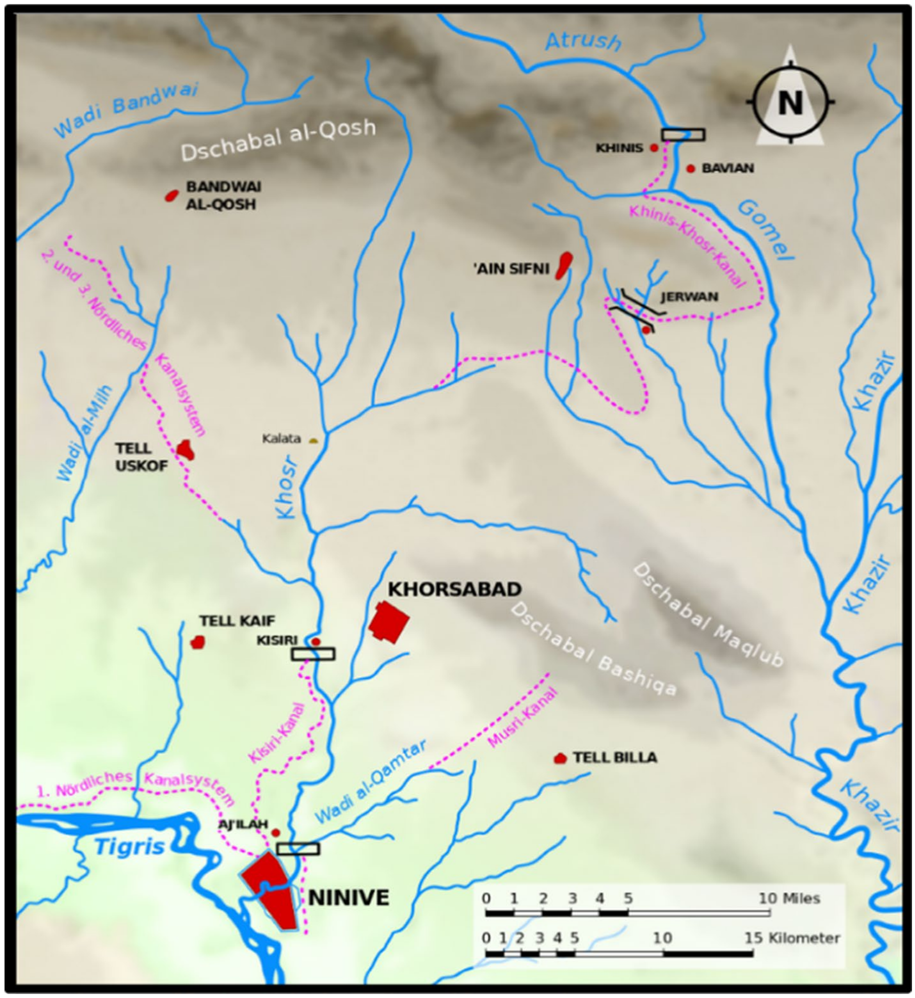

Fig. 1 The location of AL-Khusr River and the surrounding lands

Fig. 2 Front and side view of the stepped weir

Discharge coefficient calculations (C_d)

According to Eq. (4), the stepped weir works as a broad crested weir; then, the broad crested weir equation from previous studies can apply to calculate the discharge coefficient for the stepped weir:

$$C_d = 0.913 + 0.049\left(\frac{H}{W}\right) \quad (5)$$

For $0.1 < \frac{H}{W} < 0.35$ (Govinda Rao and Muralidhar 1963)

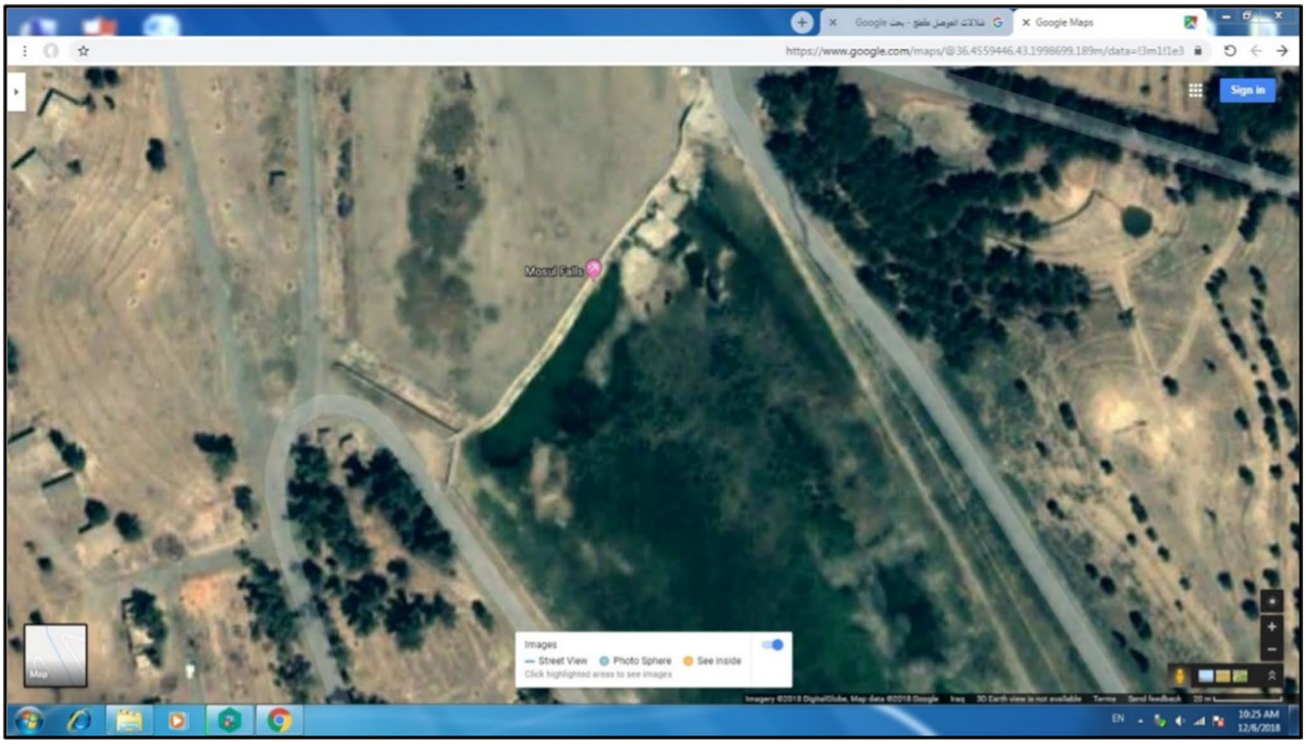

Fig. 3 Measuring the total length of the stepped weir using Google Maps

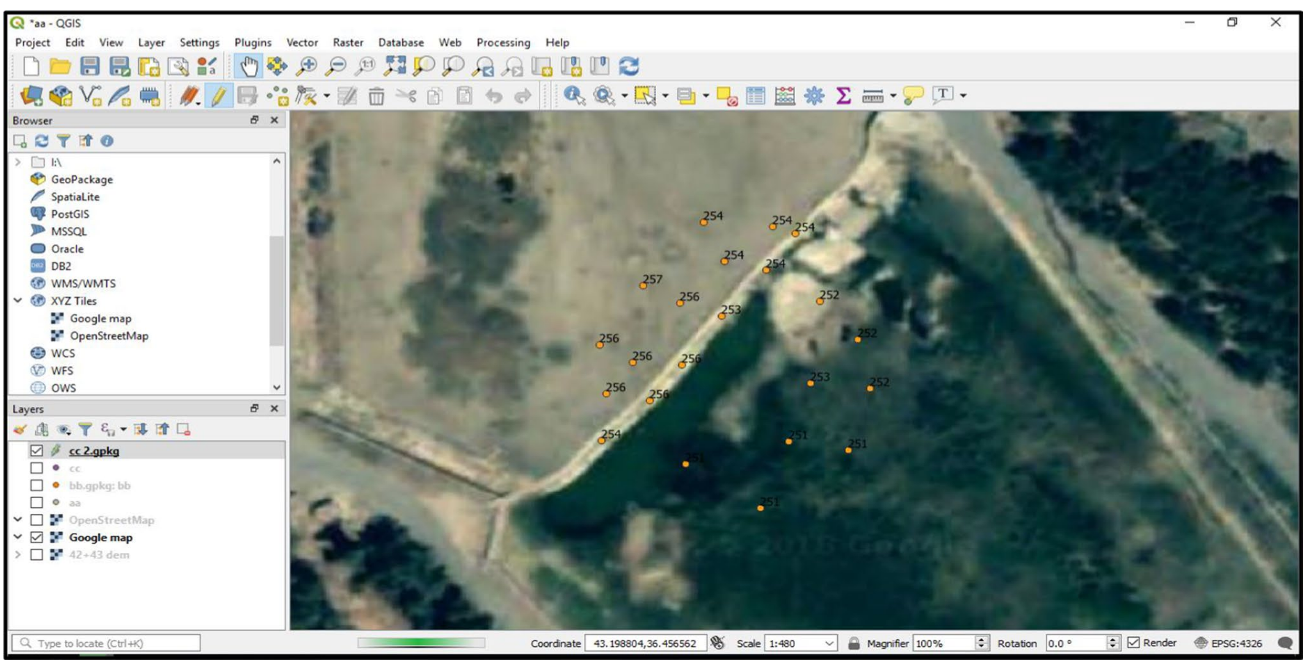

Fig. 4 The stepped weir levels using the QGIS program, 3.4.2

$$C_d = 0.9 + 0.147\left(\frac{H}{H+P}\right) \tag{6}$$

For $0.1 < \frac{H}{W} < 0.4$ (Azimi and Rajaratnam 2009).

where P: total height of stepped weir (m) (Bos 1985)

$$C_d = 0.93 + 0.1\left(\frac{H}{W}\right) \tag{7}$$

Table 1 The levels of stepped weir using the QGIS 3.4.2 program

The sequence	Levels on the crest of the stepped weir (m)	Levels upstream stepped weir (m)	Levels downstream stepped weir (m)
1	254	254	252
2	254	256	252
3	253	256	252
4	256	253	252
5	256	254	251.8
6	254	254	251
7	–	–	251
8	–	–	253
	Average = 254.5	Average = 254.5	Average = 251.85

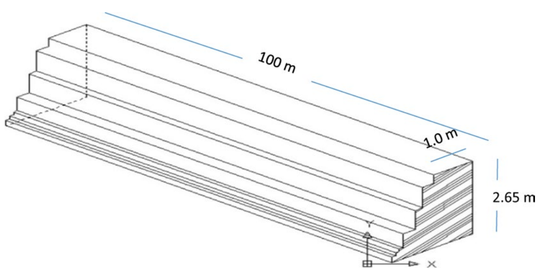

Fig. 5 3D stepped weir, scale 1:10

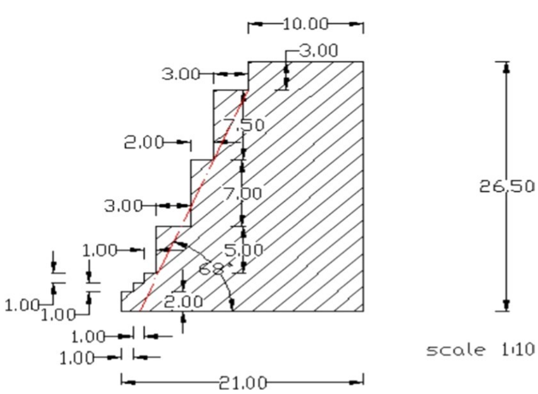

Fig. 6 Stepped weir side view, scale 1:10, all dimensions in cm

$$C_d = 0.87 + 0.038 \ln\left(\frac{H}{P}\right) \tag{8}$$

For $0.52 < \frac{H}{P} < 7$ (Zachoval et al. 2014).

It can calculate four values of the discharge coefficient for broad crested weir from Eqs. (5–8).

The discharge coefficient equation for the present work can be calculated using the theoretical method and depending on statistical programming SPSS ver.11 from Eq. 9

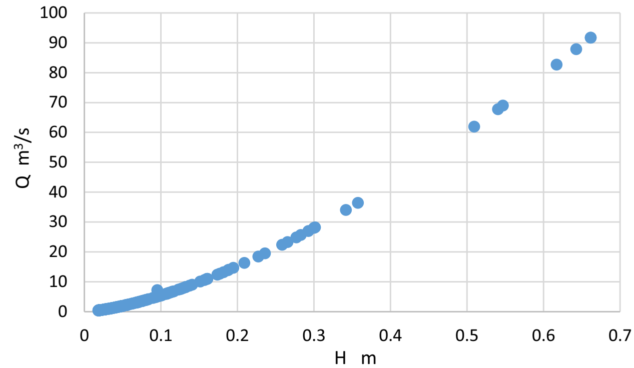

Fig. 7 The relation between head and discharge

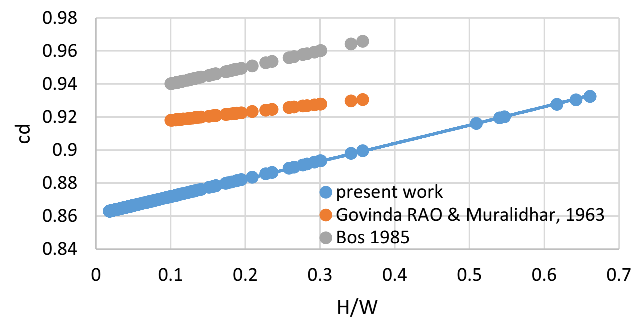

Fig. 8 The relation between discharge coefficient and head to crest width

$$C_d = 0.861 + 0.108\left(\frac{H}{W}\right) \tag{9}$$

For $0.0183 < \frac{H}{W} < 0.661$

The coefficient of determination is $R^2 = 0.906$.

In Fig. 8, it can be seen the discharge values for present work between 0.86 and 0.93, while these values appeared slightly lower than that values calculating using Govinda Rao and Muralidhar (1963) and Bos (1985) equations, by 4.5% and 7.9%, respectively, for the average values of H/W because of the laboratory conditions different from the actual condition of the region and actual weir.

The comparison of the discharge coefficient for present work and that value calculating using different previous studies is shown in Fig. 9. It can be seen that the values calculated in the present work agreed with values calculated from previous studies with percentage error which does not exceed (± 10%), because of the conditions of the natural region different from laboratory conditions. While finding the values, calculating from Zachoval et al. (2014), different from all other values because of their equation different from others by using the logarithmic function, apparently these values are irregular from natural and given percentage error greater than (± 10%).

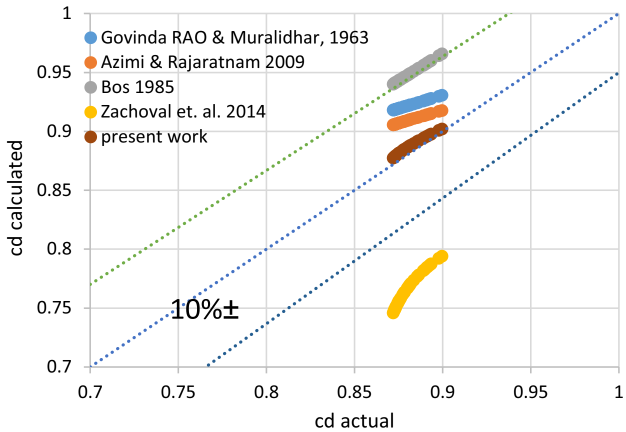

Fig. 9 Comparison between the discharge coefficient in present work and calculated from previous studies

Conclusions

The present work submitted a prototype study for Al-Shalalat stepped weir on Al-Khusr River, to evaluate and study the discharge coefficient. The study dependent on calculated discharge depends on daily rainstorm data for the period (2000–2018) collected, then predicted an equation for the discharge coefficient from a statistical method, and compared with other equations from previous studies. The study showed good agreement for the present equation compared with previous equations with coefficient of determination ($R^2=0.906$) and percentage error which does not exceed 10%. The values of the discharge coefficient for present study lower by 4.5% and 7.9%, respectively, for average values of H/W calculating using Govinda Rao and Muralidhar (1963) and Bos (1985) equations. The weir needs measuring station to get head—discharge measurements to forecast field data in future.

Acknowledgements The author would like to thank Associate Professor Dr. Mohammad E. Mohammad (Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, Luleå, Sweden) for his support and assistance to complete this research.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Azza N. Altalib. The first draft of the manuscript was written by Azza N. Altalib, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding The author(s) received no specific funding for this work.

Compliance with ethical standards

Conflict of interest The author has no conflicts of interest to declare that are relevant to the content of this article.

References

Ali AS, Yousif OSQ (2019) Characterizations of flow over stepped spillways with steps having transverse slopes. IOP Conf Ser Earth Environ Sci 344(1):012019. https://doi.org/10.1088/1755-1315/344/1/012019

Altalib AN, Mohammed AY, Hayawi HA (2019) Hydaraulic jump and energy dissipation downstream stepped weir. Flow Meas Instrum J 69(10):101616. https://doi.org/10.1016/j.flowmeasinst.2019.101616

Ashoor A, Riazi A (2019) Stepped spillways and energy dissipation: a non-uniform step length approach. Appl Sci 9(23):5071. https://doi.org/10.3390/app9235071

Azimi AH, Rajaratnam N (2009) Discharge characteristics of weirs of finite crest length. J HydraulEng 135(12):1081–1085. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000117

Bos MG (1985) Required head loss over the structure. Long-throated flumes and broad-crested weirs. Springer, Berlin, pp 64–89

Chanson H (1995) Energy dissipation on stepped spillways, discussion. J HydraulEng 121(1):80–82

Chatila JG, Jurdi BR (2004) Stepped spillway as an energy dissipater. Can Water Resour J 29(3):147–158. https://doi.org/10.4296/cwrj147

Felder S, Chanson H (2011) Energy dissipation down a stepped spillway with nonuniform step heights. J HydraulEng 137(11):1543–1548. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000455

Gandhi S, Mishra DR (2016) Review on stepped spillway and baffle blocks as energy dissipater in gravity dams. In: 4th international conference on challenges in environmental science and technology, IC-CEST-2016, (March). https://doi.org/10.13140/RG.2.1.4790.6966

Govinda Rao NS, Muralidhar D (1963) Discharge characteristics of weirs of finite-crest width. La Houille Blanche 5:537–545. https://doi.org/10.1051/lhb/1963036

Guenther P, Felder S, Chanson H (2013) Flow aeration, cavity processes and energy dissipation on flat and pooled stepped spillways for embankments. Environ Fluid Mech 13(5):503–525. https://doi.org/10.1007/s10652-013-9277-4

Jahad UA, Al-Ameri R, Das S (2016) Energy dissipation and geometry effects over stepped spillways. Int J CivEngTechnol 7(4):188–198

Krisnayanti DS, Dermawan V (2014) Study investigation of hydraulic model on stepped spillway. In: The third international conference on the sustainable built environment, pp 1–8

Krisnayanti DS, Sholichin M (2015) Calibration measurement on modelling stepped spillway. In: The 1st young scientist international conference of water resources development and environmental protection. Malang, Indonesia, pp 1–8

Krisnayantia DS, Suhardjono S, Dermawan V, Sholichin M (2016) Flow and energy dissipation over on flat and pooled stepped spillway. J Teknol 78(8):79–86

Mohammed AY (2009a). Hydraulic characteristics of free overfall with triangular end lip. In: 33rd IAHR congress: water engineering for a sustainable environment, pp 1188–1199. ISBN: 978-94-90365-01-1

Mohammed AY (2009b) Effecting of channel slope on flow charactarestics for straight vertical and skew free overfall. Alrafiden J CivEng 17(1):80–90

Mohammed AY (2012) Theoretical end depth ratio and end depth discharge relatioship for free overfall with differentend lip shape. Jordan J CivEng 6(4):410–417

Nasiralla Al-Talib A, Abd Al-MajeedHayawi H (2009) Laboratory study of flow energy dissipation using stepped weirs. AL-Rafdain Eng J 17(4):42–51

Parsaie A, Haghiabi AH, Saneie M, Torabi H (2016) Prediction of energy dissipation on the stepped spillway using the multivariate adaptive regression splines. ISH J HydraulEng 22(3):281–292. https://doi.org/10.1080/09715010.2016.1201782

Patil LG, Jadhav SS (2017) Performance evaluation of stepped spillway under nappe flow condition. Int Adv Res J Sci Eng Technol 4(1):111–114. https://doi.org/10.17148/iarjset.2017.4126

Radecki-Pawlik A, Pagliara S, Hradecky J (2017) Open channel hydraulics, river hydraulic structures, and fluvial geomorphology: for engineers, geomorphologists, and physical geographers. CRC Press, Boca Raton

Reeve DE, Zuhaira AA, Karunarathna H (2019) Computational investigation of hydraulic performance variation with geometry in gabion stepped spillways. Water Sci Eng 12(1):62–72. https://doi.org/10.1016/j.wse.2019.04.002

Saadallah AM (2014) Application of the SWAT model for estimating the sediment load connected to the Tigris River from the Khusr River. M.Sc. thesis submitted to Dams and Water Resources Dept. The University of Mosul

Shahheydari H, Nodoshan EJ, Barati R, Moghadam MA (2015) Discharge coefficient and energy dissipation over stepped spillway under the skimming flow regime. KSCE J CivEng 19(4):1174–1182. https://doi.org/10.1007/s12205-013-0749-3

Tawfiq AR (2013) Dynamic coincidental model for operating a dam reservoir based on the Khusr River. M.Sc. thesis submitted to Dams and Water Resources Dept. The university of Mosul

Varshney RS, Gupta SC, Varshney RS, Gupta RL (1978) Theory and design of irrigation structures, vol 1. New Chand Book, Roorkee

Younis AA (2012) The Khusr river in cuneiform. AL-RafdainArcheol 1(1):158–176

Zachoval Z, Knéblová M, Roušar L, Rumann J, Šulc J (2014) Discharge coefficient of a rectangular sharp-edged broad-crested weir. J HydrolHydromech 62(2):145–149. https://doi.org/10.2478/johh-2014-0014