Remodelling labyrinth weir geometry to increase performance

M. Ben Saïd and A. Ouamane, Laboratory of Hydraulic developments and Environment, University of Biskra, Algeria

Flood control remains a major concern for dam designers and operators. This concern has grown in recent decades as a result of climate change and the development of new methods for extreme flood estimation, which have shown the inadequacy of a significant number of spillways to evacuate increased extreme floods. Consequently, dam operators are seeking solutions that can increase the capacity of existing spillways and provide more efficient spillways for new dams. One possible solution is the remodelling of the existing spillway in non-rectilinear form and the adoption of this type of spillway for new dams. This article presents some standard labyrinth weir shape enhancements, which can have a positive impact on economic and hydraulic performance.

The labyrinth weir has been the subject of studies and applications for several decades, with trapezoidal and triangular plan form and vertical walls. However, other forms can also be beneficial from a hydraulic and economic point of view. The rectangular plan form, which seems to be simple and economical, has only been studied and applied in a few cases. The front wall has always been designed with a flat shape, and this generates flow disturbances.

The choice of a profiled shape of the inlet promotes a stable flow, which leads to better performance. The labyrinth weir design with overhangs, like the Piano Key Weir, can be used on gravity dam crests. The experimental study carried out on nine labyrinth weir models confirmed the performance improvement of this type of weir by the adoption of an improved form of the labyrinth.

1. Introduction

Labyrinth weirs are often designed with triangular or trapezoidal shapes in plan, with vertical walls. However, the rectangular shape can also be more effective from a hydraulic and structural point of view. This is the case with the spillway at the Bakhadda dam in Algeria, which has an interesting shape based on almost rectangular elements with inclined front walls and a curvilinear alignment.

The spillway of the Bakhadda dam was designed in 1962 after the dam had been heightened by 5 m. The maximum flood flow is estimated at 2000 m^3/s, discharged under a head of 1.25 m and the spillway width is 138.5 m. The evacuated discharge is thus around 4.6 times that of a standard weir. The increased discharge capacity is a result of the non-linear labyrinth elements' shape and their alignment, which is curvilinear, see Photo (a).

(a) Spillway at the Bakhadda dam in Algeria.

The labyrinth weir therefore offers an efficient alternative from a hydraulic and even an economic point of view; it is characterized by a non-linear shape in plan-view represented by geometric repeats, typically trapezoidal, triangular or rectangular. This configuration enables the crest length to be increased significantly.

The most important parameters in determining the linear weir capacity are the height, the crest shape, and the crest length [Falvey *et al.*, 1995[1]]. However, the labyrinth weir capacity depends on several geometric parameters, which make it difficult to solve the problem mathematically [Lux III *et al.*, 1985[2]].

Several studies have been carried out to identify the geometric parameters that affect the performance of a labyrinth weir, including the experimental work of Gentilini [1940[3]] and Kozák *et al.* [1961[4]], later an extensive investigation was conducted by Taylor [1968[5]] and Hay and Taylor [1970[6]], which proposed a design procedure for a labyrinth weir with a triangular and trapezoidal form.

Other studies have been carried out by the USBR, the results of which have been discussed by Hinchliff *et al.* [1984[7]] and Lux *et al.* [1985[2]]. These works were complemented by numerous experimental studies carried out at the University of Utah by Tullis *et al.* [1995[8]] who developed a simplified design method using the standard weir equation.

A recent study conducted by Ouamane and Lemperiere [2013[9]] has shown that the labyrinth weir with a rectangular plane form can be as efficient as the trapezoidal shape, especially for heads H^*/P of less than 0.5.

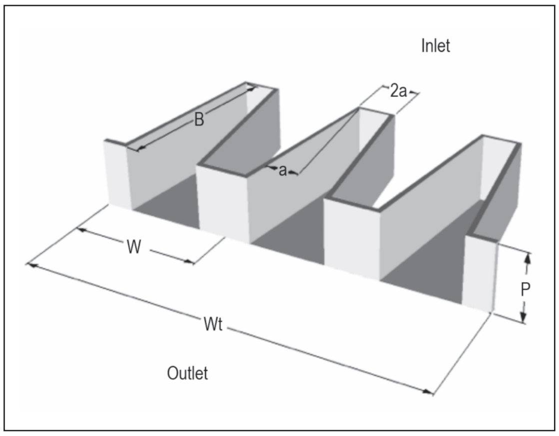


Fig. 1. Main geometrical parameters of a labyrinth weir.

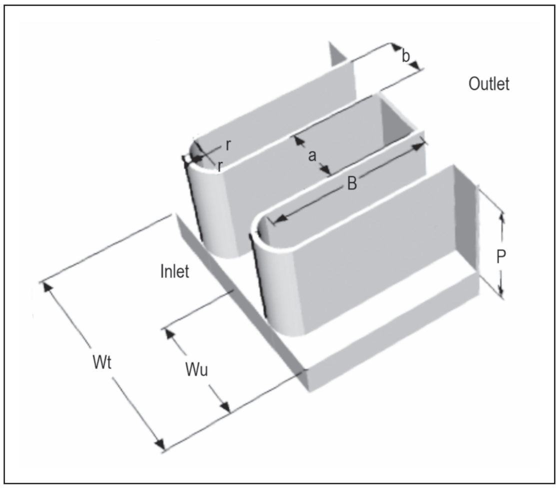


Fig. 2. Rectangular labyrinth weir in plan form with profiled entrance.

The purpose of this article is to present some standard labyrinth weir shape enhancements, which can have a positive impact on economic and hydraulic performance.

2. Enhancing performance by remodelling the labyrinth shape

Until now, most of the constructed labyrinth weirs have been designed with vertical walls, a horizontal bottom and a flat entrance, but this is not always justified from a hydraulic and structural point of view. Therefore, some modifications of the geometry seem to be possible to increase the discharge at the same cost and make the choice of a labyrinth weir more economical, when the wall height is more important.

Thus, the choice of labyrinth cycles in rectangular form enable an easy-to-build structure, improved hydraulic efficiency and the possibility to enlarge or reduce the width of upstream and downstream alveoli, simply by the displacement of the parallel side walls, without additional expense, to obtain the best performanc (see Fig. 2).

The adoption of a rounded entry shape instead of a flat shape (see Fig. 2), allows for a reduction in upstream flow disturbances thus ensuring the stable flow conditions at the weir entrance, which enhances hydraulic efficiency. The design of the labyrinth spillway with part of its crest shaped as an overhang enables this type of weir to be installed with a limited footprint and allows the apron length to be reduced (similar to those of the Piano Key Weir). The labyrinth weir may have only upstream or downstream overhang or both upstream and downstream overhangs. The choice of the number and arrangement of the overhangs depends on the specific site conditions (see Fig. 3).

3. Experimental programme

The experiment was carried out in a rectangular section of channel, 1 × 1 m wide and deep, and 12 m long. (see Fig. 4). The experimental system is equipped with two pumps, which deliver up to 180 l/s.

The discharges are measured using two flowmeters, one ultrasonic and the other electromagnetic. The water depths in the channel are measured by a series of ultrasonic level sensors. The assembly operates within a closed circuit. Tests were carried out on nine models of labyrinth spillways and were constructed from sheet metal 2 mm thick, with heights of 15 and 20 cm (see Table).

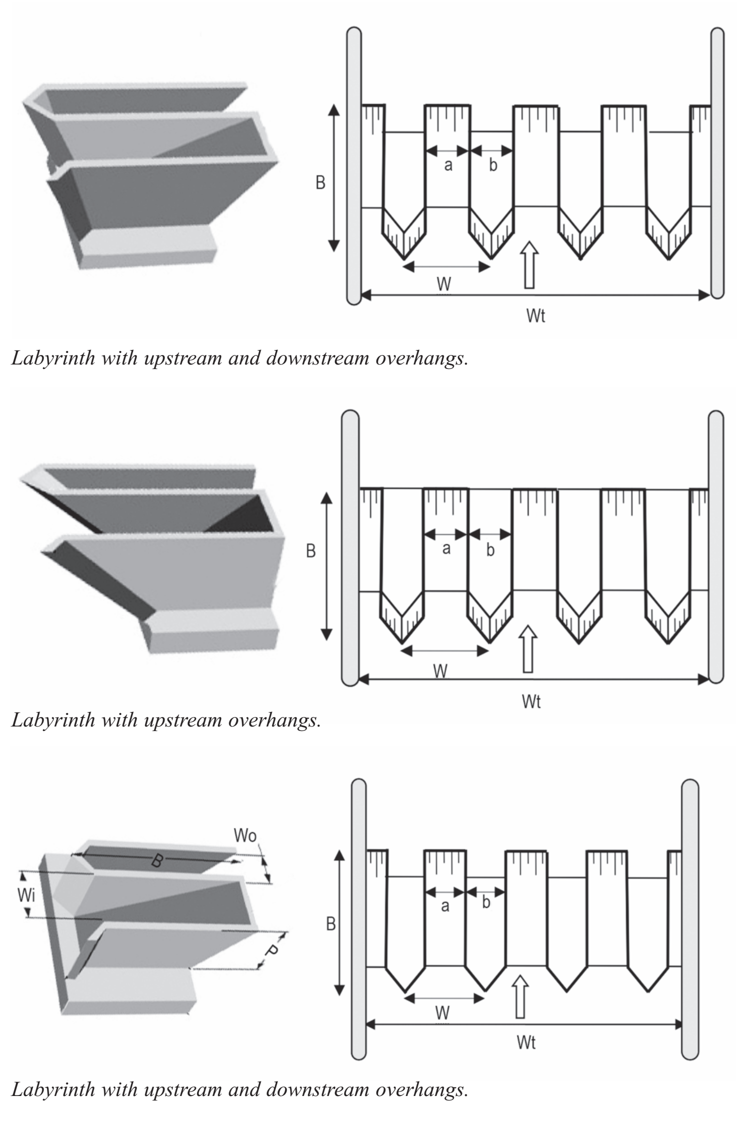


Fig. 3. Rectangular labyrinth weir in plan-view with various overhangs positions.

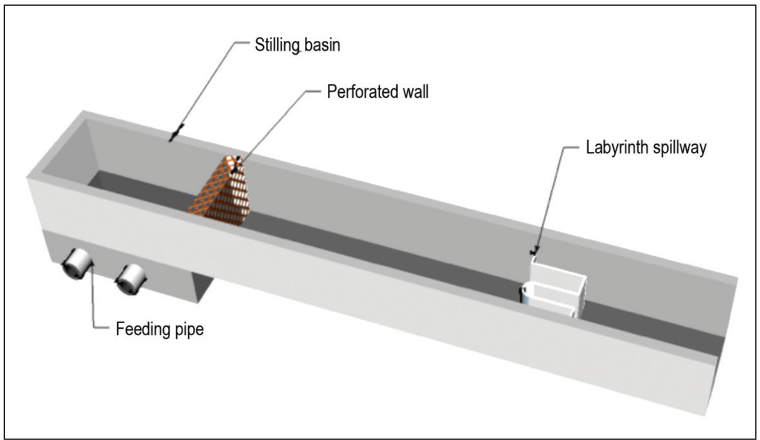


Fig. 4. Experimental channel layout of the models.

Characteristics of models														
Model	n°	*n*	*L* (cm)	*Wt* (cm)	*P* (cm)	*B* (cm)	W_u (cm)	*a* (cm)	*b* (cm)	*r* (cm)	*L/Wt*	*W/P*	*a/b*	*B/P*
Round	1	6	353	91.8	15	25	15	8.5	6.5	3.25	3.85	1	1.3	1.66
Round	2	6	355	90.8	15	25	15	9	6	3	3.91	1	1.5	1.66
Round	3	6	353	92.3	15	25	15	9.3	5.7	2.85	3.91	1	1.63	1.66
Flat	4	6	353	90.3	15	25	15	9	6	3	3.91	1	1.5	1.66
Round	6	6	442	90	15	34.5	15	9	6	3	4.91	1	1.5	2.3
Trapezoidal	5	6	470	90	15	36.5	15	-	-	-	5.22	1	-	2.43
With upstream and downstream overhang	8	4	494	99.2	20	50	25	13.5	11.3	-	4.98	1.25	1.2	2.5
With upstream overhang	9	4	502	99.2	20	50	25	13.5	11.3	-	5.06	1.25	1.2	2.5
With downstream overhang	10	4	496	99.2	20	50	25	13.5	11.3	-	5	1.25	1.2	2.5

4. Results and discussions

4.1 Comparison of the rectangular and trapezoidal labyrinth forms

Previous studies on labyrinth weirs have generally focused on the trapezoidal form. However, only limited studies on the rectangular shape have been reported. The work of Ouamane and Lempérière [2013[9]], noted that the rounded rectangular labyrinth is more efficient compared with trapezoidal labyrinth weirs, especially for relative heads (*H/P* <0.5). To verify this finding (the rectangular shape efficiency compared with the trapezoidal shape), two models were tested for a ratio of *L/W* equal to 5.

Tests conducted on these two configurations have shown that the rectangular form performance is around 5 per cent greater than the trapezoidal shape for values of $H^*/P < 0.5$. Beyond this limit, the trapezoidal shape becomes more efficient than the rectangular shape up to 7 per cent. This can be seen on the two discharge coefficient curves shown in Fig. 5. This observation may be attributed to the downstream width of the alveoli, which for the rectangular shape stays constant along the downstream alveoli and increases for the trapezoidal shape, especially for large values of H^*/P. The downstream alveoli of the labyrinth can thus have a significant effect on its performance.

Geometrically, for the trapezoidal form, the increase of the *L/W* ratio increases both the side wall length and the alveoli width in a proportional manner, thereby making it possible to contain a volume of water greater than the rectangular form; this is an interesting solution for high heads. Therefore, a high level of hydraulic performance is achieved for large H^*/P values. However, the labyrinth weirs are designed to operate under low heads (H^*/P <0.5). It should also be noted that the design of the trapezoidal shape must take into account, on the one hand, the local site conditions which should be sufficient, and on the other hand the economic aspect. However, the gain in performance achieved by the use of a weir with increased dimensions may result in increases in the volume of materials required for construction, which might not be justified for the extra structural costs involved.

Based on these findings, it may be more convenient and cost effective to adopt the rectangular labyrinth, which has a reduced length *B* (parallel to the flow direction), thus allowing for reduced dimensions of the labyrinth base and increased the hydraulic performance with lower costs.

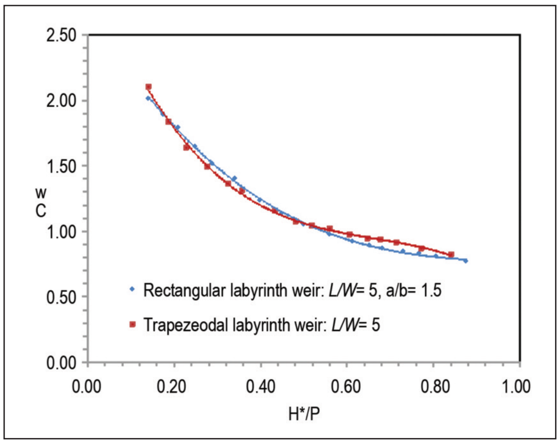


Fig. 5. Effect of the plan shape on the performance of the labyrinth.

4.2 Alveoli width *a/b*

The labyrinth weir efficiency mainly depends on the width of the inlet and outlet alveoli.

The choice of making the inlet alveoli wider than the outlet alveoli for the rectangular plane form may cause saturation of the the outlet alveolus, making it unable to evacuate all the dischagre that passes through the inlet alveoulus; this causes a reduction in hydraulic performance. It is possible that an optimum exists between the width of the inlet and outlet alveoli.

Ben Said and Ouamane [2011[10]] indicated that the optimal value of the a/b ratio is close to 1.5. The choice of a width of the inlet alveoli equal to 1.5 times the width of the outlet enables an increase in efficiency of up to 10 per cent compared with a symmetrical configuration (*a/b* = 1) and around 20 per cent higher than the model with an *a/b* ration equal to 0.66 [Ben Said and Ouamane, 2011[10]].

Three models of rounded rectangular labyrinth weirs were tested, to help identify the optimal value. These models have the same ratio *L/W* = 4 and the same geometry, with the exception of the alveoli width, which is represented by the ratio *a/b* = 1.3, 1.5, and 1.63, that is, the values either side of the previously determined value [Ben Said and Ouamane, 2011[10]].

For an *L/W* equal to 4 (see Fig. 6), and for low and moderate heads, no significant change in the efficiency of the evacuation was observed for the three ratio a/b values. However, for relative heads higher than

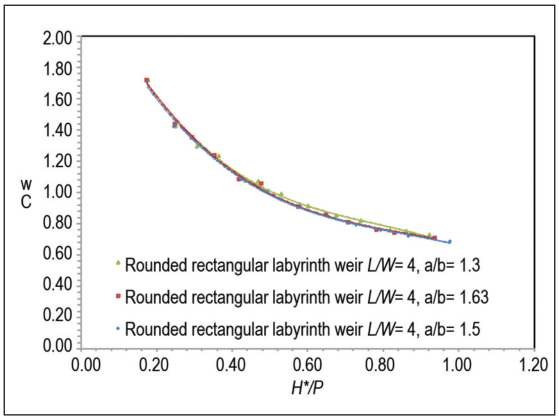


Fig. 6. The effect of the alveoli widths ratio on the discharge coefficient for L/W = 4.

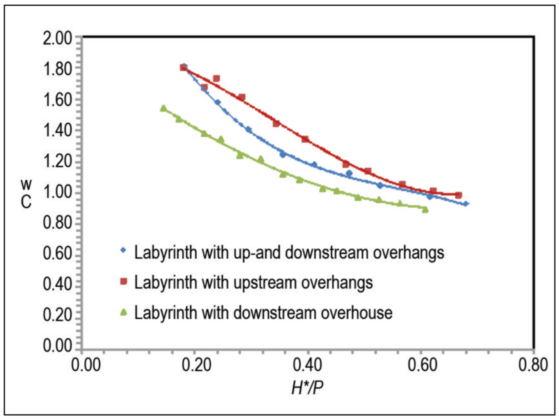


Fig. 7. Effect of the overhangs geometry.

0.5, only the labyrinth with ratio a/b equal to 1.3 resulted in a slight increase in performance (2 per cent) compared with ratios 1.5 and 1.63.

Thus, it can be concluded that the optimal value between the inlet alveoli width and outlet alveoli width is in the range of 1.3 to 1.5.

The effect of the ratio a/b on the weir efficiency can be explained by the fact that as this ratio increases, the inlet cross section also increases, allowing the passage of the greatest discharge in the inlet alveoli, thus offering the best operation of the labyrinth weir.

However, for the highest values of the ratio a/b (> 1.6), the space in the alveoli of the outlet will be insufficient to accommodate the discharge passing through the inlet alveoli; this generates considerable interference with the opposite side, which leads to a reduction in the effective length of the lateral crest, and thus the global weir efficiency.

4.3 Design of the crest overhangs

The presence of the overhangs and the inclination of the apron of the alveoli are the main differences between the geometry of the labyrinth weir and the piano key weir (PKW). These two criteria allow for construction of the PKW on a smaller base, increasing the nappe stability and the weir efficiency. Therefore, the overhangs are an interesting option for labyrinth weir design. To verify the potential of the overhangs for the labyrinth weir, three overhang arrangements were tested: with upstream and downstream overhangs (symmetrical); with only upstream overhangs; and, with only downstream overhangs (see Fig. 3).

The analysis of the experimental results showed that the model with only upstream overhangs represented an efficient variant from a hydraulic efficiency point of view, compared with symmetrical overhangs. The increase in discharge efficiency is around 15 per cent compared with the symmetric configuration but this efficiency decreases with increasing head to reach 2 per cent for a H^*/P ratio approximately equal to 0.8.

However, using only downstream overhangs decreases the weir efficiency by up to 13 per cent compared with the symmetrical overhangs model (see Fig. 7).

As the upstream part of the weir crest is mainly supplied by the transverse inlet section, using the longest possible upstream overhang enables the inlet cross section to be increased, and thus the weir capacity.

During the experimental tests, a water surface elevation at the inlet entrance was observed. It begins at relative heads H^*/P equal to 0.4. The model without upstream overhangs is largely influenced by this elevation. However, a model with only upstream overhangs provides a quasi-horizontal surface water for all ratios of H^*/P.

The use of the longer overhangs upstream reduces the length. However, it increases at the same time the bottom slope of the upstream alveoli, which reduces the flow contraction and energy losses, and so improves the orientation of the flow lines to the inlet alveoli and thus the weir efficiency.

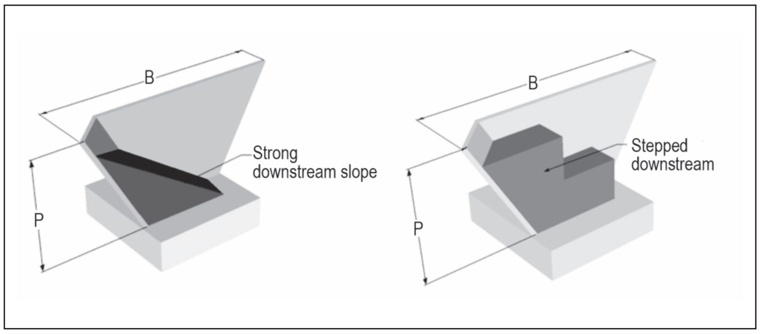
4.4 Downstream alveoli: influence of the base shape

The non-linear weirs are characterized by a high specific discharge, which makes their use more economical compared with standard weirs. However, for large discharges, which require a higher wall height, this advantage may be lost as a result of the increased cost of construction. To reduce the construction costs of the high walls, it is possible to decrease the free part of the vertical walls and reduce the volume of steel-reinforced concrete. This can be achieved by partial filling of the downstream alveoli with ordinary concrete. That reduces the free part of the walls and provides a sufficient height of the weir walls. In this context, two filling types of the downstream alveoli have been proposed for a labyrinth weir model with only upstream overhangs, a ratio L/W = 5, a total height P = 20 cm and a cycle number n = 4.

The first type is an inclined bottom shape and the second is in the form of a stepped downstream section.

For the inclined form, the results obtained show that the hydraulic efficiency of the weir with and without filling is generally very close for relative heads H^*/P higher than 0.25. However, for relative heads less than 0.25, the downstream inclined bottom model efficiency is higher than the horizontal bottom (without filling) as can be seen in Fig. 8. This can be explained by

Fig. 8. The two partial filling layouts of the downstream alveoli.



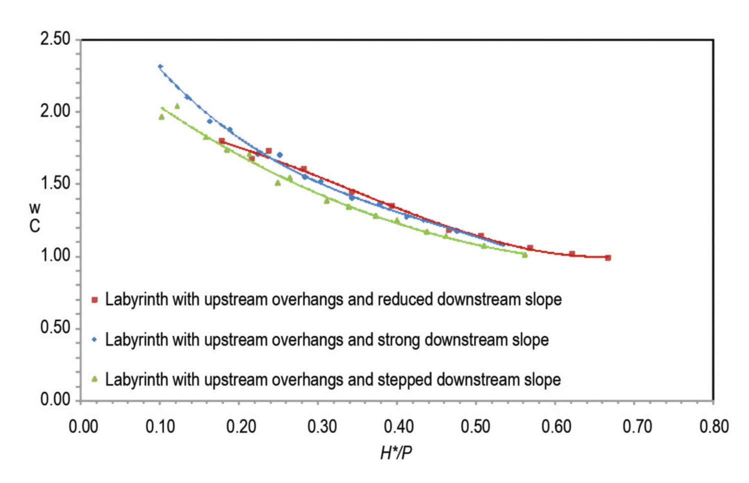


Fig. 9. Downstream alveoli bottom shape influence.

the partial filling of the alveoli, which facilitates the discharge stability (undisturbed flow), providing increased hydraulic performance of the labyrinth weir.

The second type of the downstream alveoli bottom shape corresponds to filling of the downstream with a stepped shape (two steps, 8.5 cm high for each step). The advantages of this solution are the reduction in cost of construction, and potentially enhanced energy dissipation. The results of the tests (see Fig. 9) have shown that the use of a stepped downstream section may influence the performance of the labyrinth weir, resulting in a discharge coefficient reduction, in comparison with the two cases described above (discharge coefficient reduction of around 5 to 7 per cent for the full relative head range H^*/P). It should be noted that the filling height of the first step reaches 4/5 of the downstream alveoli height.

4.5 Influence of the labyrinth entrance shape

The inlet form has always been an important parameter influencing the hydraulic structure's efficiency, particularly the weirs. It is interesting to determine the best inlet shape in term of the hydraulic performance. In this context, two models with different inlet forms were tested, the first with a flat inlet shape and the second having a rounded inlet shape, both models having the same geometric characteristics.

The experimental results obtained for a ratio a/b equal to 1.5 have shown that the labyrinth design with rounded inlet shape improves the hydraulic efficiency compared with the flat inlet shape. Thus, for H^*/P = 0.3, the weir discharge coefficient with a rounded inlet shape is around 12 per cent more efficient than the model with a flat inlet. However, this advantage decreases progressively to reach 5 per cent for a relative head H^*/P equal to 0.8.

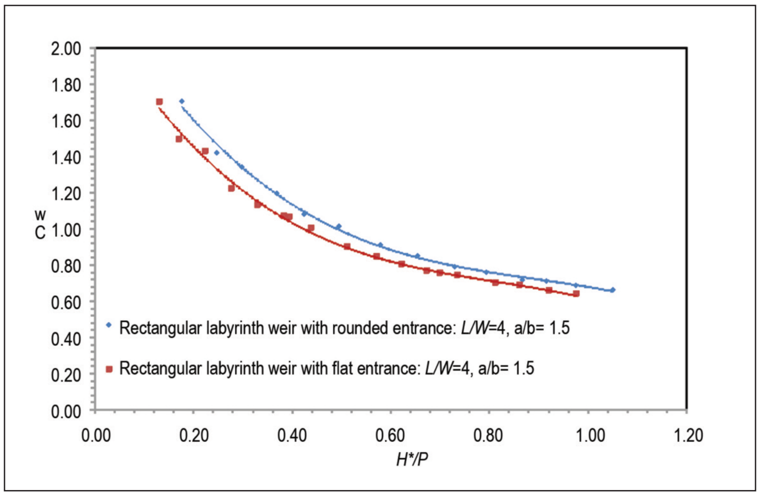


Fig. 10. The inlet shape influence on discharge coefficient.

5. Conclusion

Weir efficiency improvements have always been a concern for dam designers. Although the labyrinth weir represents an effective alternative to evacuate large discharges, some enhancements of the geometry can have a positive impact on the hydraulic efficiency and lead to a reduction in construction costs.

Some remodelling suggestions for labyrinth weirs have been presented in this paper. These proposals were verified experimentally, which led to the following conclusions:

- The choice of a rectangular plan form instead of a trapezoidal, enables an increase in hydraulic performance up to 5 per cent for H^*/P values <0.5, which corresponds to relative heads used in practice.
- The optimum performance for a rectangular labyrinth is obtained from a ratio between the width of the upstream and downstream alveoli a/b of between 1.3 and 1.5. The choice of the upstream width equal to 1.5 times the downstream width increases the gain in efficiency by around 10 per cent compared with the symmetrical configuration (a/b = 1).
- The labyrinth weir design with overhangs increased hydraulic performance by up to 15 per cent for a range of $H^*/P < 0.5$. The labyrinth design with only upstream overhangs seems to be the most efficient variant.
- To reduce the cost of the weir designed with high walls, it is possible to decrease the height of the free part of the vertical walls and therefore reduce the quantity of steel-reinforced concrete required. This can be achieved by the partial filling of the downstream alveoli with ordinary concrete. In this context, two filling types of the downstream alveoli have been proposed in the form of a slope or stepped downstream.
- A slope does not affect the hydraulic performance of the labyrinth and reduces materials costs.
- The labyrinth design with a rounded inlet shape enables an increase in discharge capacity of up to 12 per cent.
- The labyrinth design with the adopted results increases the hydraulic performance by more than 30 per cent compared with the performance of a classic labyrinth. ◊

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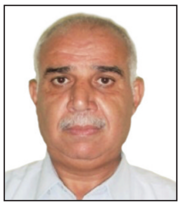
M. Ben Saïd has been a Researcher in Hydraulics and Civil Engineering since 2009 in the Scientific and Technical Research Center on Arid Regions, University of Biskra. He is a Researcher in the Laboratory of Hydraulic planning and Environment of Biskra University.

Prof A. Ouamane has been a lecturer in the Hydraulic Department at Biskra University in Algeria since 1986. He is Director of Research in the Laboratory of Hydraulic Planning and Environment. He has conducted various theoretical and experimental studies on shaft weirs, labyrinth weirs, PK Weirs, fuseplugs and CIS (combining innovative spillways). He is an innovator of Piano Key Weirs with M. François Lempérière.

Laboratory of Hydraulic Developments and Environment, University of Biskra, BP 918 RP, Biskra 07000, Algeria.

M. Ben Saïd



A. Ouamane