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Hydraulic operation of the outlet works for the Lom Pangar dam in Cameroon

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ABSTRACT

This paper shows that the outlet works is able to contain the water evacuated by the spillway and regulate the speed to acceptable standards thus avoiding downstream erosion. The Numerical modelling was carried out using the HEC-RAS software of the US Army Corps of Engineers (USACE) and verifies the restitution capacity of the three flow- regulation sluices equipped with gates. The restitution takes place through the loss of energy as the water flows from the spillway through the sluices, the gates, the hydraulic bucket and finally into the river downstream.

Keywords: Restitution, outlet works, bucket, hydraulic jump, energy loss, Lom Pangar.

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INTRODUCTION

Lom Pangar is a dam in the Eastern Region of Cameroon and its water is used in the regulation of the downstream water level during the dry season for the Sanaga River. Outlet works consists of a combination of structures designed to control the release of water from the reservoir as required for project purposes or operation. The components of outlet works starting from the upstream end typically consist of an approach channel, an intake structure, a conduit or a tunnel, a control gate chamber (located in the intake structure, within the conduit at the downstream end of the conduit), an exit chute, an energy dissipater, and a discharge channel. Outlet works are frequently used to pass diversion flows during construction, regulate flood flows, aid in emptying the reservoir in an emergency condition, and permit reservoir lowering for inspections and special repairs. The sizing of the outlet works should take into account the possibility of using it to reduce the size or the frequency of spillway discharges. The necessity of emergency drawdown capability and low flow discharge capability should be considered during the outlet works planning phase. The selection of type and arrangement of outlet works structures should be based upon consideration of the costs of operation and maintenance likely to be incurred during the project life. Reliability under emergency flood conditions is the fundamental operational requirement of the outlet works facilities.

HYDRAULIC FUNCTIONING OF THE SLUICES

Description of the structure

For the restitution of flood, the dam is equipped with a surface three sluice gates as follows:

- 2 radial sluice gates of section 5.90 m × 4.0 m each, the bottom is fixed at altitude 642.95 CGL
- 1 radial sluice gate of section (3.0 m × 2.0 m), the bottom is fixed at altitude 643.50 CGL.

For each of the two large downstream sluices gates the flow speed at maximum overture is calculated with respect to the centre of the gate (Mason, 1993):

$$V_d=\sqrt{2gh} \tag{1}$$

Where h is the difference between the height of the reservoir and altitude 640.95CGL

When energy loss is taken into account, it will lead us to take a flow coefficient of 0.67 (Bollaert, 2004).

The orifice law is written as (Mason and Arumugam, 1985):

$$Q_{real} = 0.67 \times V_d \times S \qquad (2)$$

Where, S is the surface area of the sluice gates.

For the small sluice gate which is fixed at 643.50CGL, the flow velocity is calculated also with respect to the centre of the sluice gate:

$$V_d = \sqrt{2gh}$$

Where h is the height difference between the reservoir height and 645CGL.

When the loss of energy is taken into account, the flow coefficient is equal to 0.68 (Bollaert, 2004).

The orifice law is written as (Mason and Arumugam, 1985):

$$Q_{real} = 0.68 \times V_d \times S$$

Where S is the surface area of the sluice gates.

Restitution capacity

The different possible restitution capacity when the gates are fully opened, are presented in Figure 1.

The total restitution capacity of the gates is 860 m^3/s at normal reservoir level with the small gate accounting for 95m^3/s.

Energy loss at the sluice gates

At the passage of a sluice gate the water contracts to the size of the overture as illustrated in Figure 2.
With:

$$a_r = \frac{a}{a_o} \quad \text{being the relative overture} \qquad (3)$$

$$\eta = \frac{a_c}{a} = \frac{1}{1+\sqrt{C(1-a_r^2)}} \quad \text{coefficient of contraction} \qquad (4)$$

The coefficient of energy loss K is defined as follows:

$$K = K_1 + K_2 = K_1 + \left[\frac{1}{\eta . a_r} - 1\right]^2 \qquad (5)$$

Where, K_1 is the coefficient of energy loss for a sluice gate that is completely open.

The parameters of the variant C can be obtained with the help of Figure 3.

Performances of the flood discharge gates

Calculations relative to the amount of water that can be evacuated by the flood discharge gates are done by determining the singular and regular loss of energy along the water channel. By applying the Bernoulli theorem between a section situated upstream in the reservoir and a contracted section downstream at the sluice gates, we

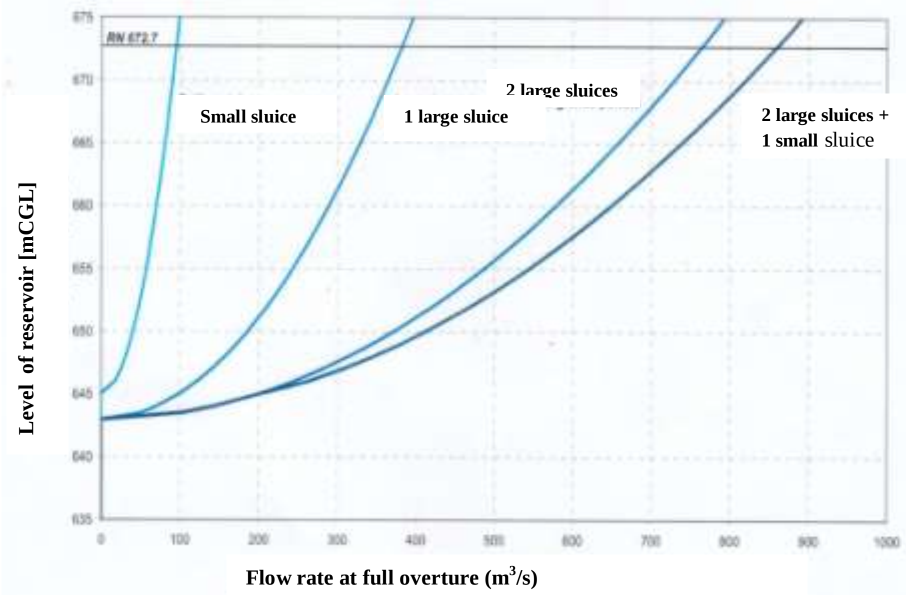

Figure 1. Restitution capacity of the gated sluices.

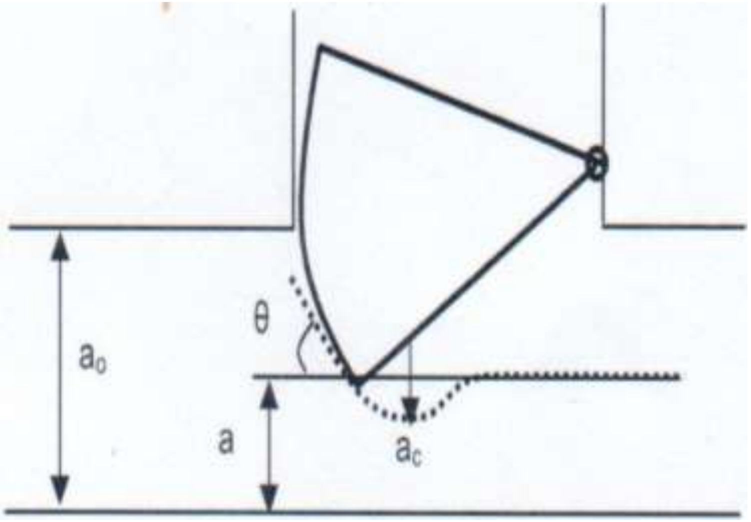

Figure 2. Flow under a guard gate.

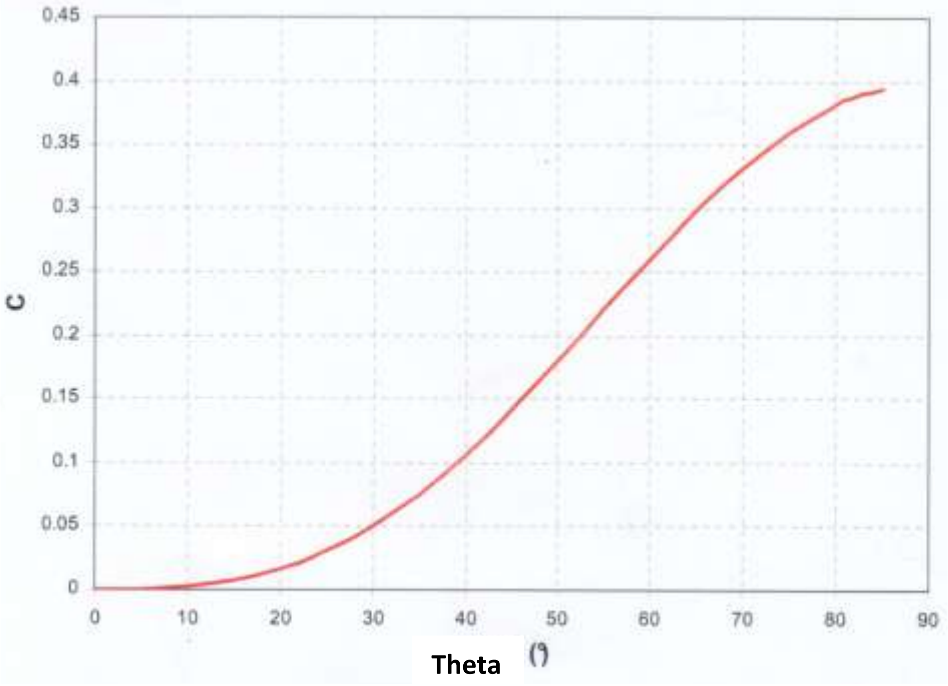

Figure 3. Evolution of the variant C as a function angle θ.

obtain (Genetti, 1990; Chanson, 2004):

$$Z_{upstream} - Z_{downstream} = j_1 + j_2 + j_3 + j_4 + j_5 + \frac{V_c^2}{2g} \qquad (6)$$

Where:
$Z_{upstream}$: water level in reservoir
$Z_{downstream}$: water level at the contracted section downstream
V_c: speed at the contracted section
j_1 to j_5: progressive loss of charge explained here after;

The different loss of energy is as follows:

j_1: loss of energy at the entrance of the gallery (upstream entrance)

$$j_1 = 0.5 \times \left({}^{Q}/_{S}\right)^2 / 2\,g \qquad (7)$$

Where:
Q (m^3/s): flow rate
S = 41.3 m^2: surface area of the two large guard gates of

the large sluices
$S = 7$ m^2: surface area of the small guard gate
j_2: regular loss of energy in the channel

$$j_2 = L \times (Q/S)^2 / (K^2 \times R_H^{4/3}) \qquad (8)$$

Where:
Q (m^3/s): discharge flow rate
$S = 41.3$ m^2: surface area of the two large guard gates
$S = 7$ m^2: surface area of the small guard gate
$K = 70$: Manning–Strickler coefficient for hydraulic concrete
$L = 26$ m: length of gallery
$R_H = 2.58$: hydraulic radius of the large sluices
$R_H = 0.78$: hydraulic radius of the small sluice

j_3: energy loss at the passage of the groove and bottom furrow of the guard gates (Davis, 1973; Steiner et al., 2008):

$$j_3 = 0.4 \times (Q/S)^2 / 2\,g \qquad (9)$$

Where;
$S = 41.3$ m^2: surface area of the channel of the two large guard gates
$S = 7$m^2: surface area of the channel small guard gate

J_4: energy loss at the convergent zone upstream of the guard gate ((Davis, 1973; Steiner et al., 2008):

$$j_4 = (1 - \tfrac{S'}{S}) \times (Q/S)^2 / 2\,g \qquad (10)$$

Where:
$S = 41.3$ m^2 surface area of the channel of the two large guard gates
$S' = 24.3$ m^2 surface area of channel of the two large gates
$S = 7$m^2 surface area of the channel of the small guard gate
$S' = 6$m^2 surface area of the channel of the small gate

j_5: loss of energy at the passing of the gate (Davis, 1973; Steiner et al., 2008):

$$j_5 := K \times (Q/S'')^2 / 2\,g \qquad (11)$$

Where:

S''	contracted section at downstream of gate
$K = K_1 + K_2$	global coefficient of energy loss
$K1 = 0.3$	coefficient of energy loss for a completely open gate

Synthesis of results

Large sluices

The results obtained for a total overture of the gates correspond to the orifice law with a flow coefficient of 0.71.

With the previous knowledge, the orifice law is written as (Roth and Hager, 1999; Steiner et al., 2008):

$$Q = 0.71 \times S\sqrt{2g \times (Z_{upstream} - 640 - \tfrac{a}{2})} \qquad (12)$$

On a conservative basis, the coefficient of flow has been reduced 5%, a coefficient of 0.67. The associated curve is represented with non-continuous lines in Figure 4.

Small sluice

The principle of representation is identical to that used for the large sluice. The associated orifice law obtained is characterized by a flow coefficient of 0.72 brought to 0.68 after reduction of 5% (Figure 5).

ANALYSIS OF THE DOWNSTREAM RESTITUTION

Evaluation of the risk of a hydraulic jump in the bucket

Data

For a reservoir with normal water retention level at 672.70 CGL and the sluice gates completely open, the discharge rates from the sluices are as follows:

- Q = 395 m^3/s for each of the large sluices of 5.0 m × 4.0 m
- Q = 94 m^3/s for the only small sluice 3.0 m × 2.0 m

The geometric characteristics of the bucket are as follows:

- An angle of curvature of 23° and a radius of curvature of 17 m for the two large sluices. The bucket is fixed at altitude 641.35 CGL.
- An angle of curvature of 15° and a radius of curvature of 15 m for the small sluice. The bucket is fixed at altitude 644.00 CGL.

Results

The characteristics of the flow at the entrance of the bucket are calculated at the level of the contracted section. The characteristics of the flow under the gates are obtained from calculations done previously.

In the case of the small sluice, there is the risk of the formation of a hydraulic jump in the bucket for an overture less than 30%. As concerns the two large gates, the overture limit for the formation of a hydraulic jump is fixed at 40%. Management of the sluices should

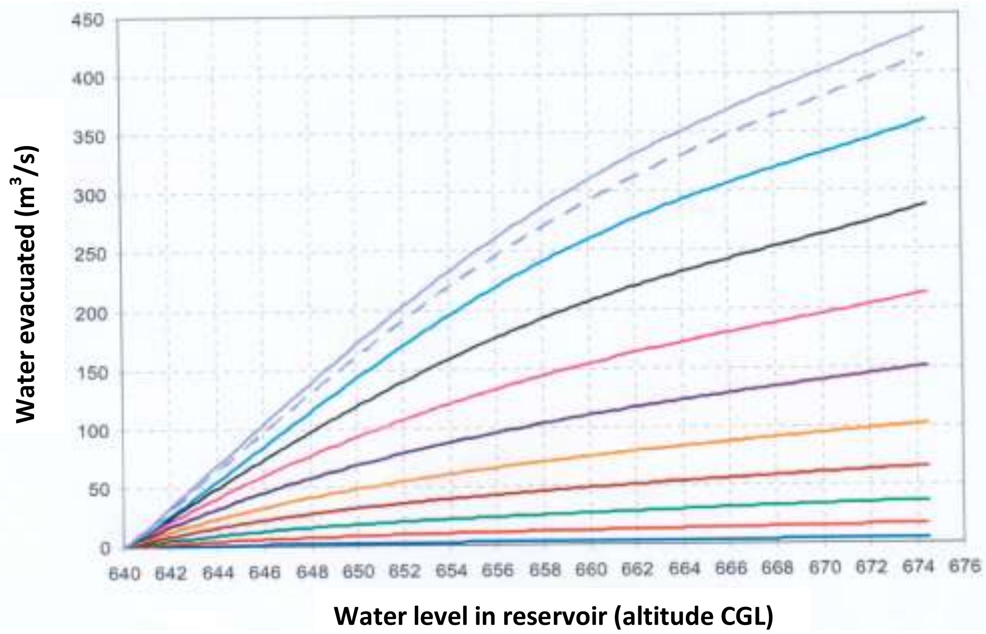

Figure 4. Height – flow rate law of large sluice.

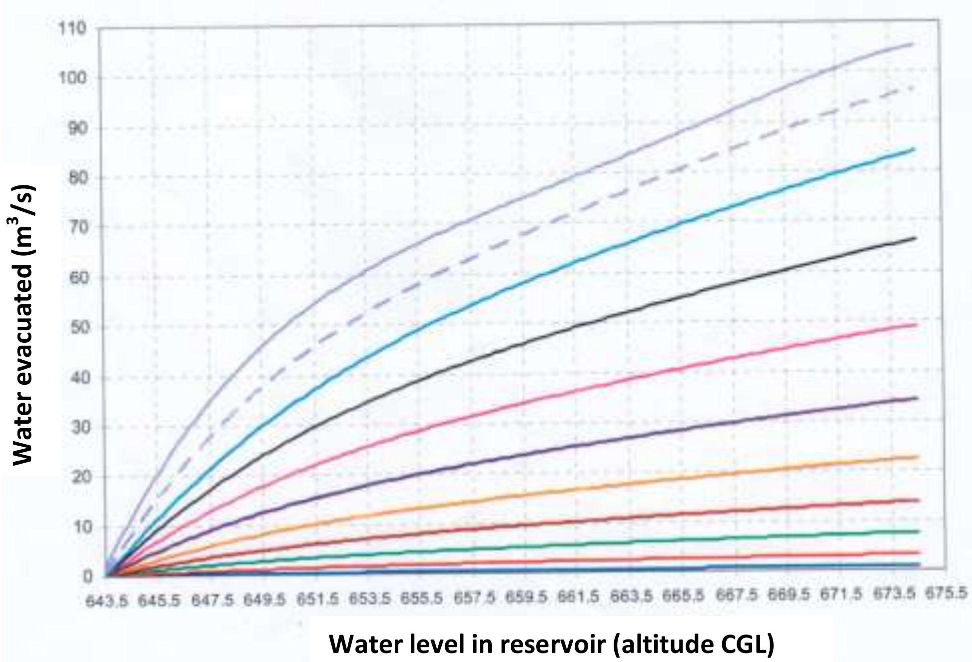

Figure 5. Height – flow rate law of small sluice.

consequently be adapted.

Maximum dynamic pressure on the bucket

The maximum dynamic pressure on the bucket is attained for an overture of 90%. The results are presented in Table 1.

Zone of recirculation and height of downstream waves

Evolution of the flow rate as a function of the gate overture

The law of the gate overture-flow rate is presented in Figure 6 and Table 2.

Table 1. Maximum dynamic pressure on the bucket.

Parameter	% overture	a_c [m]	F_c [-]	H_{PT} [mCe]	H_{PM} [mCe]	X_{PM} [m]
Large sluice	90	5.31	3.14	10.07	4.72	0.11
Small sluice	90	2.70	4.17	5.23	4.25	0.06

Source: Coyne and Bellier (2010).

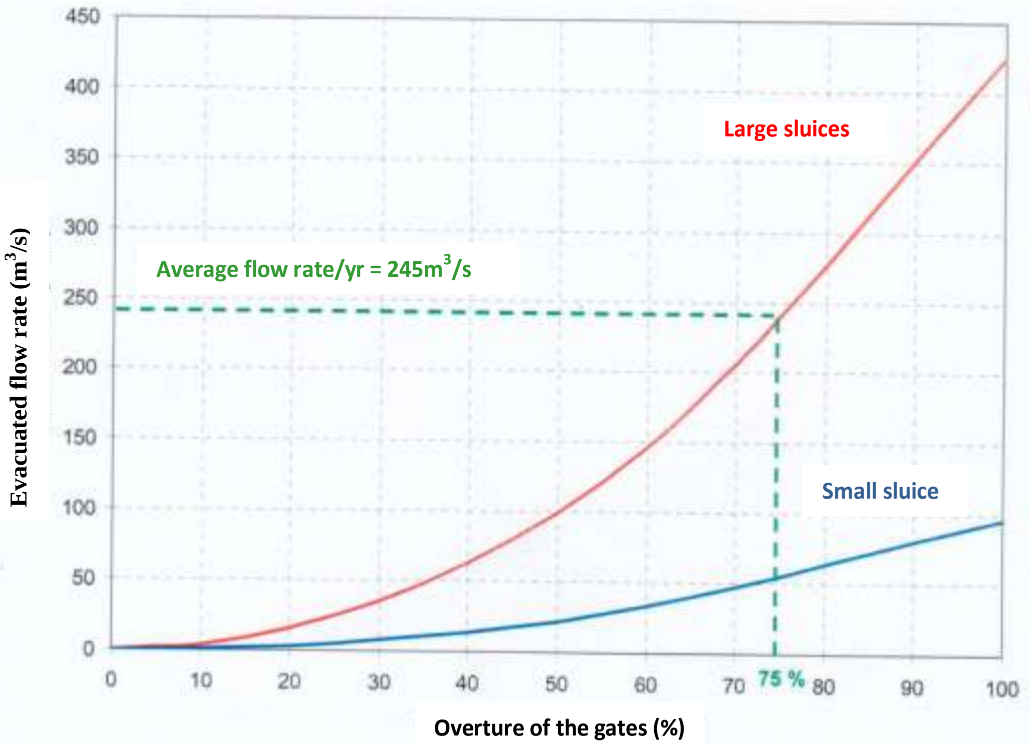

Figure 6. Overture – flow rate at full capacity.

Table 2. Recirculation zone and height of downstream waves.

Parameter	Overture [%]	Q_{sluice} [m^3/s]	Q_{global} [m^3/s]	$h_{downstream}$ [m]	t_u [m]	h_s [m]
Small sluice	40	13.61	140.33	2.08	2.37	1.68
	50	22.03	220.31	2.57	2.17	2.33
	80	58.00	61.2.96	4.32	2.25	4.92
	100	94.43	945.79	5.57	F_c<3	F_c<3
Large sluice	40	63.36	140.33	2.06	F_c<3	F_c<3
	50	99.14	220.31	2.57	8.03	7.65
	80	277.48	612.96	4.32	F_c<3	F_c<3
	100	424.68	945.79	5.57	F_c<3	F_c<3

Source: Coyne and Bellier (2010).

Results

The height of the waves downstream is determined with the help of the formula given where the Froude number is greater than 3 (Chen and Yu, 1965). The level of water downstream is determined thanks to the calibration curve of the global restituted flow rate: all the sluices are supposed to function at the time with same overtures.

Trajectory of the water jet

Flow characteristic on leaving the bucket

Two calculations on trajectory have been carried out for each of the two nappes in order to take into account the air-water friction (Chen and Yu, 1965). The parameters of the trajectory are given in Table 3.

Trajectory of the water jet coming out of the sluices

The trajectory has been designed for a complete overture of the gates. The distances of Tables 3 and 4 take into account the air-water friction.

Trajectory of water jet coming out of the small sluice

The same analysis has been done for the small sluice (Table 5, Figure 7).

Depth limit of the erosion pit

The method of calculation of the erosion pit is the same as that detailed above. The results are presented in Table 6.

It should be noted that the actual size the pits are limited due to the reduced width of the sluices compared to that of the riverbed.

Table 3. Outlet angles of lower and upper water nappes.

Parameter	Overture [%]	Q [m^3/s]	a_c [m]	V_c [m/s]	F_c [-]	α_u [^{o}]	α_o [^{o}]
Small sluice	40	13.61	0.82	8.32	2.99	10.97	12.31
	50	22.03	1.02	10.83	3.43	10.90	12.24
	80	58.00	1.50	18.26	4.41	10.53	11.82
	100	94.43	3.099	16.07	2.98	0.58	10.75
Large sluice	40	63.36	1.67	0.04	2.24	16.39	18.40
	50	99.14	2.05	11.54	2.57	16.09	10.06
	80	277.48	3.12	19.11	3.28	14.62	16.41
	100	424.68	5.90	17.14	2.25	11.76	13.20

Source: Coyne and Bellier (2010).

Table 4. Outlet works – Distance between the point of impact of the water jet and the outlet point of the bucket.

Overture [%]	Q_{sluice} [m^3/s]	Q_{global} [m^3/s]	$N_{downstream}$ [m]	t_u [m]	Distance of impact of the lower nappe [m]	Distance of impact of the upper water nappe [m]
40	63.68	140.33	636.06	$F_c<3$	10.5	11.5
50	99.14	220.31	636.57	$F_c<3$	12.5	14.0
80	277.48	618.91	638.36	8.03	17.5	27.0
100	424.68	945.79	639.57	$F_c<3$	10.0	22.0

Source: Coyne and Bellier (2010).

Table 5. Outlet works – Distance between the impact point of the water jet and the outlet from the bucket.

Overture [%]	Q_{sluice} [m^3/s]	Q_{global} [m^3/s]	$N_{downstream}$ [m]	t_u [m]	Distance of impact of the lower nappe [m]	Distance of impact of the upper water nappe [m]
40	63.63	140.33	636.06	$F_c<3$	10.5	11.5
50	99.14	220.31	636.57	$F_c<3$	12.5	14.0
80	277.48	618.91	638.36	8.03	17.5	27.0
100	424.68	945.79	639.57	$F_c<3$	10.0	22.0

Source: Coyne and Bellier (2010).

CONCLUSION

The results from simulations carried out show that the outlet works will be able to contain the water from the reservoir and discharge it without any problems. Water coming out of the bucket at full overture will fall a

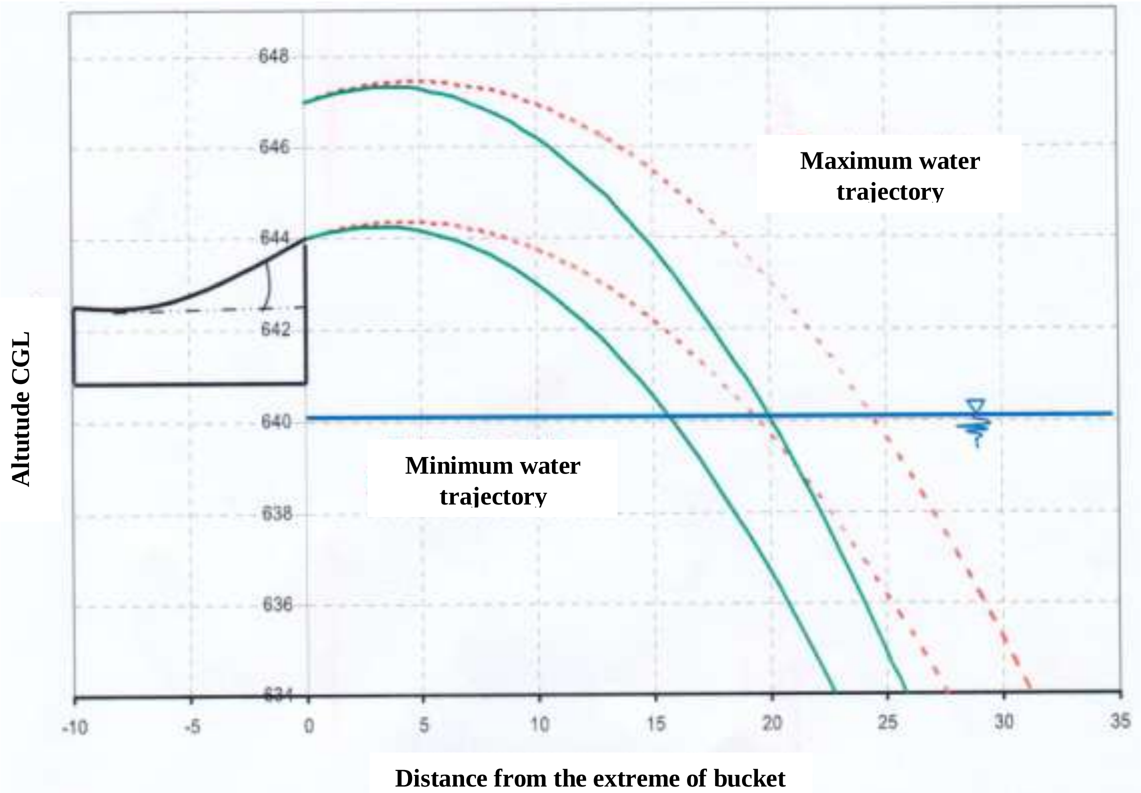

Figure 7. The sluice 3.0 m × 2.0 m - Trajectory of water at full overture.

Table 6. Outlet works – depth of erosion pit.

Parameter	Overture [%]	Upstream level [CGL in m]	Downstream level [CGL in m]	Specific flow [m^3/s/m]	Scouring depth [m]
Large sluice	40	672.70	636.08	15.84	16.90
	50	672.70	636.57	24.79	21.5
	80	672.70	638.08	69.37	37.2
	100	672.70	639.67	106.17	46.3
Small sluice	40	672.70	636.06	6.81	10.0
	50	672.70	636.57	11.01	13.0
	80	672.70	638.36	31.98	23.0
	100	672.70	639.57	48.22	28.3

Source: Coyne and Bellier (2010).

reasonable distance and does not cause any damage to the structure. From Figure 6, it can be seen that at 75% overture the sluices can discharge and restitute the water sent out by the reservoir.

The water loses energy progressively from the friction in the passageway, the friction in the sluice gates, the hydraulic bucket (jump) and the pool downstream.

As shown in Tables 7 and 8 that for both sluices when the small and large sluices are opened greater than 30 and 40% of their overture, there is a hydraulic jump. The hydraulic jump is used to dissipate part of the energy. After going through the bucket, the resultant hydraulic jump reduces much of the speed as the water falls in the pool downstream and enters the river causing very little or no erosion. Also the water falls at least 20 m (Figure 8) from the bucket, a reasonable distance that avoids any damaging of the structure.

We can therefore conclude consequently that, well managed, the outlet works can restitute sufficiently the quantity of the water discharged thus ensuring a

Table 7. Evaluation of the risk of the formation of a hydraulic jump in the bucket of the small sluice.

% overture	A [m]	H [-]	Ac [m]	Q [m^3/s]	Fo [-]	W [-]	Fo+ [-]	Fo- [-]	Conclusion
10	0.30	0.73	0.22	0.82	1.27	2.34	4.10	3.26	Jump
20	0.06	0.71	0.42	3.27	1.89	1.20	2.79	2.30	Jump
30	0.09	0.69	0.62	7.46	2.43	0.82	2.30	1.92	No jump
40	1.20	0.68	0.82	13.61	2.94	0.62	2.03	1.72	No jump
50	1.50	0.68	1.02	22.03	3.43	0.50	1.86	1.59	No jump
60	1.80	0.68	1.23	33.30	3.89	0.41	1.73	1.50	No jump
70	2.10	0.70	1.47	47.48	4.25	0.35	1.63	1.42	No jump
80	2.40	0.73	1.75	63.95	4.41	0.29	1.55	1.36	No jump
90	2.70	0.79	2.12	80.82	4.17	0.24	1.47	1.31	No jump
100	3.00	1.00	3.00	96.43	2.96	0.17	1.35	1.22	No jump

Source: Coyne and Bellier (2010).

Table 8. Evaluation of the risk of the formation of a hydraulic jump in the bucket of the large sluices.

% overture	A [m]	η [-]	Ac [m]	Q [m^3/s]	Fo [-]	W [-]	Fo+ [-]	Fo- [-]	Conclusion
10	0.59	0.78	0.46	4.10	1.00	2.93	4.75	3.90	Jump
20	1.18	0.75	0.88	15.94	1.47	1.53	3.18	2.61	Jump
30	1.77	0.72	1.28	35.30	1.86	1.06	2.60	2.16	Jump
40	2.36	0.71	1.67	63.36	2.24	0.81	2.28	1.91	No jump
50	2.95	0.69	2.05	99.14	2.57	0.66	2.08	1.76	No jump
60	3.54	0.69	2.46	146.51	2.89	0.55	1.93	1.64	No jump
70	4.13	0.70	2.91	206.03	3.16	0.46	1.81	1.55	No jump
80	4.72	0.73	3.46	277.48	3.28	0.39	1.70	1.47	No jump
90	5.31	0.78	4.17	351.43	3.14	0.32	1.60	1.40	No jump
100	5.90	1.00	5.90	424.68	2.25	0.23	1.45	1.29	No jump

Source: Coyne and Bellier (2010).

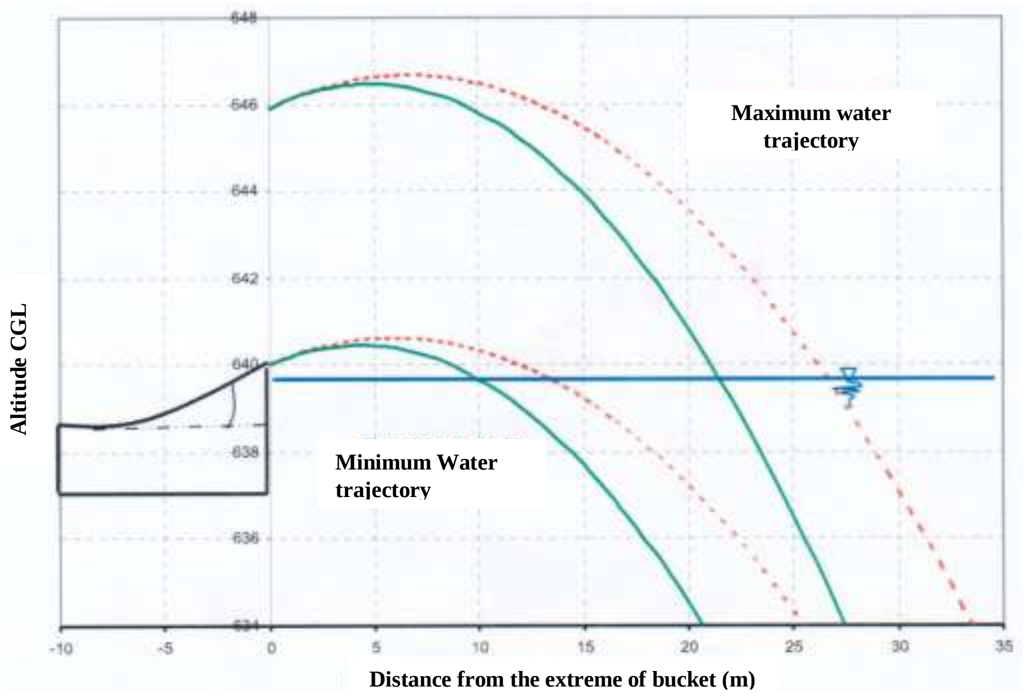

Figure 8. Sluices 5.9 m × 4.0 m. Water trajectory at full overture.

satisfactory management of the reservoir.

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