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L. Cassan, J.-P. Baume, Gilles Belaud, X. Litrico, P.-O. Malaterre, J.  
Ribot-Bruno

► **To cite this version:**

L. Cassan, J.-P. Baume, Gilles Belaud, X. Litrico, P.-O. Malaterre, et al.. Hydraulic modeling of a mixed water level control hydro-mechanical gate. *Journal of Irrigation and Drainage Engineering-ASCE*, 2011, 137 (7), p. 446 - p. 453. hal-00632474

**HAL Id: hal-00632474**

**<https://hal.science/hal-00632474>**

Submitted on 14 Oct 2011

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# Title: Hydraulic modeling of a mixed water level control hydro-mechanical gate

Ludovic Cassan<sup>1</sup> ; Jean-Pierre Baume<sup>1</sup> ; Gilles Belaud<sup>2</sup> ; Xavier Litrico<sup>1</sup> ; Pierre-Olivier Malaterre<sup>1</sup> ; José Ribot-Bruno<sup>1</sup>

## Abstract:

The article describes the hydraulic functioning of a mixed water level control hydro-mechanical gate present in several irrigation canals. According to the flow conditions, this automatic gate maintains the upstream level close to a target value for low flow, then it controls the downstream level close to a target, and switches back to control the upstream level to avoid overflow. Such a complex behaviour is obtained via a series of side tanks linked by orifices and weirs. We analyze this behaviour and propose a mathematical model for its functioning, assuming the system is at equilibrium. The proposed model is analyzed and evaluated on real data from a canal in the South of France, showing the ability of the model to reproduce the functioning of this complex hydro-mechanical system.

## CE database Subject headings:

Numerical models; hydraulic structures; gates; water levels; field tests

## Introduction

Irrigation canals have been managed for millennia with static devices (spillways, proportional diversions) or manually operated moving structures (gates). Automatic hydro-mechanical gates have been developed in the 20th century in order to better control water levels, and ensure a better water distribution. The first automatic gates developed at an industrialized scale have been, to our knowledge, the so-called AMIL gates. These gates are hydro-mechanical gates using a float and two counter weights in order to control the water level upstream of the gate close to a target level. These gates have been designed in the 1930s by a French company named Neyrpic (later on called Neyrtec, then Alstom Fluide and now belonging to the Gec-Alstom Group). Other hydro-mechanical gates have been designed using alternative approaches and technologies for the same objective of controlling an upstream water level: the Begemann and Vlugter gates, designed by Dutch engineers (Vlugter, 1940; Burt et al., 2003; Litrico et al., 2005; Belaud et al., 2008). All these gates are adapted to the classical way of controlling irrigation canals called upstream control (Malaterre et al. 1998). This type of control is compatible with a water distribution to users according to a fixed rotation schedule. This strategy is easy to implement for the canal managers but rigid for the users and is the source of possible important water losses. Neyrpic Company then developed hydro-mechanical gates for the control of downstream water levels. These gates named AVIS and AVIO have the important advantage of being adapted for a type of canal regulation called downstream control (Malaterre et al. 1998). This type of control allows on-demand water distribution to users as opposed to fixed rotation schedule. To our knowledge, the AVIS and AVIO gates are the only hydro-mechanical gates designed for downstream

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<sup>1</sup> UMR G-EAU, Cemagref, 361 r J F Breton Domaine Lavalette BP 5095 34196 MONTPELLIER CEDEX 5

<sup>2</sup> UMR G-EAU, Supagro Montpellier, 2 place Pierre Viala 34 060 Montpellier cedex 1 -France.

control of irrigation canals. In some cases, the upper reaches of large irrigation canals are managed by an upstream control strategy, while the lower reaches are managed by a downstream control strategy. This prevents frequent head discharge changes in the upstream part, while adapting the release to water demand in the downstream reaches. These two approaches can cooperate only if some intermediate storage volume is available and used along the canals in the intermediate reaches. This task can be managed by a third type of gates named mixed gates, also developed by Neyrpic. These gates are the only example of such advanced automatic operated gates using only hydro-mechanical principals.

All these hydro-mechanical gates are very interesting compared to electronically motorized gates since they do not require power or any electronic component. They just need regular maintenance (painting and greasing). They are very well suited for difficult environments such as those prevailing in developing countries or in remote locations. Their properties are all the more interesting in a context of increasing energy cost or possible power cuts. Several successful examples of irrigation canal using such gates exist in the world such as the Tadla canal in Morocco where original gates installed in the 1950s are still very well maintained. Due to their performances and robustness properties, they are still installed on new irrigation canals (PHLC canal in Pakistan, Atbarra canal in Sudan) even though the electronically controlled and motorized gates are increasing their market shares. All these gates have then been built in several countries such as France, Algeria, Morocco, Spain, Portugal, Brazil, USA (Cemagref 2004) and have been installed on hundreds of irrigation canals.

Although mixed gates have been built and used for several decades, their functioning has not been analyzed and modeled. Their behaviour is rather complex, as it is based on a series of tanks connected by multiple orifices and weirs. The tanks and connections are designed so that the mixed gate can both fix a downstream level and store water in the upstream reach. The mixed gate can be used without human operator thanks to two security modes which prevent overflow and drying of reaches. Mathematical models of these gates are useful to design and analyze hydraulic management strategies in irrigation canals equipped with them. They are also useful to help adjusting the characteristics in the fields or in a design process.

The purpose of this paper is to describe such gates and to model their complex functioning. We develop a mathematical model of the mixed gate, so that it can be implemented into a software solving open-channel flow equations. The paper is organized as follows: first we provide a physical description of the gate and detail its general functioning. Then we develop a model of the gate, taking into account the various hydraulic devices. Subsequently, we use the model to study its sensitivity to various parameters. Finally, we compare the model results to experimental measurements from an operating gate installed in a real channel network.

## Gate design and behaviour

The mixed gate is a regulation hydraulic structure which is designed to manage a difference between a discharge  $Q_p$  provided into the network by pumping or derivation, and a demanded discharge  $Q_d$  corresponding to water offtakes.

If  $Q_p > Q_d$  the upstream reach will be used as a storage and the upstream level will increase. If this difference persists or if the discharge variation is too fast, the gate will open completely to avoid overflow.

If  $Q_p < Q_d$  then the mixed gate allows the system to fulfil the demand as the discharge through the gate equals  $Q_d$ , until the upstream level reaches a minimum value. If this

difference persists or if the discharge variation is too fast, the gate closes completely, therefore maintaining the level in the upstream reach but no longer fulfilling the demand. The overall functioning of the gate can be described by the theoretical relation between the upstream level  $Z_u$  and the downstream level  $Z_d$  as depicted in Figure 1 (Alsthom 1993). This curve shows that the mixed gate is similar to a constant downstream level gate (AVIS) with two security modes. These modes for low and high value of downstream level allow respectively to avoid the complete emptying and the overflow of the upstream reach.

[Figure 1 about here]

### ***Physical description of the mixed gate***

A mixed gate consists of three main parts: a gate leaf, a set of side tanks and floats (Figs. 2 and 3). The gate leaf has a cylindrical trapezoidal section and is placed across the channel to regulate the flow of the canal. The second part is an auxiliary circuit composed of side tanks connected by weirs and orifices. Figures 3 and 4 show the pattern of tanks and their connections.

[Figure 2 about here]

The inlet tank is connected to the upstream reach of the channel via a circular orifice  $O_1$ . Part of the flow goes through this orifice to be diverted into the side tanks. Water can flow into the upstream regulation tank through a submerged orifice  $O_3$ , or above the weir  $W_{10}$  if the flow depth is sufficient. Water is evacuated by three different orifices depending on the water depth:

- the orifice  $O_4$  is always submerged, it connects the upstream tank to the downstream tank
- the grid  $G_7$  has a specific form, with a decreasing width as the water level rises
- the orifice  $O_9$  flows directly into the downstream reach.

The downstream tank has a weir  $W_5$  to maintain a minimum level. It is connected to the downstream reach through the orifice  $O_6$ . Similarly a mid-tank is linked with the downstream reach through the orifice  $O_8$ .

The third part is composed of a sector float fixed to the gate leaf thanks to a metal frame. The set can revolve around a rotational axis. The floats are weighted so that the gate leaf and the floats are in indifferent equilibrium for the whole set of possible openings. This means that, without water in the tanks, the torque on the axis of rotation due to the weight of the gate leaf is exactly compensated by the torque due to the ballast (Fig. 6). Therefore, the opening or closing of the gate will be only due to the difference in water levels between the upstream and downstream tanks, respectively  $Z_3$  and  $Z_4$ .

[Figure 3 about here]

[Figure 4 about here]

### ***Operation modes***

Five different modes can be distinguished in the relationship between the upstream and the downstream levels as depicted in Fig. 1. These five modes can be linked to the flow patterns between the tanks (Fig. 5 a to e).

Mode 1 (Fig. 5a), corresponding to the line between points a and b in Fig. 1, ensures a regulation of the upstream level  $Z_u$ . This mode occurs when a free flow exists on the weir  $W_5$ . In that case there is no influence of the downstream level  $Z_d$  on the levels in the upstream and downstream tanks, and the gate is similar to an AMIL gate.

In Mode 2 (Fig. 5b), corresponding to the line between points b and c in Fig. 1, the floats impose a constant gap between the upstream and downstream tanks,  $D=Z_3-Z_4$ . As  $O_4$  is a submerged orifice, the discharge through it, denoted  $Q_4$ , is also constant. Since  $O_1$ ,  $W_2$ ,  $O_3$ ,  $O_4$ ,  $W_5$  and  $O_6$  are submerged, the head losses  $Z_u-Z_1$ ,  $Z_2-Z_3$ , and  $Z_5-Z_d$  are constant too and  $Z_1 \approx Z_2$  and  $Z_4 \approx Z_5$ . As a consequence the water depth difference between the upstream and downstream levels is also constant. This mode occurs when  $Z_3$  is lower than the level of the grid bottom ( $G_7$ ).

Mode 3 (Fig. 5c), corresponding to the line between points c and d in Fig. 1, imposes a linear relationship between  $Z_u$  and  $Z_d$ . As the previous mode the discharge in the downstream tank  $Q_4$  remains constant, but  $Z_2-Z_3$  depends on the additional flow through the grid  $G_7$ . The shape of  $G_7$  ensures that  $Z_2$  increases linearly with  $Z_3$ .

Mode 4 (Fig. 5d), corresponding to the line between points d and e in Fig. 1, begins when a flow occurs through the orifice  $O_9$ . It provides a constant level downstream regulation. An increase in  $Z_u$  causes a limited increase of  $Z_3$ , due to  $O_9$  and  $G_7$ , and then a limited variation of  $Z_d$ . The flow through  $O_9$  may be adjusted thanks to a shutter, allowing to control the variation of  $Z_d$  with  $Z_u$ .

Mode 5 (Fig. 5e), corresponding to the line between points e and f in Fig. 1, occurs when there is flow above the weir  $W_{10}$ . The principle is identical to mode 4 but here  $Z_u$  will be maintained almost constant thanks to the weir  $W_{10}$ .

[Figure 5 about here]

### Gate equilibrium design

The torque due to floats on the axis of the gate is a function of the gap  $D$  between the upstream and downstream tanks levels. This torque is calculated as follows (Alsthom 1993):

$$C_0 = \frac{\rho \cdot g \cdot L_f \cdot D \cdot (r_1^2 - r_2^2)}{2g} \quad (1)$$

where  $L_f$  is the width of floats and  $r_1$  and  $r_2$  are the outer and inner radius of the floats, respectively.  $\rho$  is the water density and  $g$  is the gravitational acceleration.

[Figure 6 about here]

To maintain the gate in equilibrium for any opened position (with water in tanks), a counterweight is placed in the upstream float in order to produce an opposite torque, exactly compensating  $C_0$ . This ensures that, for any value of the discharge, there is a constant gap  $D$  between the upstream and the downstream levels in tanks. Indeed, if the difference in upstream and downstream level decreases, the counterweight will tend to close the gate and conversely if this difference increases, the counterweight will tend to open the gate. Flows in side tanks will vary with changing water levels in order to establish a new equilibrium state. This state only depends on the water levels in the upstream and downstream reaches, so the relationship between water levels in the upstream and downstream tanks is independent of the discharge in the main channel.

## Modeling of the mixed gate

The proposed model assumes that the gate is in equilibrium for any given upstream  $Z_u$  and downstream  $Z_d$  water levels in adjacent reaches. Therefore transient dynamic effects of the gate are neglected, which is justified by a shorter time for transfer between tanks than for the evolution of  $Z_u$  and  $Z_d$  during the storage and removal (Ramirez Luna 1997). We end up with a formal relationship between upstream and downstream levels, according to the different physical devices included in the mixed gate.

The hydraulic behaviour of the gate has been modeled to replicate a curve  $Z_u = f(Z_d)$  that reflects the actual water levels in the tanks. We recall below the discharge equations that will be used to compute the flow through the hydraulic structures present in the mixed gate. For a given hydraulic structure, we denote  $h_1$  the upstream head,  $h_2$  the downstream head,  $w$  the orifice opening,  $L$  the equivalent width (Chow 1959),  $C_d$  the discharge coefficient,  $D_o$  the orifice diameter and  $Q$  the discharge. The following discharge formulas are used (Cemagref 2004):

For a free flow weir ( $h_2 < 2/3.h_1$  and  $h_1 < kD_o$ ):

$$Q = C_d L \sqrt{2g} (h_1)^{3/2} \quad (2)$$

For a submerged weir ( $h_2 \geq 2/3.h_1$  and  $h_1 < kD_o$ ):

$$Q = C_d \frac{3\sqrt{3}}{2} L h_2 \sqrt{2g(h_1 - h_2)} \quad (3)$$

For a free flow orifice ( $h_1 \geq kD_o$  and  $h_2 < 2/3.h_1$ ):

$$Q = C_d \frac{2}{3\sqrt{3}} L \sqrt{2g} \left( h_1^{3/2} - (h_1 - kD_o)^{3/2} \right) \quad (4)$$

For a partially submerged orifice ( $h_1 \geq kD_o$  and  $h_2 < 2/3.h_1 + kD_o/3$ ):

$$Q = C_d L h_2 \sqrt{2g} \left( h_2 \sqrt{(h_1 - h_2)} - \frac{2}{3\sqrt{3}} (h_1 - kD_o)^{3/2} \right) \quad (5)$$

For a completely submerged circular orifice ( $h_1 \geq kD_o$  and  $h_2 \geq 2/3.h_1 + kD_o/3$ ):

$$Q = C_d L k D_o \sqrt{2g(h_1 - h_2)} \quad (6)$$

$$k = \frac{w}{D_o} \quad (7)$$

where  $k \in [0, 1]$  is a coefficient giving the relative orifice opening.

All orifices may function as a weir for low upstream water level ( $h_1 < w$ ). In order to ensure a flow continuity through the orifice and to take into account the contraction for orifice flow ( $C_{do} = 0.6$  as recommended in Bos 1989), a continuous increase of  $C_d$  with the dimensionless depth ( $h_1/w$ ) is proposed as follows :

$$C_d = \frac{(C_{do} + C_{dw})}{2} + \frac{(C_{do} - C_{dw})}{\pi} \arctan \left( \beta \frac{h_1 - w}{w} \right) \quad (8)$$

where  $C_{do}$  is equal to 0.6 and  $C_{dw}$  is equal to 0.4. Parameter  $\beta$  defines the transition steepness between weir flow and orifice flow. A value  $\beta=10$  gives a correct description of this transition, with a monotonic increase of  $Q$  with  $h_1$ .

According to Figure 4, the flow network in a mixed gate requires to write ten hydraulic structure equations. We further assume that the difference between the water level in the upstream tank and the water level in the downstream tank are constant:

$$Z_3 - Z_4 = D \quad (9)$$

This is provided by the correct balancing of the gate as explained previously. The calculation is done sequentially from the downstream condition:

- The first step is to calculate the levels  $Z_5$ ,  $Z_4$  and  $Z_3$  from discharge conservation ( $Q_4$ ) in  $O_4$ ,  $W_5$  and  $O_6$ . We have a non-linear system of 3 discharge equations and Eq. (9), and 4 unknowns. The system is solved by a bisection method.
- The second step is the calculation of the flow through grid  $G_7$ . The two discharge equations in  $G_7$  and  $O_6$  give  $Z_6$  and the flow in mid-tank ( $Q_7$ ).
- In the third step, the flow  $Q_9$  through orifice  $O_9$  is calculated from level  $Z_3$  and downstream level  $Z_d$ .
- Finally, water depth  $Z_2$ ,  $Z_1$  and  $Z_u$  are determined from the equations of discharge through hydraulic structures ( $W_2$ ,  $W_{10}$ ,  $O_1$  and  $O_3$ ) and the discharge balance in the upstream tank (Eq. 10).

$$Q_3 + Q_{10} = Q_4 + Q_9 + Q_7 \quad (10)$$

Grid  $G_7$  has a specific design that imposes a given relation between its discharge  $Q_7$  and  $Z_3$ . This grid is made of several horizontal openings, the widths of which decrease with the elevation. Therefore the discharge flowing through this grid will vary as a complex function of the hydraulic head. To simplify, we computed an equivalent width, denoted  $L_7$ . This equivalent width of the grid  $G_7$  is calculated from the wetted area which depends on the difference between  $Z_3$  and  $Z_7$ . Given  $Z_3$ ,  $Z_7$  and  $L_7$ , the flow through the grid is described by Eqs. (2)-(6), according to the flow conditions.

## Sensitivity analysis

Before testing the model on experimental data, a sensitivity analysis was performed to ensure that our model can reproduce the theoretical curve of a mixed gate. The design characteristics of the gate are presented in Table 1.

[Table 1 about here]

[Figure 7 about here]

Figure 7 shows that all modes of operation can be simulated and the transition between modes can be almost identified with the geometric characteristics of the gate. In this case it is assumed that  $Z_u = Z_1$ ,  $Z_d = Z_4$  and  $Z_d$  is constant for mode 4. Then, the change of modes occurs when flow begins through or over the associated device (see operation modes). Compared with the curve based on previous method, the modelled curve is not strictly constant in mode 4. The difference between both curves can be significant around the transition between modes 3 and 4. This shows an advantage of using a complete model, which enables to predict the upstream level more accurately. In addition, the water level transitions

do not exactly correspond to the heights of structures because they also depend on flows. Thus the upstream water level is often higher than the corresponding height of the device.

The mixed gate has orifices with adjustable openings that can modify the shape of the curve. We performed a sensitivity analysis of the theoretical curve by varying the values of the orifice opening  $k_i$  where shutters are settled ( $i=3, 4, 6, 9$ ). Figure 9 shows that the orifice openings can either increase or decrease  $Z_u$ .

Openings  $k_4$  and  $k_6$  act on the difference  $Z_4-Z_d$ . This difference is generally limited, since the discharge in the downstream tank is low, and then the head losses in  $O_4$ ,  $W_5$  and  $O_6$  are small compared to those in the upstream part. This explains why both  $k_4$  and  $k_6$  have a limited influence.

The modification of  $k_3$  (orifice  $O_3$ ) influences the exchange between the upstream reach and the upstream tank. If  $k_3$  is decreased, head losses through  $O_1$ ,  $W_2$  and  $O_3$  increase, which means that  $Z_u-Z_3$  increases. Since  $Z_3$  and  $Z_4$  is fixed by the value of  $D$ , the difference between  $Z_u$  and  $Z_d$  increases.

Orifice  $O_9$  becomes effective when level  $Z_3$  is high enough, therefore in modes 4 and 5. Opening  $O_9$  causes the discharge in the upstream tank to increase, then the head loss in  $O_1$ ,  $W_2$  and  $O_3$ . Therefore, for a given downstream level, the upstream level  $Z_u$  is increased when  $k_9$  increases.

The upstream level  $Z_u$  is mostly sensitive to  $D$  settled by the floats (Fig. 8). The most useful mode for the downstream regulation is mode 4, and the curve for this mode can be easily adjusted by reducing the flow in the downstream part by acting on the openings of  $O_4$ ,  $O_3$  and  $O_9$  as described before. The sensitivity analysis is useful to adjust the shutters according to given objective control levels:

- since  $Z_4 \approx Z_d$  (downstream tank) and  $Z_3 = Z_4 + D$  (upstream tank), the upstream tank level ( $Z_3$ ) is little influenced by any of the shutters.
- For a given  $D$ ,  $Z_u$  is mainly adjusted using shutters on  $O_3$  and  $O_9$ .

However this adjustment could increase the transitional time necessary to reach a steady state. It may therefore disturb the normal functioning of the gate. For instance, if  $Z_4$  decreases, the gate will open because the difference between  $Z_3$  and  $Z_4$  will be greater than  $D$ . If  $Z_3$  is not rapidly adjusted by the flow through orifices (emptying of upstream tank) to get a head loss equal to  $D$ , the gate will deliver a larger discharge during a long time. This transitional aspect is not taken into account in our steady state model, but imposes additional conditions for the adjustment of the orifice openings.

[Figure 8 about here]

[Figure 9 about here]

## Experimental Results and Discussions

To test our model on experimental data, we equipped a mixed gate located on the Bas-Rhône Languedoc canal in Southern France with a set of sensors automatically recording water levels and gate opening. The characteristics of this gate are provided in Table 2. Four sensors measured the water level  $Z_1$ ,  $Z_3$ ,  $Z_4$  and  $Z_6$ . Since  $Z_4$  is equal to  $Z_d$  and  $Z_1$  is close to  $Z_u$ , the sensors were settled into the side tanks in order to protect them. A position sensor measured the distance from a float to the ground. This measurement was then converted to get the value of the opening angle  $\alpha$ . The sampling rate was 3 minutes and the measurements were made continuously during 2 months. During this period, three significant flow changes were observed, corresponding to a decrease in the flow which caused a decrease of the upstream water level. The noise due to sensors or transitional flows were filtered by a moving



average method over 15 min. Most of the time the upstream and downstream water levels present the same oscillations with two periodicities. The first period is about 3 hours and is due to waves in the channel; the second one is about 1 day, corresponding to changes in water uses. When the water level decreased, the gate opened in order to maintain a constant discharge. The mixed gate was efficient and regulated the water depths and flow in the channel.

When the provided discharge is stopped ( $Q_p=0$ ) the upstream water level decreases and the gate opens to ensure the required discharge. This situation ends after few hours because the storage in the upstream reach is not sufficient. The mode of regulation changes and the downstream water level decreases too.

The data corresponding to very small gate openings ( $\alpha < 1.5$  deg) were not considered in the analysis. Indeed in this case we remarked that the parameter  $D$  increased linearly with  $Z_3$  instead of being constant. This behaviour cannot be explained by a default of the counterweight mechanism which must maintain a constant distance from the rotational axis. At small opening a torque seems to act which could come from friction caused by the asperities of gate bay. The model cannot accommodate this torque because the calculation of the opening angle does not affect the theoretical curve between upstream and downstream levels. So this kind of data has not been used for the analysis.

Given the number of adjustable parameters, optimization of these factors would have little meaning because we can not verify and accurately measure the openings of the hydraulic structures inside the tanks. Moreover not enough data are available to get the setting of each orifice. To fit the model to experiments, only the most sensitive opening orifice coefficients  $k_3$ ,  $k_9$  and the discharge coefficient  $C_{dw7}$  are adjusted. First,  $D$  is fixed by the relationship between  $Z_3$  and  $Z_4$  (Fig. 10). Second, the flow balance in the mid tank allows to fit the model to the experimental water level ( $Z_3$ ,  $Z_4$  and  $Z_6$ ) by adjusting  $C_{dw7}$ , independently of other opening coefficients (Fig. 10). Third, the opening coefficients are adjusted to reproduce the theoretical curve (Fig. 11). As shown on figure 9,  $k_3$ ,  $k_9$  act on an opposite way on the curve and are limited to 1, then a only one solution is possible to fit curves for all modes ( $k_3 = 0.88$ ,  $k_9 = 0.78$ ).

[Table 2 about here]

[Figure 10 about here]

[Figure 11 about here]

Figure 11 shows that the model can satisfactorily reproduce the relationship between  $Z_1$  and  $Z_4$ . On the same graph the curve giving  $Z_u$  as a function of  $Z_d$  is depicted. As expected both curves are similar since experimental observation showed that  $Z_u$  and  $Z_d$  are respectively almost equal to  $Z_1$  and  $Z_4$ .

We note that even if the experimental curve is similar to the theoretical curve (Fig. 1), only modes 4 and 5 are possible. Indeed for modes 1, 2 and 3, the difference between the weir height  $W_5$  and  $W_2$  is not sufficient to permit flow in tanks ensuring the opening of the gate. Furthermore, the difference of height between the bottom of the orifice  $O_9$  and the weir  $W_5$ , is lower than  $D$ . Then flows both through  $O_9$  and over  $W_5$  are possible. The regulation of low-level is provided by a mixed mode between modes 1 and 4.

## Conclusion

We derived a model of the mixed gate, a particular hydromechanical gate that is able to combine upstream control strategy in the upstream pool and downstream control strategy in its downstream pool. A numerical algorithm has been proposed, that establishes the relation between the flow and the different water levels in the tanks and in the reaches. We obtained a

univocal relation depending on flow and design characteristics. With this model, we analyzed the influence of the different shutters installed on the orifices connecting the tanks, and showed how they can be used to obtain desired water levels. Comparison between model and experiment has been done on an operating gate. A good agreement was observed between model and data obtained on an operating mixed gate in the South of France.

The model derived here was implemented recently in SIC, the canal simulation software developed by Cemagref (Cemagref 2004) and used to analyze management strategies in modernizing irrigation schemes in Morocco.

## Acknowledgments

The authors would like to acknowledge the support provided by BRL Exploitation company for the field measurements.

## Notation

- $C_0$  = torque due to floats (N.m)
- $C_{counterweight}$  = torque due to counterweight (N.m)
- $C_d$  = discharge coefficient of the hydraulic structures
- $C_{dO_i}$  = discharge coefficient of hydraulic structure  $i$  (functioning as an orifice)
- $C_{dW_i}$  = discharge coefficient of hydraulic structure  $i$  (functioning as a weir)
- $D$  = water level gap between upstream side tank and downstream side tank (m)
- $D_0$  = orifice diameter (m)
- $g$  = gravitational acceleration ( $m/s^2$ )
- $h_1$  = upstream device water head (m)
- $h_2$  = downstream device water head (m)
- $k_i$  = opening orifice coefficient of the orifice  $O_i$
- $L$  = equivalent width of device (m)
- $L_7$  = equivalent width of the grid  $G_7$  (m)
- $L_f$  = width of float (m)
- $O_i$  = name of orifice  $i$
- $Q$  = discharge ( $m^3/s$ )
- $Q_i$  = discharge through or over the device  $i$  ( $m^3/s$ )
- $Q_d$  = required discharge ( $m^3/s$ )
- $Q_p$  = provided discharge ( $m^3/s$ )
- $r_1$  = outer radius of floats (m)
- $r_2$  = inner radius of floats (m)
- $w$  = orifice opening (m)
- $Z_1$  = water level in the inlet tank upstream of  $W_2$  (m)
- $Z_2$  = water level in the inlet tank downstream of  $W_2$  (m)
- $Z_3$  = water level in the upstream tank (m)
- $Z_4$  = water level in the downstream tank (m) upstream of  $W_5$  (m)
- $Z_5$  = water level in the downstream tank (m) downstream of  $W_5$  (m)
- $Z_6$  = water level in the mid tank (m)
- $Z_7$  = level of the grid bottom (m)
- $Z_u$  = water level in the upstream reach (m)
- $Z_d$  = water level in the downstream reach (m)
- $\alpha$  = opening angle of the gate leaf (*degree*)
- $\beta$  = parameter of the discharge coefficient law for orifice
- $\rho$  = water density ( $kg/m^3$ )

$\theta$  = angle of the orifice water level (rad)

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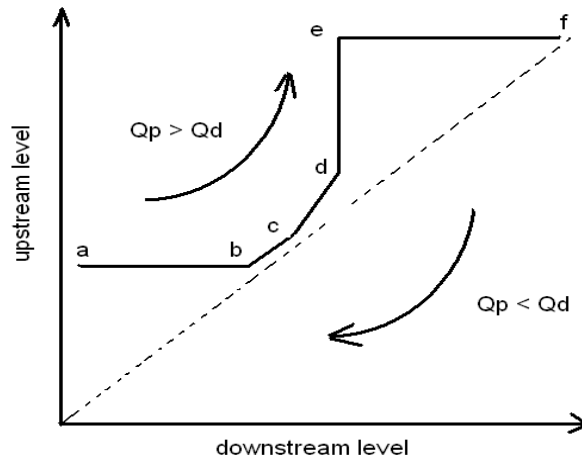


Figure 1 : Theoretical curve of the upstream level as a function of the downstream level.

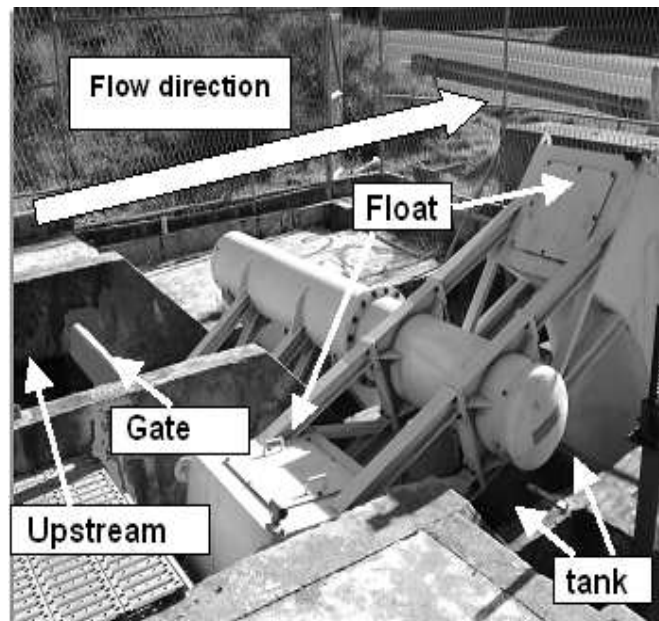


Figure 2 : Photography of a mixed gate

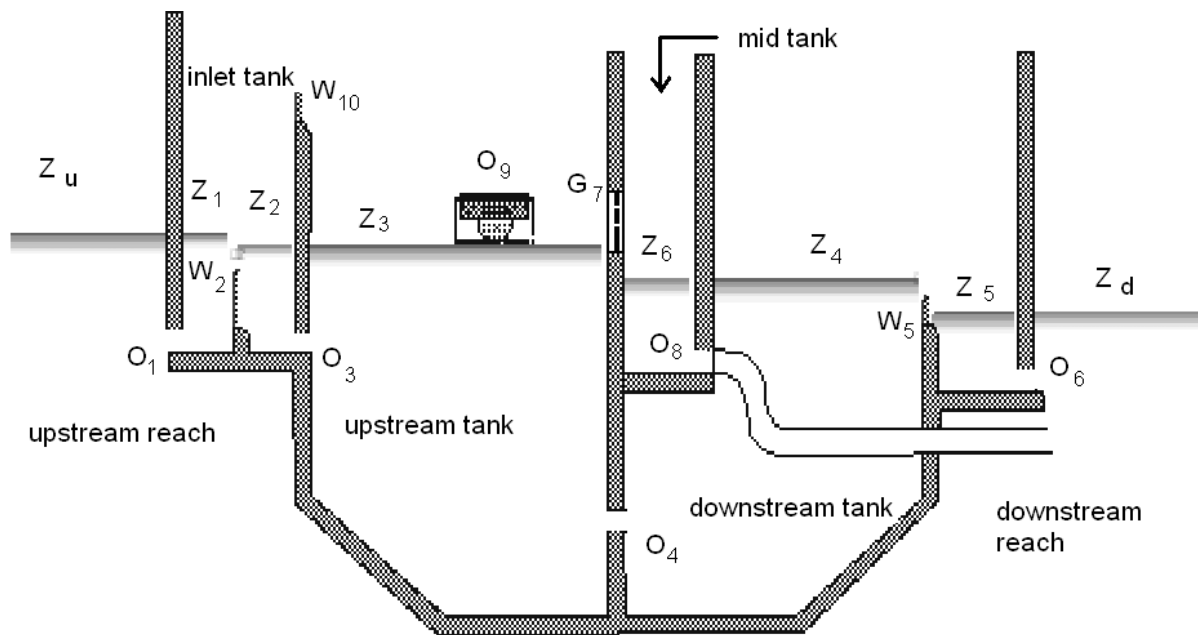


Figure 3 : Hydraulic structures and position of side tanks

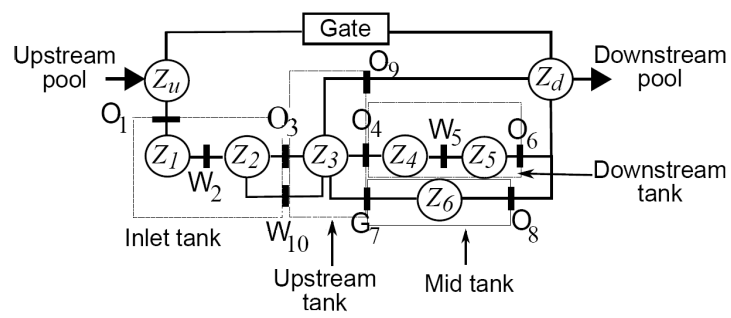


Figure 4 : Flow chart of the mixed gate



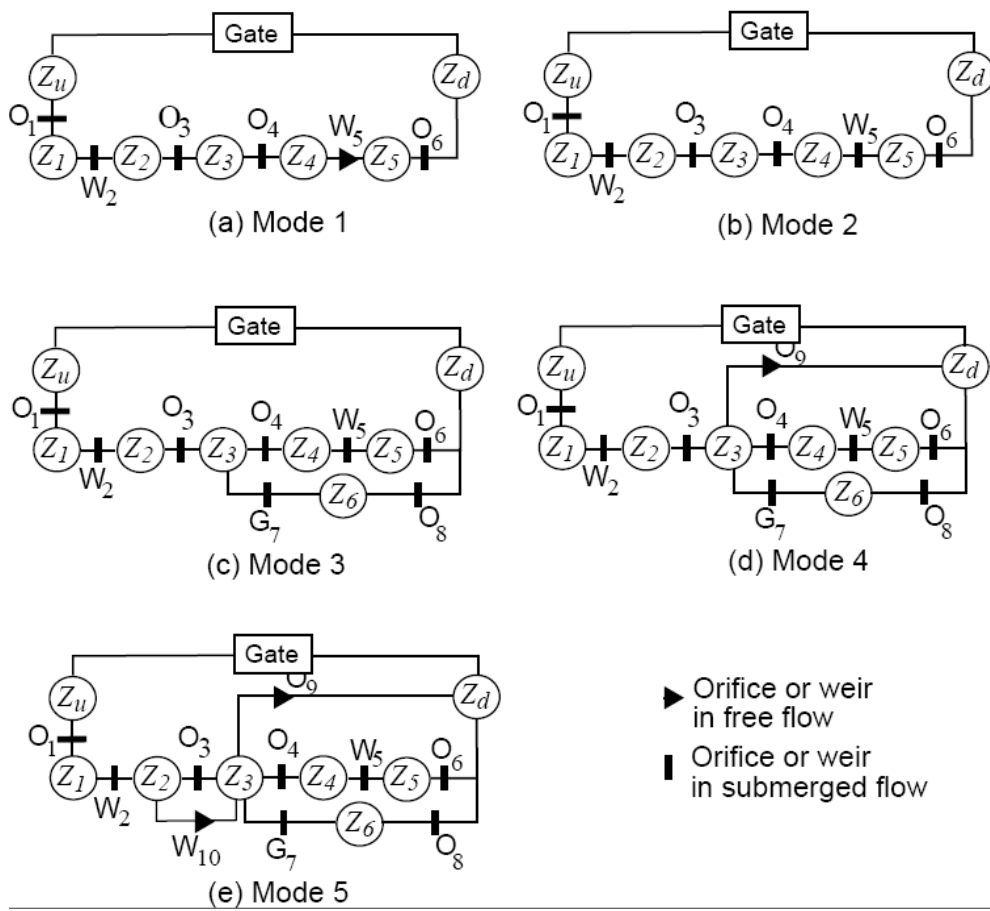


Figure 5 : Flow chart for the 5 modes.

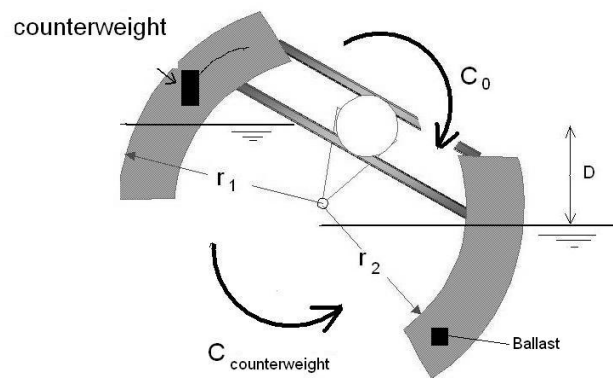


Figure 6 : Description of torques acting on gate and the counterweight system

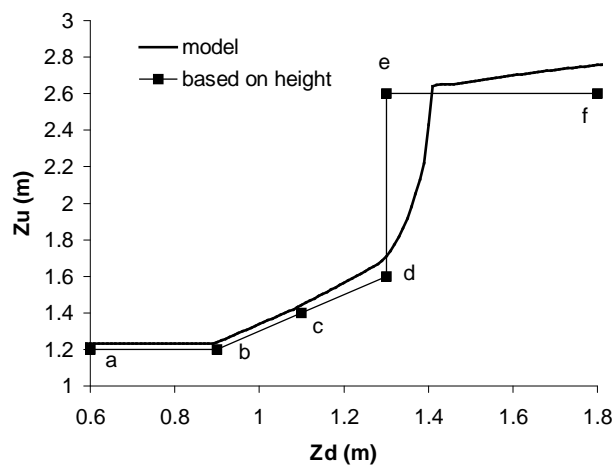


Figure 7 : relationship between upstream and downstream water levels from model calculation and height of hydraulic device. Letter labels refer to Fig. 1 and mode analysis.

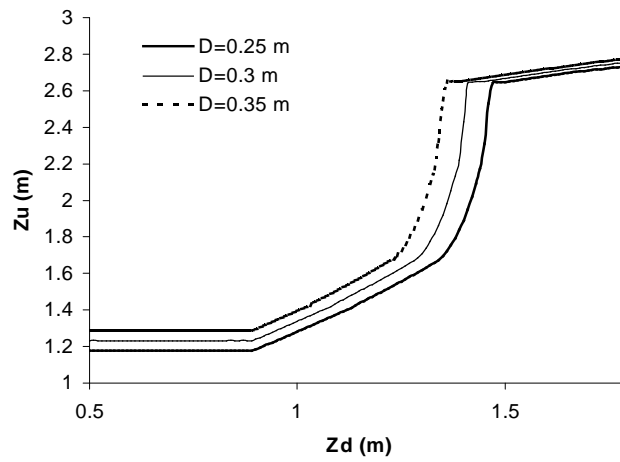


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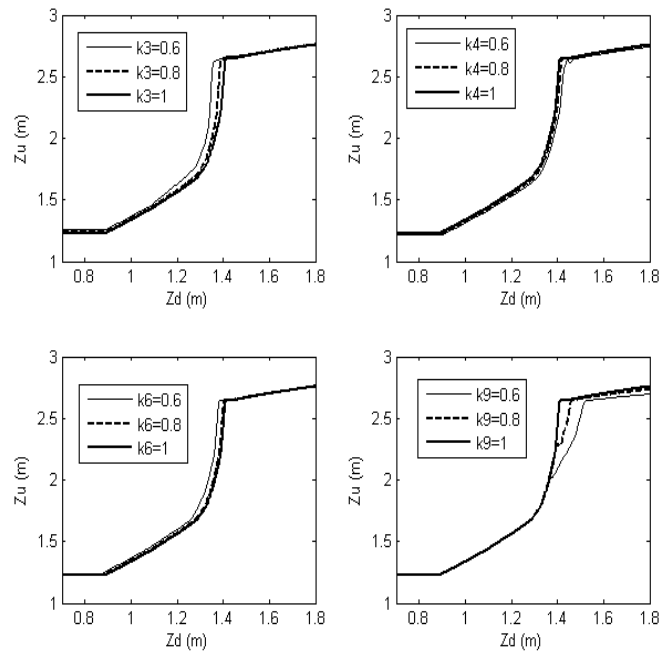


Figure 9 : Curves of  $Z_u$  as a function of  $Z_d$  for various opening orifice coefficients ( $D=0.3$ ).  
Discharge coefficients of orifices are given by Eq. (8) (0.6 for orifice and 0.4 for weir).

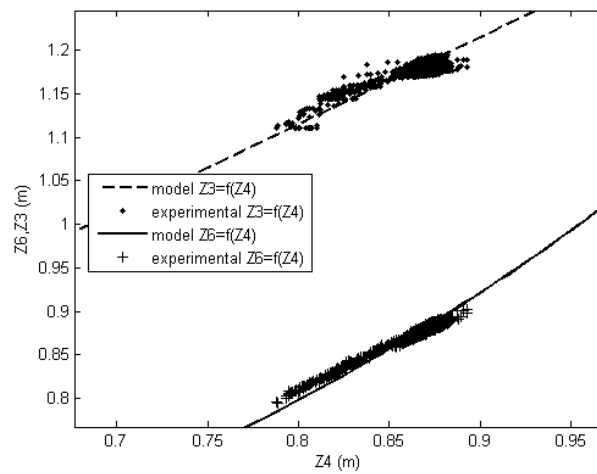


Figure 10 : Comparison between modeled curve (line) and measured data (sign) ( $D=0.31$ ,  $C_{d0}=0.6$ ,  $C_{dw}=0.4$ ,  $C_{dw7}=0.2$ ,  $k_9 = 0.78$ ,  $k_3=0.88$ ).

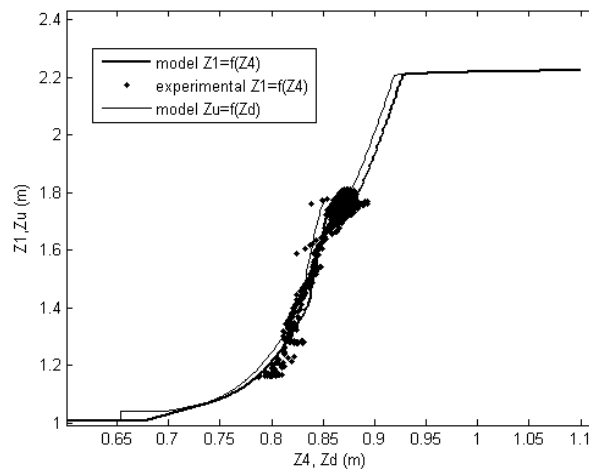


Figure 11 : Comparison between modeled curve (-) and measured data (.) ( $D=0.31$ ,  $C_{dO}=0.6$ ,  $C_{dW}=0.4$ ,  $C_{dW7}=0.2$ ,  $k_9 = 0.78$ ,  $k_3=0.88$ ). The modeled curve of  $Z_d$  as a function of  $Z_u$  is added.

N°	Type	Crest level (m)	$C_{dW}$	$C_{dO}$	L or diameter (m)
1	Orifice	0.7	0.4	0.6	0.2
2	Weir	1.1	0.4	/	0.8
3	Orifice	0.7	0.4	0.6	0.1
4	Orifice	0	0.4	0.6	0.05
5	Weir	0.9	0.4	/	1.2
6	Orifice	0.5	0.4	0.6	0.1
7	Orifice	1.4	0.4	0.6	computed
8	Orifice	0.6	0.4	0.6	0.1
9	Orifice	1.6	0.4	0.6	0.15
10	Weir	2.6	0.4	/	1.2

Table 1: Design characteristics of the modeled gate



N°	Type	Crest level (m)	$C_{dW}$	$C_{dO}$	L or diameter (m)
1	Orifice	0.588	0.4	0.6	0.2
2	Weir	0.996	0.4	/	0.8
3	Orifice	0.588	0.4	0.6	0.0875
4	Orifice	0	0.4	0.6	0.04
5	Weir	0.9	0.4	/	1.2
6	Orifice	0.653	0.4	0.6	0.1
7	Orifice	1.055	0.2	0.6	computed
8	Orifice	0.533	0.4	0.6	0.7
9	Orifice	1.067	0.4	0.6	0.14
10	Weir	2.208	0.4	/	1.2

Table 2 : Description of the experimental mixed gate