DOI: 10.24850/j-tyca-2022-01-03

Articles

# Evaluation of the operation in a main canal reach of an irrigation district with an economic approach

# Evaluación de la operación de un tramo del canal principal de riego con un enfoque económico

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## Abstract

In an irrigation district, the water distribution network is an essential point in the management and delivery of water to users. In the design of a new irrigation district, the way of management is established, and specific tools and methods are applied to achieve it. In contrast, if the district is already built and in operation, to improve the use of water, a modernization project is developed that must consider the engineering and social aspects of the area. In this work, an economic and hydraulic analysis is presented to implement an automatic control model of the gates in an irrigation district. The hydraulic operation of the canal network is analyzed with a numerical simulation model, with different automatic control options that can be established, and an analysis of the shadow prices in agricultural production based on dynamic numerical simulation scenarios. This methodology is applied to an irrigation district located in the northwest of Mexico and different scenarios are obtained that can be considered in the modernization of the canal network.

**Keywords**: Automatic control, numerical simulation of irrigation channels, irrigation water value.

## Resumen

En un distrito de riego, la red de distribución del agua es un punto esencial en el manejo y la entrega de agua a los usuarios. En el diseño de un nuevo distrito de riego se establece la forma de manejo, y se aplican herramientas y métodos específicos para lograrla; en cambio, si el distrito ya está construido y en operación, para mejorar el uso del agua se desarrolla un proyecto de modernización que debe tomar en cuenta los aspectos de ingeniería y sociales de la zona. En este trabajo se presenta una análisis económico e hidráulico para implementar un modelo de control automático de las compuertas de un distrito de riego. El

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funcionamiento hidráulico de la red de canales se analiza con un modelo de simulación numérica, con diferentes opciones de control automático que se pueden instaurar, y un análisis de los precios sombra en la producción agrícola a partir de los escenarios dinámicos de simulación numérica. Esta metodología se aplica a un distrito de riego ubicado en el noroeste de México y se obtienen diferentes escenarios que pueden ser considerados en la modernización de la red de canales.

**Palabras clave**: control automático, simulación numérica de flujo en canales de riego, valor del agua de riego.

Received: 20/07/2020

Accepted: 02/12/2020

# Introduction

In the design of an irrigation channel network, it is considered that the operating efficiency depends on the regulation technique and the way the regulation gates are operated. When the design is new, the operation and control are defined with structures to have a highly efficient system. However, these design conditions are not the most common because in many countries irrigation districts and canal networks are already operating, and modifying the form of regulation has a high cost.

The need for more rational use of water and competencies in the demand for water, such as the need to meet the requirements of urban use due to population growth or the increase in the value of water intended for industrial use, make it necessary to evaluate whether it is feasible to modernize the irrigation water regulation systems in the district. In the particular case of irrigation canals, a recurring option is to automate the gates with the same type of regulation.

Studies on automation projects such as that of Clemmens, Sloan, and Schuurmans (1994) do not clearly indicate the profitability of these actions, but they do indicate that the volumes saved are an offer to improve water management. However, the results of these modernization strategies have not always achieved the objectives set in the design process. For example, after the installation of AMIL-type self-operating gates in channels already built (Pedroza & Hinojosa, 2014; García, 2015), vandalism problems, difficulty in calibrating the structures, and, in some cases, continuous oscillations of the gate are observed.

Efforts to improve the canals operation include automatic control works, for example, in the Alto del Río Yaqui Canal (Aguilar-Chávez, Pedroza-González, Kosuth, & Daval, 1994) and La Begoña principal canal (González Trinidad, León-Mojarro, Carmona-Ruiz, & Rendón-Pimentel, 1999). The result obtained in the implementation of these projects was a good design and installation of automatic control systems, but it was not possible to convince the operators and users of the benefits that would be obtained by using these systems. In the case of operators, it is more complicated because they have extensive experience in manual control and regulation, and the effects of automation are not directly perceived because they do not have continuous records of volume deliveries, but only sporadic verifications.

Regarding the appropriation of new technologies, Van-Overloop *et al*. (2014) consider that to automate a channel, the participation of the human being in its operation should not be totally eliminated, so they propose adding a manual control strategy to the automatic control model (MPC) to have a combined control MoMPC (Mobile Model Predictive Control). This type of control is more accepted because it allows incorporating the knowledge of the manual operator (Van-Overloop *et al*., 2014).

For their part, Hashemy, Hasani, Majidi, and Maestre (2016), and Hassani *et al*. (2019) suggest to operate the main canal from an economic perspective, where the objective is to optimize the allocation of water to maximize the economic income derived from agricultural activities. This operating framework includes an economic model fueled by production costs, crop yields, water rates, sales prices of crops, water availability, concessions, irrigation requirements, efficiencies, etc., with the objective of maximizing the profits of the irrigation district. In addition, water distribution schemes are proposed to agricultural units based on the weighted average of the economic value of water. For the application of this strategy, Hassani *et al*. (2019) use a simulation model of the operation and evaluate the reallocation of water volumes. The results maximize the global profit of the irrigation district by taking care of the allocation of the most profitable crops.

In an irrigation canal automation project, it is necessary to find a point of equilibrium in which the benefits that users can have, in this case, the producers, and more sustainable management of the resource are considered. In this regard, it is important to include the asymmetries between users, considering their location along the canal, since the volumes and delivery times of water are met with greater certainty to the users upstream and downstream the efficiency decreases.

In some countries, in the agricultural production process, it is considered that the essential water element has a cost that is evaluated as an input and impacts production, an action that has a direct benefit in the face of any modernization action. But there are other scenarios where the cost of water does not have an economic value, for example, in Mexico, where the law indicates that the use of water for agriculture is exempt from payment of a fee according to article 224 section IV of the Law Federal Rights (Ley Federal de Derechos, 1981). This non-charging aspect of agricultural water use does not directly reflect the importance of the value of water as a resource in production, but it does not mean that it can be analyzed in another way.

According to the World Bank's experience in Bangladesh and Nepal, "poor users are willing to pay more for water as long as the system is of quality and reliable" (Norton, 2004). The reliability point is an additional value that must be considered in any improvement study in the operation of an irrigation canal. Therefore, to analyze the implementation of a canal automation project with a socio-hydraulic approach, it is necessary to have the characteristics of the engineering project, the options of

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hydraulics and electronic or fluidic automation, but also a detailed analysis of the impact on the social and economic benefit of the project.

In this work, in addition to the engineering aspects, it is proposed to dynamically evaluate the volumes delivered to each intake and the impacts on production. For example, the overall volume can be delivered but with variations in the flow rate supplied during the day, or the scheduling of an additional intake nearby produces decreases in volume. To evaluate the impacts of these variations on the water deliveries to each user, these will be analyzed based on the shadow price of the crops in the area. This analysis seeks to identify the social and environmental value of water, compared with the crop production process.

The idea of applying an economic indicator when evaluating the performance of channel control has antecedents such as the work of Álvarez, Ridao, Ramírez, and Sánchez (2013), in which the performance of a decentralized predictive control model was evaluated in the irrigation canal "La Pedrera" in Murcia, Spain. In this evaluation, an economic index was used to penalize the volume of wasted water with 0.2 €/m$^3$ and the unsatisfied demand with 0.5€/m$^3$. Regarding the amount of the penalties, Ramírez (2018) comments that "they were chosen so that they were reasonable and different numbers from each other, to indicate that the conditions of unsatisfied demand or loss of water are not equally tolerable". Figure 1 shows typical variations in the supply of flow rate and distinguishes between excess and missing deliveries concerning the expected of this.

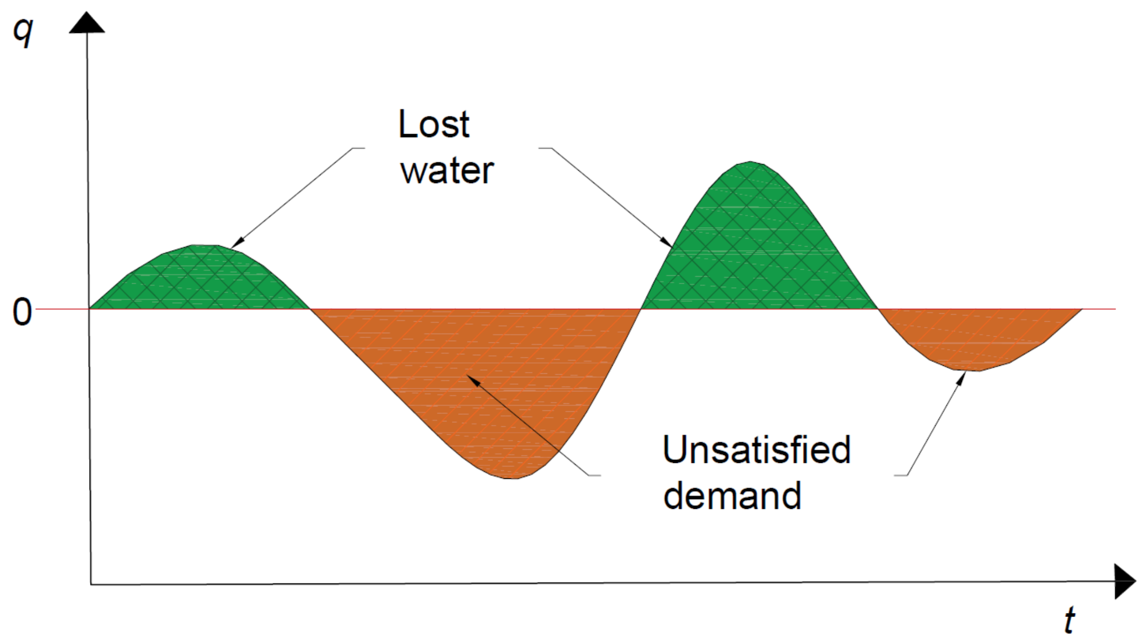


**Figure 1**. Errors in the transit of an increase in flow rate. A distinction is made between unsatisfied and excess demand and a financial indicator is applied to evaluate the performance of a decentralized predictive controller. Based on Álvarez *et al*. (2013).

## Economic and hydraulic aspects in the operation of canals in irrigation districts

The studies of the hydraulic operation of a network of channels are based on the controls of circulating flow rate and volumes delivered in the lateral intakes. In this work, a methodology that takes into account the engineering aspects (hydraulic and structural operation) and the points related to the social acceptance of the improvements and the impacts on the economy, but which in turn takes care to seek an environmentally sustainable framework is proposed. Figure 2 shows a conceptual map that involves the aspects that can be analyzed.

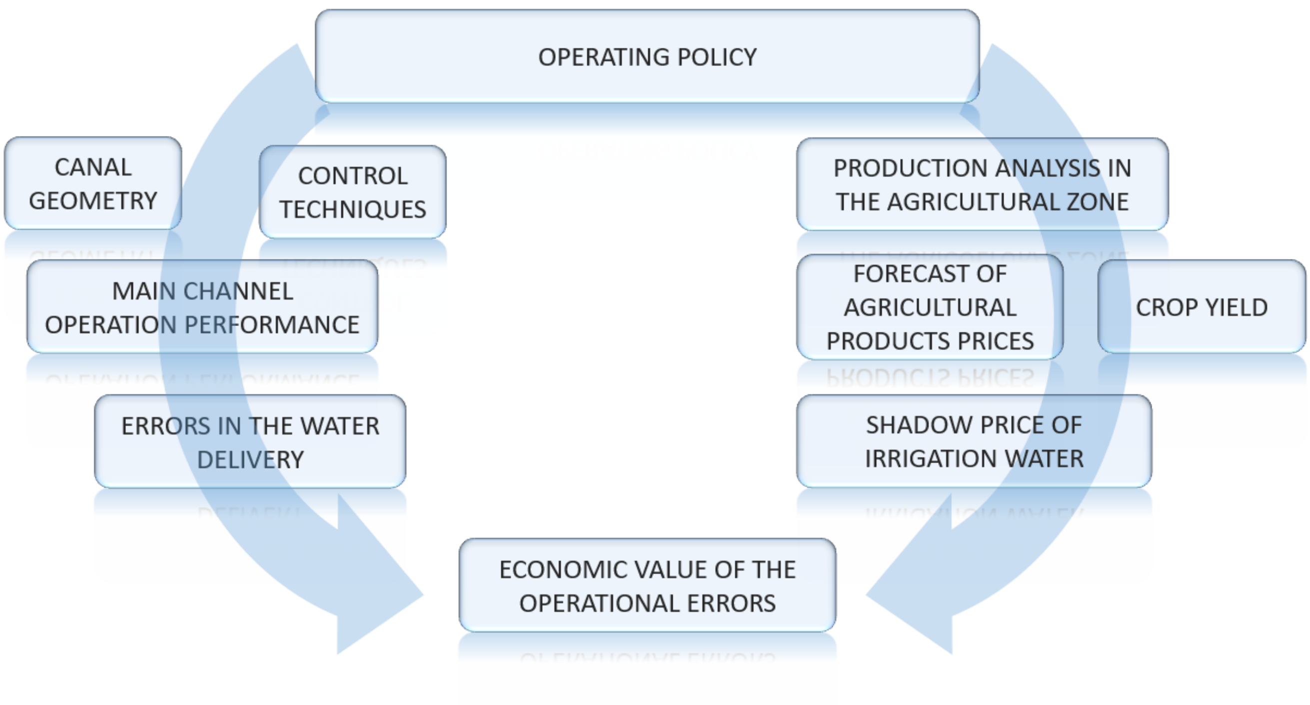


**Figure 2**. Conceptual map of integral operation of irrigation canals. The interaction between the technical aspects of the canal operation and the economic aspect of the agricultural zone is shown. The economic value of the errors in the operation is a consequence of the efficiency of the

control techniques in the face of the specific market conditions, crop yield, and water availability of a cultivation area.

On the left of the diagram in Figure 2 the factors that directly influence the hydraulic operation of the canal operation and on the right the social factors are shown. The hydraulic operation obeys the social needs of the site.

An engineering work seeks to satisfy a social need. In most orthodox cases, it is a question of installing the regulating gates so that they can be operated manually. On the other hand, any improvement action that is proposed, such as the automation of the gates and the types of algorithms with which the operation is handled, must be evaluated not only in the response of the local control but also globally. In this sense, this methodology focuses on measuring the impact generated by an operation and control technique. The starting point is to analyze the operating policy generated by the irrigation requirements at the delivery points located along the canal.

With the above, an operation scenario that is tested in a simulation model previously loaded with the channel topology is generated. The simulation results dynamically present the reliability in the delivery of flow rate to users. Ideally, there should be no difference between demand and delivery, but in reality, there are discrepancies called failures. With these values, the economic analysis will be carried out, considering the growing area, the water requirement, and the prices in the market. To evaluate the failures, three ways are proposed: i) the shadow price of corn; ii) the price of the irrigation district operation, and iii) the productivity of the irrigation zone.

The shadow price of water represents the value by which net income would increase if an additional unit of water were available (Zetina-Espinosa, Mora-Flores, Martínez-Damián, Cruz-Jiménez, & Téllez-Delgado, 2013). The price of the irrigation district operation is the minimum with which the irrigation district would cover all its operating expenses (Torres-Sombra & García, 2015). The productivity of the area refers to the relationship between each cubic meter of water required and the average rural price (PMR) estimated with a projection of future market prices. Because irrigation areas have different levels of productivity and water availability, it is proposed to analyze the crops in the area for each case, which involves their water consumption, yields, production costs, and market prices.

## Operation scenarios of an irrigation canal

To determine with certainty the circulating and delivered volumes at each extraction point of the canal, it was necessary to adapt a numerical model that solves the dynamics of the circulating flow and the boundary conditions of the control and regulation structures and to evaluate the flow rate that they deliver in each lateral outflow. The model used is the SFT (Transient Flow System in irrigation canals) (Cruz-Mayo, Aguilar-Chavez, & De-la-Torre, 2019) and solves the Saint-Venant equations in its conservative version (Abbot, 1979), which includes lateral flow rates and section changes.

The SFT is a non-linear finite difference model (Aldama & Aguilar, 1996), with a coupling of the boundary conditions for the regulation gates that allows generating a multitrack model (Cruz-Mayo *et al*., 2019). In addition to the numerical model for the solution of the flow equations, the SFT allows monitoring of the levels and flow rates at different points of the channel and running in parallel a control model of the gate openings.

## Channel operation

The objective of channel control is to provide each user with the required volumes at the right time, to reduce losses as much as possible, to protect the infrastructure (Malaterre, 2007), and to reduce fluctuations in the flows rate delivered. Failure to comply with the above affects the reliability of the water distribution system, especially for users located in the tail of the canal (Clemmens *et al*., 1994). The physical part of the system to analyze the control strategies is the channel network. In this case, an operation scenario is proposed, and control models with different methodological proposals that are analyzed with the SFT model will be used.

According to Hashemy and Roozbhani (2015), when choosing the type of control in the main channel, criteria that cover the technical, economic, and social aspects suitable to the place of study should be used. The technical criteria are to evaluate the method of operation by controlling levels and flow rates discharge. The economic criterion refers to the costs of implementing the operating technique (sensors, data loggers, automatic actuators, etc.). The social aspects refer to the willingness of the users to operate, take care of the equipment, and safety issues of the facilities to mitigate vandalism.

This work considered the condition that most of the main channels in Mexico operate with control upstream of the regulatory structures and, therefore, it is required to have a constant level to provide a constant derivation of flow rate to the secondary channels. This condition is the main evaluation point of the volumes required by users.

## Gate control methods analyzed

### Control with delays

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The irrigation canals operator prepares irrigation schedules based on the volumes previously requested by users. In this way, the day, time, and volume to be delivered in each outflow are known in advance. The following describes the manual control algorithm based on the delay of a wave crossing the channel, which is estimated as:

$$\Delta T_{m,i} = L_i / U_i \quad (1)$$

where $\Delta T_{m,i}$ is the delay in the ith structure of the channel for a flow rate ($Q_m$) m-th established at the beginning of the channel (dynamic condition of manual control operation); $L_i$ is the distance between the head of the channel and the control structure and $U_i$ is the absolute velocity in the section upstream of the gate.

With the condition of circulating flow rate in the section, the openings ($w_i$) are determined with the discharge law of the gate, from the conditions of the gradually varied flow profile simulated before each condition of expected flow rate ($Q_m$) and operation level ($y_f$).

The absolute speed ($U_i$) depends on the average speed $u_i(A_J^0$ and the wave speed ($\sqrt{gD_J^0}$) with which a wave crosses each section i (Chaudhry, 2008) and is calculated with the following expression:

$$U_i = u_i + \sqrt{gD_J^0} \quad (2)$$

In the calculation of $u_i$ and $c_i$, the area $A_J^0$ and $D_J^0$ of the initial condition is considered since it is sought that there are no variations in the operation level.

Finally, the gate actuation time $H_m$ is calculated, with the accumulated values of the delays $\Delta T_{m,i}$. This method is preloaded in the SFT. Some of the limitations of this method are: it does not consider unexpected extractions, the delay induced by some operations is not evaluated, and it depends on the punctuality and ability of the channel operator to make the gate openings and closings.

## Mass balance control

This global control strategy consists of counting every certain time the errors made in the water deliveries and applying for compensation in a period that the operator establishes. In the case of this study, the mass balance control strategy was applied with the following methodological sequence:

1. An extraction downstream of section *n* is detected.
2. Local control is activated for 30 minutes.
3. A mass balance is calculated, and volume compensation is programmed for the next 20 minutes.

4. The next 10 minutes are to stabilize the flow, so the gates do not move.

5. Finally, the last corrections are made with the local control at the operation level.

Volume compensation is global and is applied proportionally by sections, establishing the missing volume and the gate opening in the upstream gate.

## Local control generated with disturbance techniques (Perturbation)

If the objective of the control is to keep constant over time the operating level $\bar{y}_r$ and a known flow rate discharge $Q$, in this case, it is considered that the only dynamic values of the system are the gate opening $w(y_3, y_r; t)$ and $y_3\,(t)$, $y_r(t)$ downstream and upstream water level, respectively. Through a series expansion of Fréchet-Taylor (Milne, 1980) the opening and the upstream tie were expressed as a function of the target tie and the possible perturbations in the discharge of a gate. Thus, the opening of the gate is evaluated with the model (3) (see appendix A):

$$w^{n+1} = w^n + K_L K_{p_1} y_r' \quad (3)$$

where $w^n$ is the current gate opening and $w^{n+1}$ the update; $F_1$ contains the invariant terms of the discharge $F_1 = \frac{Q}{C_d b\sqrt{2g}}$; $K_L$ is a coefficient with values from 0 to 1 that applied to the derivative $Kp_1$ helps to smooth the perturbations generated by the movement of the gate; the coefficients $K_{p1}$ y $K_{p2}$are defined as:

$$K_{p_1} = -\frac{1}{2} F_1 \cdot (y_r - y_3)^{-1.5} \quad (4)$$

$$K_{p_2} = \frac{3}{8} F_1 \cdot (y_r - y_3)^{-2.5} \quad (5)$$

For this algorithm, it is required to define the time interval in which the control remains active ($T_{control}$) and the time interval in which the new gate motion will be calculated ($T_{motion}$). This control allows estimating the value of the coefficients $Kp_s$ based on the same physical properties of the discharge. As can be seen in its formulation, it focuses on level control.

## Stringam Control

Stringamand Wahl (2015) proposes a formula designed for people who are not familiar with control techniques. It is a proportional type control algorithm since a proportion is established between the current gate opening ($ngp$) and the flow rate ($pQ$ ), with the new gate opening ($ngp$)) to circulate the desired flow rate ($nQ$). Given the ratio, it is possible to obtain the new gate opening for any flow rate by applying a rule of three:

$$\frac{ngp}{nQ} = \frac{pgp}{pQ} \tag{6}$$

If the new gate opening ($ngp$) is expressed in terms of the change of the gate position ($\Delta gp$) and the current gate position ($pgp$), by substituting $ngp$ in the previous proportion and solving for $\Delta gp$, it results that the opening change of the gate depends proportionally ($K_p = \frac{pgp}{pQ}$ ) on the flow change ($e = nQ - pQ$).

$$\Delta gp = \frac{pgp}{pQ}(nQ - pQ) = e\left(\frac{pgp}{pQ}\right) \tag{7}$$

Thus, it is observed that this equation contains the proportional gain coefficient. Stringam and Wahl (2015) mention that this method is appropriate when the phenomenon is of short frequency so that in the case of channels it can enter into resonance if very fast gate movements are made. The control times depend on the volume change ($\Delta V$) required in the channel to achieve the proposed flow rate change:

$$\Delta V = LB(\Delta y) \tag{8}$$

where $L$ is the length of the channel section; $B$ is the average of the width of the free surface in flow ranges under analysis and $\Delta y$ is the change in the tie necessary to obtain the new flow rate. So, the time required to make the expense change is:

$$\Delta t = \frac{\Delta V}{\Delta Q} = LB\frac{\Delta H}{\Delta Q} = LB\frac{dH}{dQ} \tag{9}$$

The term $\frac{dH}{dQ}$ depends on the flow rate control structure performance. This control is focused on flow rate and can be applied to a manual operation.

## Proportional-integral-derivative control (PID)

The PID control is of the feedback type; it feeds on the errors of the past and is defined as a function of the error of the control variable $e(t)$ . The errors are affected by the proportional ($K_p$), integral ($K_i$) and derivative ($K_d$) gain coefficients of the controller (Astrom & Murray, 2008). The output signal $y(t)$ will be given by model (10):

$$y(t) = K_p e(t) + k_i \int_0^t e(t)\, dt + k_d \frac{de}{dt} \tag{10}$$

In the calibration of the coefficients $K_p$, $K_i$ and $K_d$, the control systems design and analysis tools of MATLAB® (The Mathworks, I. N., 2019) are applied. When the plant model is not known, one option to identify the physical system, that is, to calculate the coefficients $K_p$, $K_i$ and $K_d$, is to start from data measured at the input and output of the system. For the application case shown in this article, the channel responses are used when applying delay control. The error in the tie is taken as input and the gate openings as output.

## Artificial neural network control (ANN)

The numerical method of artificial neural networks tries to imitate the behavior of the human brain. It goes through a training process in which, through an input variable, it is sought to recognize a known output variable. Once the system has learned, it can identify and classify previously unseen patterns (Nunes- da-Silva, Hernane-Spatti, Andrade-Flauzino, & Bartocci-Liboni, 2017). This method has shown good results in non-linear problems (Durdu, 2004; Ruslan, 2014; Mohapatra & Lenka, 2016). In the identification of the channel dynamics with ANN, the variations of the tie ($\Delta y_J^n$) concerning the target of the water level ($y_f$), and variations in flow at the beginning of the section ($\Delta Q_1^n$) and variations in gate opening ($\Delta w^n$) as output variable:

$$\Delta y_J^n = y_J^n - y_f \tag{11}$$

In this study, a network with NARXNET architecture (for the acronym of Nonlinear Autoregressive Network with exogenous inputs) is used, since it showed good results in the identification of the "El Bocal" section, according to Hernandez, Feliu and Rivas (2017). This type of network is dynamic and autoregressive with feedback connections at various layers of the network. The NARX model is described by equation (12) (Haykin, 2010) (Figure 3):

$$w^{n+1} = F(w^n, \ldots, w^{n-q+1}; x^n, \ldots, x^{n-q+1}) \tag{12}$$

where $w^{n+1}$ is the next value of the dependent output signal, in this case, the gate opening; $F$ is a nonlinear function; $x^n$ represents the inputs originating from outside the network, which will be made up of $\Delta y_J^n$ and $\Delta Q_1^n$.

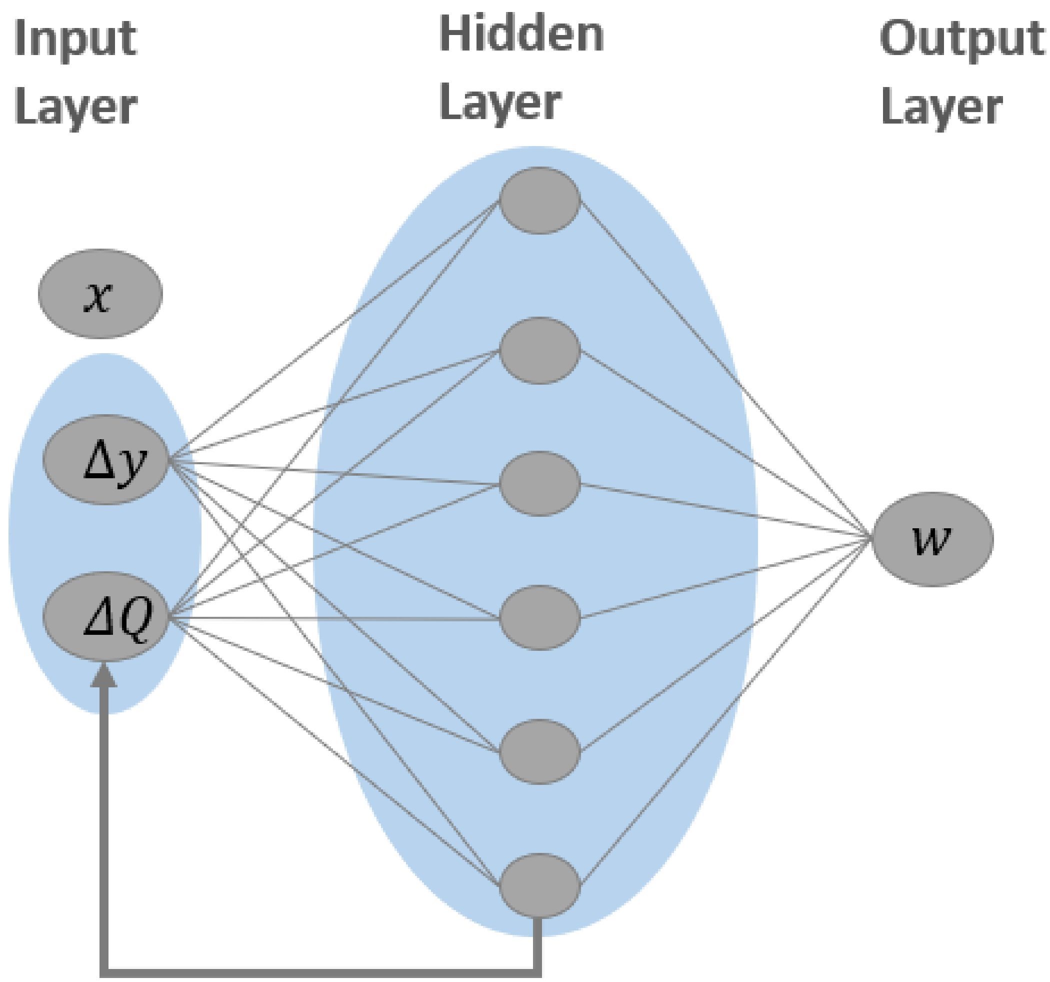


**Figure 3**. Architecture of NARX AAN. In the input x (t) there are two data classes $\Delta y_J^n$ and $\Delta Q_1^n$.

The training data series was generated with a 24-hour SFT simulation, in which a sequence of pulses ranging from 63 m$^3$/s to 77 m$^3$/s with 2-hour intervals was assigned as the hydrograph at the head of the channel. As

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a control strategy, a local PI control was applied, with $kp = 0.3533$ and $k_i = -0.0087$. The parameters used were: $t_{control} = 900\ s$; $t_{motion} = 1200\ s$ and $\Delta t = 30\ s$. In the hidden layer, a sigmoidal tangent and pure-line activation function was used in the output layer, while the Levenberg-Marquardt method was applied in the training.

## Mixed control

Mixed control consists of a combination of global and local control, usually automatic. This type of control is an alternative to fully manual or automatic control systems. Van-Overloop *et al*. (2014) mention that this strategy allows the human being to be fully involved in the control cycle and at the same time offers better results than control by delays. In addition to providing security for the equipment, it promotes the acceptance of new technologies and has less gate movement than a fully automatic control.

In this control strategy, the important gate openings are programmed to have flow rate control. Subsequently, local automatic control is activated to make small corrections during a window of time, called control time, and thus correct the operation level. Table 1 shows the combinations proposed for this study.

**Table 1**. Mixed control strategies.

| Name | Control involved | Description |
|---|---|---|
| Mixed 01 | Delay + Perturbation | Program the strong changes of the gate based on the delay method and the minor settings with a perturbation local control |
| Mixed 02 | Delay + PID | Program the strong changes of the gate based on the delay method and the minor settings with a PI local control |
| Mixed 03 | Mass Balance + Perturbation | Changes in the flow rate based on compensation of mass balances and minor movements with a perturbation local control |

## Control performance indicators in irrigation canals

The ASCE proposed performance indicators to compare the performance of different control algorithms (Clemmens et al., 1998). In this study, the maximum absolute error (MAE), the absolute integral of the error (IAE), and the absolute integral of the movements of the gate (IAW), described in equations (13) to (14), are used. These indicators allow monitoring the maximum error generated by the control algorithm, the response speed, and the trend of the final error to zero.

$$MAE = \max(|y_f - y_o|) / y_o \quad (13)$$

$$IAE = \frac{\frac{\Delta t}{T_{(12-24h)}} \sum_{t=0}^{T} |y_f - y_o|}{y_o} \quad (14)$$

$$IAW = \sum_{t=t_1}^{t_2} (|W_t - W_{t-1}|) - |W_{t_1} - W_{t_2}| \quad (15)$$

where: $y_f$, is the operating depth in meters; $y_o$, is the depth measured at the control point.

To calculate the economic and hydraulic indicator, the following process is applied:

1. Simulate the operation policy of the irrigation canal in the SFT system with the different models of control of the opening of the gates for a scenario of modification of the desired expense ($Q_n$).
2. Calculate the differences in volumes between the desired flow rate ($Q_n$) and the one actually delivered ($Q_{nr}$). It is distinguished if the error is due to flow rate delivered in excess ($\Delta V_e$) or missing ($\Delta V_f$) with the following expression

$$\Delta V_{e/f} = \int_{t_1}^{t_2} (Q_n - Q_{n_r}) dt = \sum_{n=1}^{N} (Q_n - Q_{n_r}) \ dt \quad (16)$$

Three ways of economically evaluating errors in the delivery of water volumes are analyzed. The first is based on the price per cubic meter of water that must be paid to cover the operating costs of the irrigation district. The second refers to the shadow price of water in the crop with the highest production in the irrigated area and the third has to do with the economic productivity of a crop and its water consumption in a given irrigated area. The procedure to economically evaluate the volume of water consists of analyzing the operation and calculating the value of the production of the cubic meter of water in the irrigation zone, as described below:

1. Calculate the yield of crops in the area.
2. Calculate the net sheet of water required for each particular crop and subsequently evaluate the volume required to irrigate the entire area corresponding to each crop.
3. Make a forecast of the sale price of the product according to historical data. For this, use will be made of the database of the National Market Information and Integration System (SNIIM) of the Ministry of Economy (Secretaría de Economía, 2019).
4. Calculate the relationship between the price of production and the volume of water used.

# Case study

The main canal El Carrizo, located in the Irrigation District 076 (Valle del Carrizo, Sinaloa) was designed to convey water from the Josefa Ortiz de Domínguez dam to irrigate 43,000 ha of the Carrizo district; 35,000 ha of the Fuerte-Mayo expansion; 6,000 ha of the La Capilla and Los Llanos modules, making a total of 84,000 ha. For this study, the first 32 km of the main channel of the Carrizo, known as the dead section, have been selected, since it does not have extractions until km 32 + 000 (Figure 4).

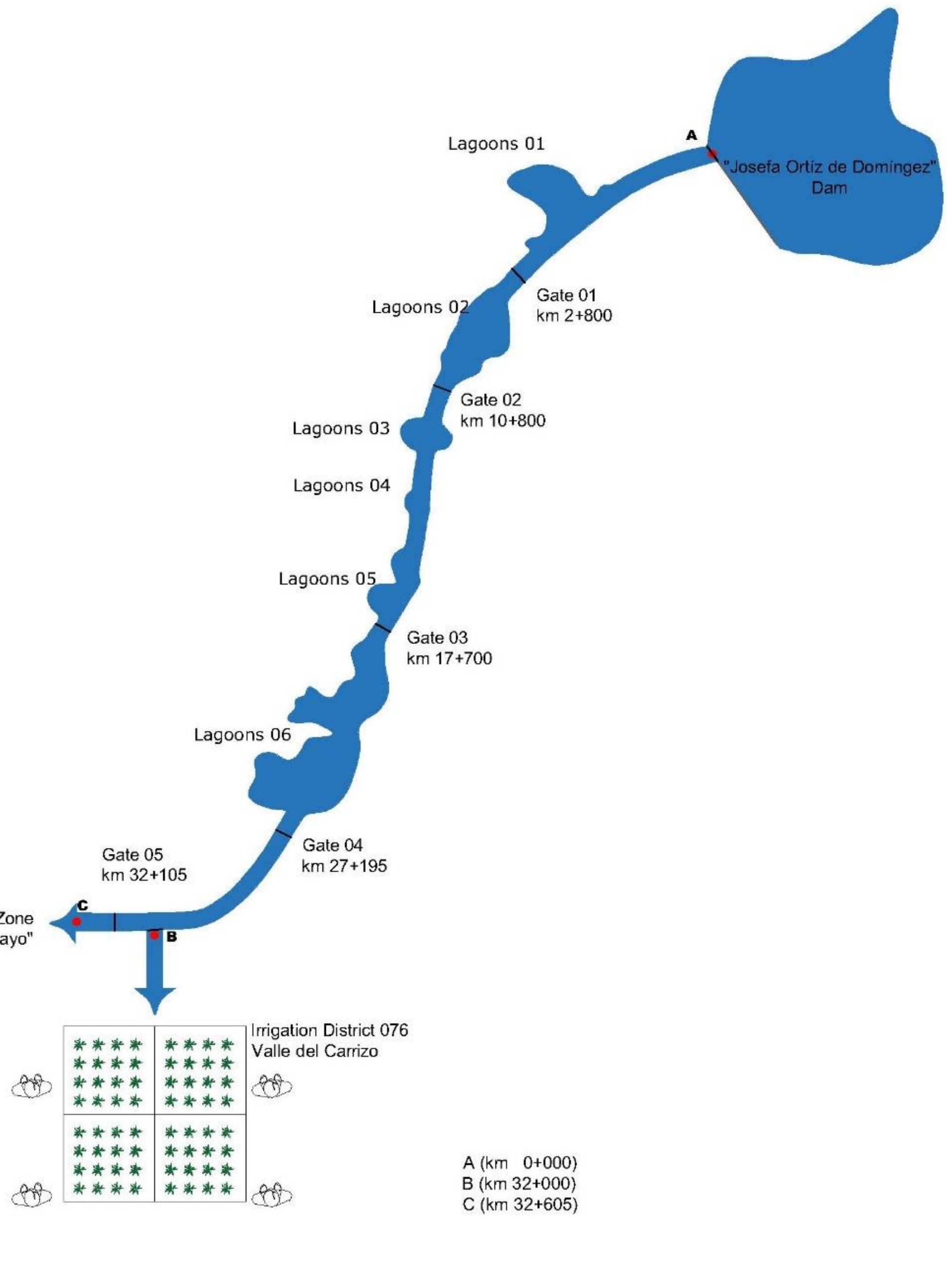


**Figure 4**. Scheme of the main channel under study. Point A is the beginning of the canal, at point B the lateral intake towards the DR 076

Valle del Carrizo is located, and point C is the end of the section of the canal understudy, flow continues to El Fuerte-Mayo.

This is an interesting case to evaluate since it crosses regulation lagoons that extend from 1.7 km to 0.6 km the smallest, measured on the axis of the channel. In total there 8,740 km of unlined and vegetated lagoons, which induce an additional delay or can also be used to advance volumes in the operation, but in both cases, they influence the dynamics of the canal. The dead section leads the water to supply DR 076 Valle del Carrizo in the first intake and the canal continues towards the Fuerte-Mayo irrigation zone. The water is intended for agricultural and domestic use, and is a possible point of conflict due to disputes over the delivery of volumes, since it is an arid area.

Geometry of the section. The main channel has a trapezoidal section of 5 m template, slopes of 1.5: 1, and slope of $S_o = 0.0003$ from km 0 + 000 to km 20 + 800 and from this mileage to km 26 + 100 the slope is 0.0005. The rest of the parameters are preserved in the channel cross section.

Geometry of the structures. In this section of the canal, there are dams with two gates that are 4.15 m wide, so the discharge coefficient will be calculated with the Swamee (1992) model. In this study, it is considered that the dikes do not receive contributions from the rain in the canal's operating season.

Channel hydraulic data. The section from 0 + 000 to 32 + 000 is operated with a flow rate of 70 $m^3/s$ and a normal depth of 4.26 m. The canal has sections lined with concrete with roughness $n = 0.015$ and in the channel section without revesting, sinuous, with the low-velocity flow and a little grass, $n = 0.015$ (Chaudhry, 2008).

Channel operation. The canal's supply source is the Josefa Ortiz de Domínguez dam, the point at site A in Figure 4. From this site to km 32 + 080 there is a diversion to DR 076 Valle del Carrizo (B) and the canal continues towards the Mayo-Fuerte irrigation zone (C). The water that carries this canal is for agricultural use but has a continuous annual demand for urban public use of 0.5 $m^3/s$. The agricultural cycles are autumn-winter and the demand for crops is suspended in the spring-summer period. For the analyzes, it is proposed to simulate the 8-hour operation in the SFT program, as indicated in Table 2, and an increase in demand is evaluated at point B (DR 076 Valle del Carrizo), but it would be kept for the delivery cost at point C (Fuerte-Mayo district) (Figure 5).

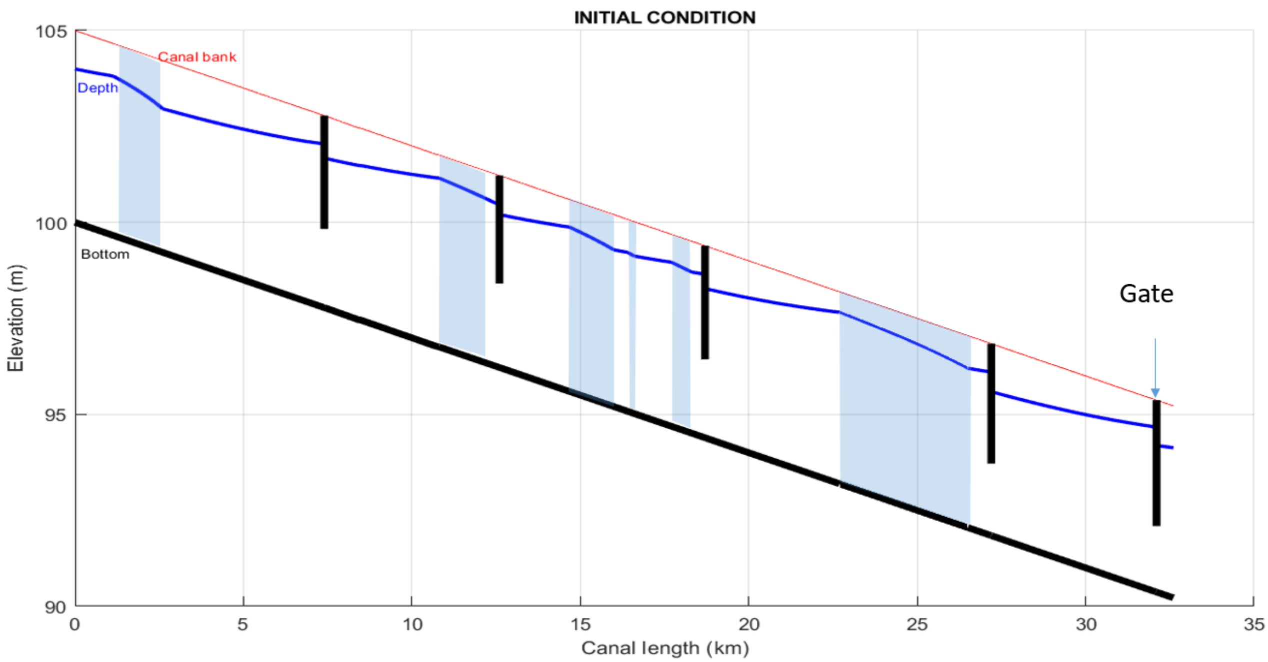


**Figure 5**. Channel flow profile. The shaded stripes show the location of lagoons on the channel axis ($n = 0.30$), gates and flow profile for $Q = 70\, m^3/s$ and extraction $q_{lat} = 15\, m^3/s$.

**Table 2**. Eight-hour operating program. There is an increase in the demand of the intake in B and in C continues constant.

| Schedule | Delivery points | | |
|---|---|---|---|
| | A | B | C |
| 0:00 | 70 | 15 | 55 |
| 0:05 | 70 | 15 | 55 |
| 0:10 | 77 | 15 | 55 |
| 1:10 | 77 | 15 | 55 |

| | | | |
|---|---|---|---|
| 1:15 | 77 | 22 | 55 |
| 8:00 | 77 | 22 | 55 |

In the operation of the gates, the changes in the opening must be less than or equal to 5% of the current opening (Stringam & Wahl, 2015), to avoid abrupt openings or closings that induce instability in the system.

## The economic value of water in the irrigation zone

As mentioned above, three ways of evaluating operation failures are considered. To evaluate the price of irrigation water for corn, the study presented by Bierkens, Reinhard, De-Brujin, Veninga, and Wada (2019), where they analyze the shadow price of irrigation water in the countries with the greatest depletion of groundwater, among which Mexico appears. In the production function used by Bierkens *et al*. (2019) the use of green water (precipitation), blue (irrigation), non-renewable (underground) is considered and the costs of seeds, fertilizers, herbicides, energy, labor, and capital are involved.

Table 3 shows the shadow prices calculated for five crops in Mexico, based on FAOSTAT, for the period 1991-2010 (Bierkens *et al*., 2019). Torres-Sombra and García (2015) mention that, to cover the operating costs of the agencies that manage the resource in the irrigation districts of Sinaloa, Mexico, water should cost US $ 0.014 /MX$0.221 m3 (US$1 = MX$15.82).

**Table 3**. The shadow price of irrigation water in five crops in Mexico. Source; Bierkens *et al*. (2019).

| **Period** | **Wheat (US$)** | **Potato (US$)** | **Corn (US$)** | **Rice (US$)** | **Citrus (US$)** |
|---|---|---|---|---|---|
| 2006-2010 | 0.022 | 0.156 | 0.053 | 0.004 | 0.081 |

On the other hand, a projection of the productivity of the cubic meter of water in the irrigation areas is made, in which the surface and yield of the 11 main crops (Conagua, 2018) are considered. The net sheet required for each crop and subsequently the required volume was evaluated at an efficiency of 76%. Based on the price records of the National Information and Market Integration System (SNIIM) of the Ministry of Economy (Secretaría de Economía, 2019), a projection was made for the following months. With the cultivated areas and the yield reported by Conagua (2018), Table 4 shows the calculation of the volume of water required by a crop and the sale prices. The results are that the average productivity of water is US$ 0.70/$m^3$ and that of corn, the largest crop after wheat, is US$0.26/$m^3$.

**Table 4**. Irrigation sheet and net volume required by the crops in the irrigation zone. Source: Prepared by the authors with data from *Conagua (2018) and ** Secretaría de Economía (2019).

| | Num. | Crop | A * | Ya * | $Ln\_total$ | 2019 P.M.R. ** | Water productivity |
|---|---|---|---|---|---|---|---|
| | | | (ha) | (ton/ha) | (m) | (US$) | $/m$^3$ |
| Autumn-winter | 1 | Wheat grain | 62,745 | 5.6 | 0.552 | 176.14 | 0.14 |
| | 2 | Corn grain | 6,357 | 9.6 | 0.811 | 291.58 | 0.26 |
| | 3 | Tomato | 1,919 | 18.5 | 0.737 | 311.85 | 0.60 |
| | 4 | Beans | 906 | 1.6 | 0.442 | 753.63 | 0.21 |
| | 5 | Sorghum grain | 832 | 5.7 | 0.941 | 151.71 | 0.07 |
| | 6 | Asparagus | 507 | 5.9 | 1.106 | 4417.88 | 1.80 |
| | 7 | Pumpkin | 491 | 15.0 | 0.460 | 467.77 | 1.16 |
| | 8 | Safflower | 20 | 1.6 | 0.491 | 436.59 | 0.11 |
| | 9 | Garbanzo Garbanzo | 259 | 1.6 | 0.430 | 1031.18 | 0.29 |
| | 10 | Potato | 130 | 24.5 | 0.552 | 779.63 | 0.003 |
| | 11 | Watermelon | 115 | 45.0 | 0.460 | 415.80 | 3.10 |

# Results

## Global control

The gate opening schedule resulted in the schedule in Table 5. The operator must move approximately 25 km/h from one control point to the next, which is conditioned by the state of the dirt roads. In a second test, it was verified that there are no significant changes in the results when rounding the gate actuation hours to multiples of 5 minutes.

**Table 5**. Gate movement operation with delay control.

| Gate | Location | Movement 1 | | Movement 2 | |
|---|---|---|---|---|---|
| | | HH:MM:SS | Gate opening | HH:MM:SS | Gate opening |
| 3 | Km 2+600 | 0:28:59 | 2.38 | - | - |
| 6 | Km 10+800 | 0:42:21 | 2.64 | - | - |
| 13 | Km 17+700 | 0:57:35 | 2.44 | - | - |
| 18 | Km 27+195 | 1:19:02 | 2.11 | 2:34:02 | 2.11 |
| 23 | Km 32+085 | 1:32:05 | 1.85 | 2:47:05 | 1.72 |

## Local control

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With the control derived from the perturbation method, the coefficients $k's$ are updated in each control time interval. The PID control gain coefficients obtained after channel identification in the "Analysis and design of control systems" module in MATLAB® (The Mathworks, I. N., 2019) are shown in Table 6.

**Table 6**. PID controller coefficients.

| **Gate** | $kp$ | $ki$ |
|---|---|---|
| 1 | -0.3533 | -0.0087 |
| 2 | -0.4060 | -0.0061 |
| 3 | -0.4060 | -0.0061 |
| 4 | -0.3533 | -0.0081 |
| 5 | -0.4060 | -0.0061 |

The control of Stringam and Wahl (2015) calculates with equation (7) the correction $\Delta w$ every 5 minutes and executes the change in the opening of the gate in 2 minutes. In this way, the operating level upstream of gate C was stabilized in approximately 20 minutes.

In the initial condition, the gate of the side intake (intake B) has an opening $w_o = 0.28\ m$; at 1:20 am it begins to open until it reaches the opening $w_1 = 0.42\ m$. With this change in the side gate the extraction

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changes from 15 to 22 m$^3$/s. The operation of the side hatch is supposed to be manual, its opening lasts 5 minutes and is subsequently fixed at $w_1$. Due to this, and as can be seen in Figure 6, the lateral discharge depends only on the tie upstream of intake B, which will depend on the control in gate C. Meanwhile, in the gates of the main channel, the operation is done according to the control algorithms mentioned above. In Figure 7 the variations of the opening of gate C on the main channel are shown.

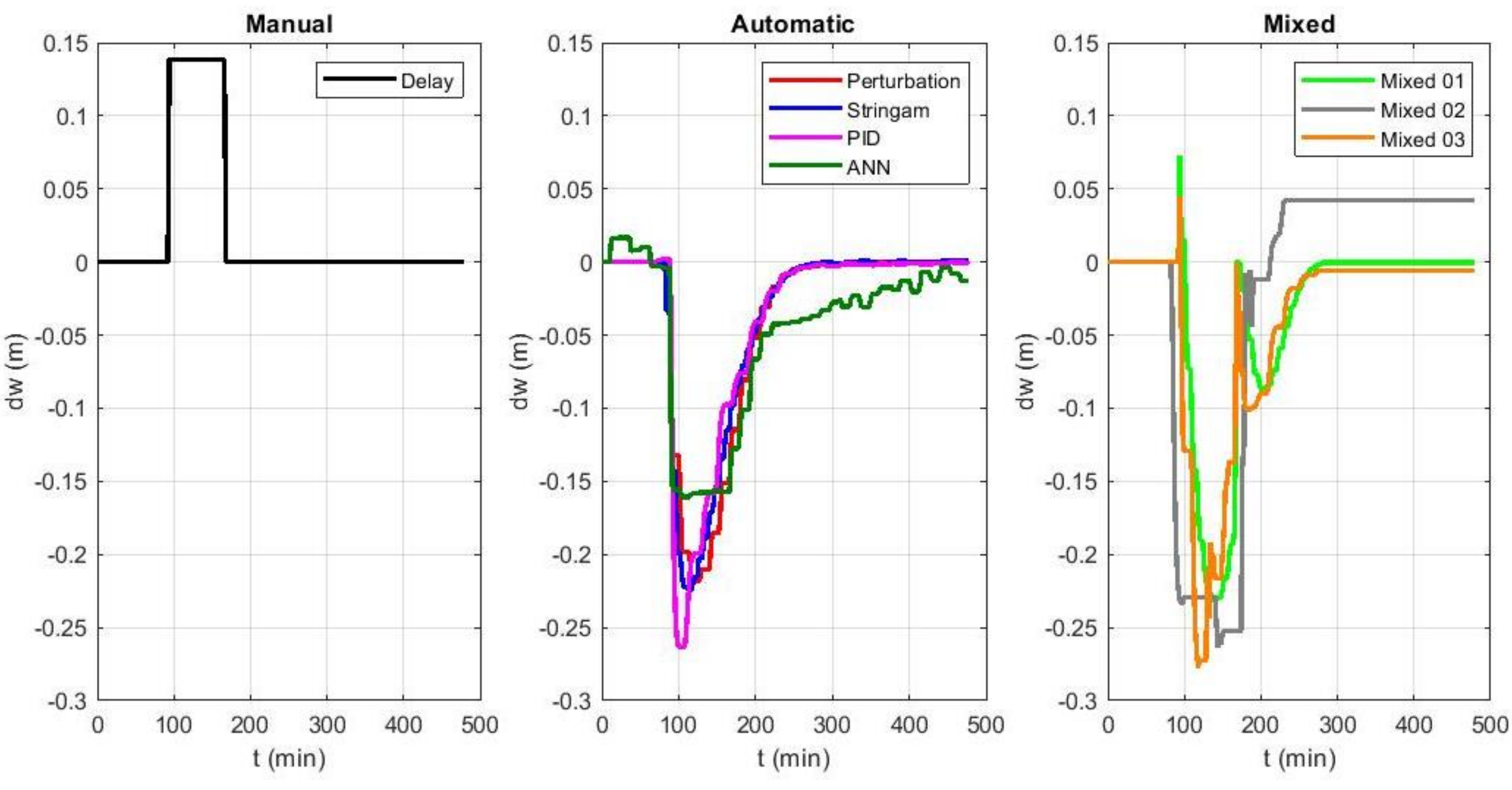


**Figure 6**. Adjustments in gate C opening (main channel). This graph shows the gate movements executed by each category of the control algorithm. Here the response of the control algorithms to the increase in

lateral extraction can be seen (which starts at 1:10 h), since gate C begins to respond at 1:32 h (Delays), 1:10 h (PID), 1:14 (Stringam), 1:16 (perturbation), 1:32 h (mixed 1 and 3) and 1:20 h (mixed 2).

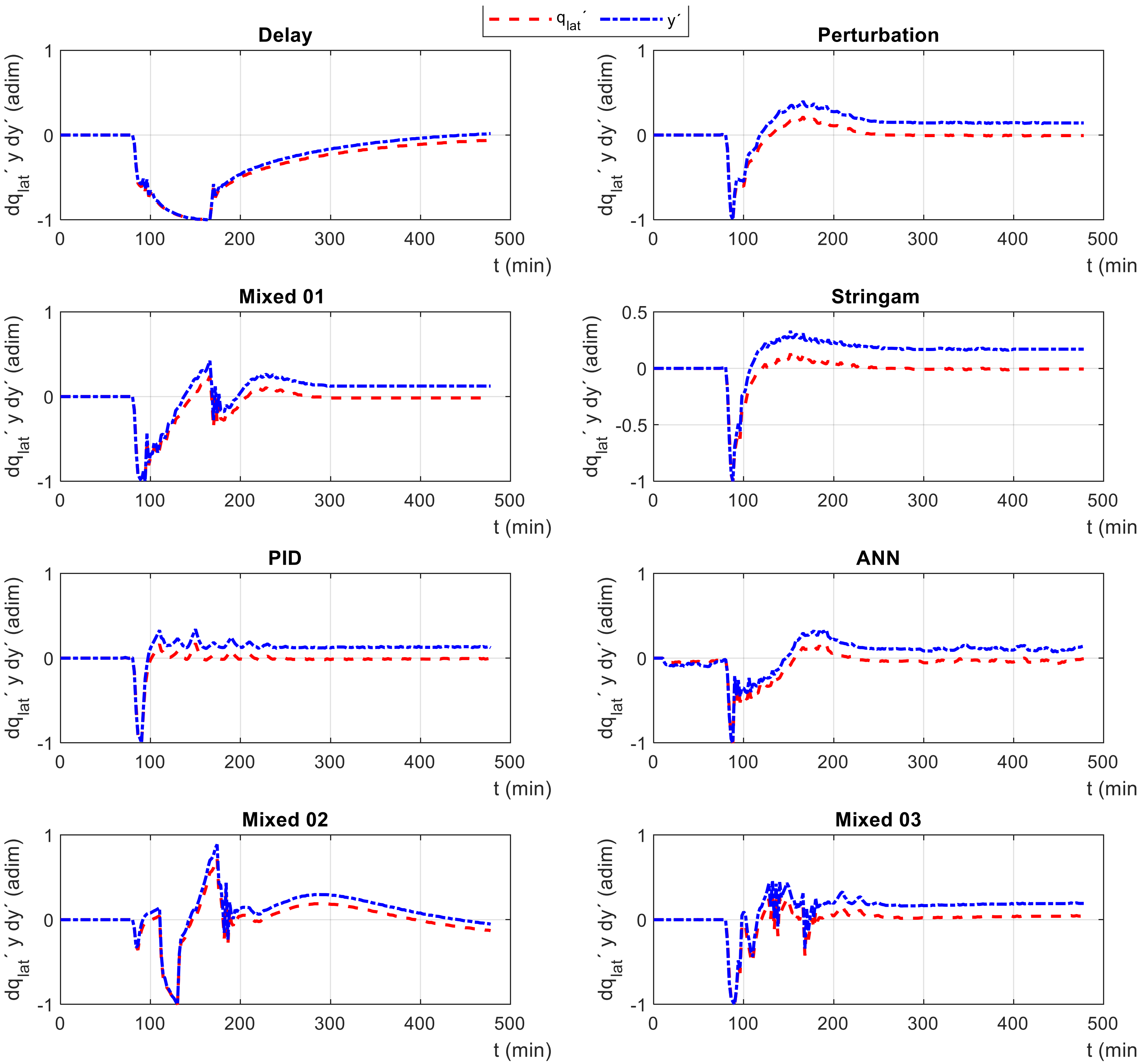


**Figure 7**. Normalized errors of lateral flow and level of operation in intake B, concerning the maximum error $(x' = (x^n - x^0)/máx(|x^n - x^0|))$.

Figure 8 shows the results in flow rate and water level on the main channel (point C), after applying the control algorithms. In gate C, except for delay control, the discharge depends directly on the gate opening. In the mixed control algorithm 2, the channel entrance hydrograph according to the mass balances executed every 30 minutes during the simulation was calculated.

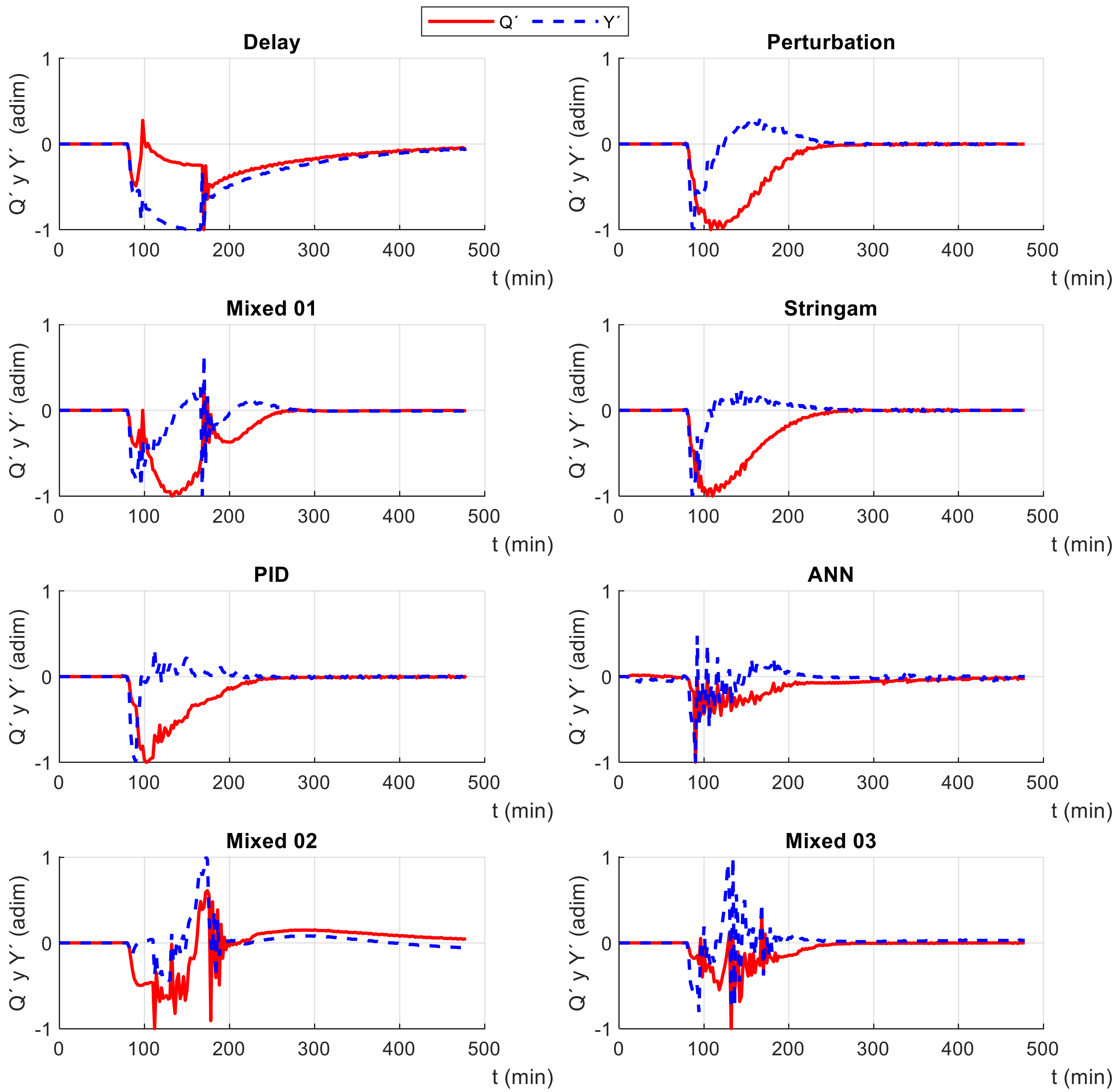


**Figure 8**. Normalized errors of the flow and operation level in gate C. Q´ and Y´ are the normalized variations of the flow rate discharged by gate C and operation water level.

# Discussion

When comparing the performance indicators of the control algorithms in Table 7 with those reported by Clemmens *et al*. (1998), it is observed that the performance of the control algorithms on the main channel (see Figure 8) are within the values reported in the literature: IAE ≈ 0.60 % and MAE = [2.2-2.5]%.

**Table 7**. Performance indicators in the lateral intake B, km 32 + 00.

| **Method** | **MAE** | **IAE** | **Dy** |
|---|---|---|---|
| | **%** | **%** | **M** |
| Delay | 3.52 | 0.24 | 0.15 |
| Perturbation | 1.95 | 0.08 | 0.08 |
| Mixed1 (D+P) | 2.04 | 0.08 | 0.09 |
| Stringam | 1.65 | 0.07 | 0.07 |
| PID | 2.07 | 0.07 | 0.09 |
| AAN | 1.96 | 0.07 | 0.08 |
| Mixed2 (B+P) | 3.28 | 0.14 | 0.14 |

| | | | |
|---|---|---|---|
| Mixed3 (D+PID) | 2.04 | 0.09 | 0.09 |

Figures 6 and 8 show that the response of control of flow rate and water level of the local control algorithms (perturbation, Stringam, PID, and AAN) is faster and more stable, as indicated by the IAE ≈ 0.07 %. Local control methods, except for AAN, achieved net losses of less than US$13.00 (see Table 8). The Stringam method and the PID method had net losses of US $ 9.5; It is not a coincidence that these methods have such similar results since according to Stringam and Wahl (2015), their method is a simplification of the PID. However, the Stringam method can be executed for manual control and the PID is only for automatic control.

**Table 8**. Evaluation of losses in lateral intake B (DR 076 del Carrizo).

| Control method | Excess Volume | | Missing volume | | Surplus (Operation) | Missing (Shadow) | Net losses |
|---|---|---|---|---|---|---|---|
| | $m^3$ | % | $m^3$ | % | US$ | US$ | US$ |
| Delay | 0 | 0.00 | 3765 | 0.63 | 0.0 | 199.6 | 199.6 |
| Perturbation | 180 | 0.03 | 290 | 0.05 | 2.5 | 15.4 | 12.9 |
| Mixed 1 (D+P) | 97 | 0.02 | 635 | 0.11 | 1.4 | 33.6 | 32.3 |
| Stringam | 78 | 0.01 | 198 | 0.03 | 1.1 | 10.5 | 9.4 |
| PID | 68 | 0.01 | 197 | 0.03 | 1.0 | 10.4 | 9.5 |
| AAN | 80 | 0.01 | 561 | 0.09 | 1.1 | 29.7 | 28.6 |
| Mixed 2 (B+P) | 776 | 0.13 | 694 | 0.12 | 10.9 | 36.8 | 25.9 |
| Mixed 3 | 273 | 0.05 | 288 | 0.05 | 3.8 | 15.3 | 11.4 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| (D+PID) | | | | | | | |
| Expected | 598 320.00 | | | | | | |

Better results were expected from the ANN model since in its approach the errors both in tension and expenses are included as inputs. However, the quality of the AAN depends a lot on the quality of the training data, which in this case were produced with another numerical model, which could cause errors to be dragged. This could have been avoided by using data from direct measurements in the field. Despite the drawbacks, the net losses calculated with RNA are much lower than the lag method.

While delay control is the method that generates the greatest losses in intake B (US$199.6), it shows good performance over the main channel (percentage of operating errors less than 5% (Luján, 1991), because it is designed to deliver on time the expenses on the main channel, precisely, and not in the lateral intakes.

In general, it is possible to appreciate that the automatic control models guarantee a more uniform delivery compared to manual operation. However, the mixed control 3 test shows an improvement over the traditional delay control, ranging from $ 199.6 to $ 11.5 in net losses in water volume. Although this control strategy generates greater losses than the fully automatic PID control, as well as the MoMPC control proposed by Van-Overloop *et al*. (2014), this strategy continues to involve the human being in the control cycle, which is associated with better surveillance of the control equipment.

*Tecnología y ciencias del agua*, ISSN 2007-2422, 13(1), 89-143. DOI: 10.24850/j-tyca-2022-01-03

## An economic evaluation of manual control

The missing volume in manual operation (Delays) represents less than 1 % of the volume required in the lateral intake, but in economic terms, it is US$199.5 of losses in water volume. If the productivity of water in the area is considered (table 3), it can be said that in this area US$1 135.00 in corn has ceased to be produced. Maize is taken as an example because it is the crop sown in the largest area in the irrigated area, after wheat, which has been discarded as a parameter of productivity due to its resistance to water stress.

As mentioned above, the best way to improve lag control without completely taking the human out, in this case, was to combine with PID control. In this test, the missing and excess volumes would have generated a maximum loss of US$0.26 x (288 $m^3$ + 273 $m^3$) = US$145.9. With manual operation based on the calculation of delays, an efficiency of 97.8% was obtained, which indicates that manual operation should not be directly related to efficiencies lower than 90 %. Then, the points to take care of the manual operation would be to identify the channel very well and the punctuality of both the operators and the users, as mentioned by Luján (1991), Pedroza and Hinojosa (2014), and García (2015).

# Conclusion

From the evaluated scenario applying the different control algorithms, it was observed that the Stringam and PID control manage to maintain the level within the margin $\Delta y < 0.10\ m$ and have a performance of IAE = 0.07%. It is also observed that there are no changes in the flow rate at the side discharge gate. However, downstream of the canal, due to the desire to maintain control at the end of the section, variations are generated in the discharge towards point C. In the same way, the advantages of applying automatic controls that are not so complex, but with solid foundations such as Stringam (Stringam & Wahl, 2015) and disturbances, such as the one presented in annex A. It is observed that automatic control models improve the uniformity in the deliveries of water volumes, and even when combined with automatic local controls with manual global control.

Water is an irreplaceable good and assigning a price to errors in operation increases the interest of water users in improving efficiency from the pipeline. Pricing water before each control algorithm seeks to raise awareness about the use of water as a good for which it is not paid, but which contributes to improving planning from an integrated basin vision (Turner, Georgiou, Clark, & Brouwer, 2004).

This article does not suggest in any way that water should be charged or viewed as an economic good, it simply discloses an estimated value of water in agricultural production and explores some scenarios to improve its use and utilization. The results obtained can serve for users to consider the benefits of modernizing their hydraulic infrastructure and in parallel reducing the volumes of use, to contribute to better care of the natural water resource.

**Acknowledgments**

The authors express their gratitude to the National Autonomous University of Mexico (UNAM), the Mexican Institute of Water Technology (IMTA), the National Council of Science and Technology (CONACYT), and all those who contributed to the development of this study.

# ANNEX A. Controller derived by perturbation method

Let the equation of the discharge of a gate be $F_1 = \frac{Q}{C_d b \sqrt{2g}}$, and the objective is to keep constant the operation level $\bar{y}_r$ and a known discharge flow rate

$Q$. Only the opening gate $w(t)$, the downstream $y_3\ (t)$ and upstream $y_r(t)$ water levels are dynamics values of the system:

$$Q = Cd\, w\, b\, \sqrt{2g(y_r - y_3)} \tag{A.1}$$

If the opening of the gate of equation (A.1) is cleared and the terms considered as invariants $F_1 = \frac{Q}{C_d\, b\sqrt{2g}}$ are grouped, for the case in which the extraction is to be kept constant, the variations in channel openings are a function that depends on the water level observed upstream and downstream of the gate:

$$w(y_r\ , y_3; t) = f(y_r\ , y_3;\ t) = F_1\big(y_r - y_3(t)\big)^{-\frac{1}{2}} \tag{A.2}$$

The dynamic model of the above equation can be decomposed into two scales, one on the target level or level to be controlled and $\overline{\ } y_r'$ and a variation or disturbance $y_r'$, and it is said that $\bar{y}_r \gg |y_r'|$ (see Figure 1.A). With the above, it is possible to consider the separation of scales $y_r = \bar{y}_r + y_r'$, that is, one of low and one of higher frequency. Applying this separation of scales to equation (A.2), such that $w(y_r) = w(\bar{y}_r + y_r')$ to determine the different scales on the gate opening function, it is proposed to apply a Fréchet series -Taylor (Milne, 1980), then you have:

$$w(y_r) = w(\bar{y}_r) + y_r' \left.\frac{\partial w}{\partial y_r}\right|_{\bar{y}_r} + \frac{{y_r'}^2}{2!} \left.\frac{\partial^2 w}{\partial y_r^2}\right|_{\bar{y}_r} + \cdots \tag{A.3}$$

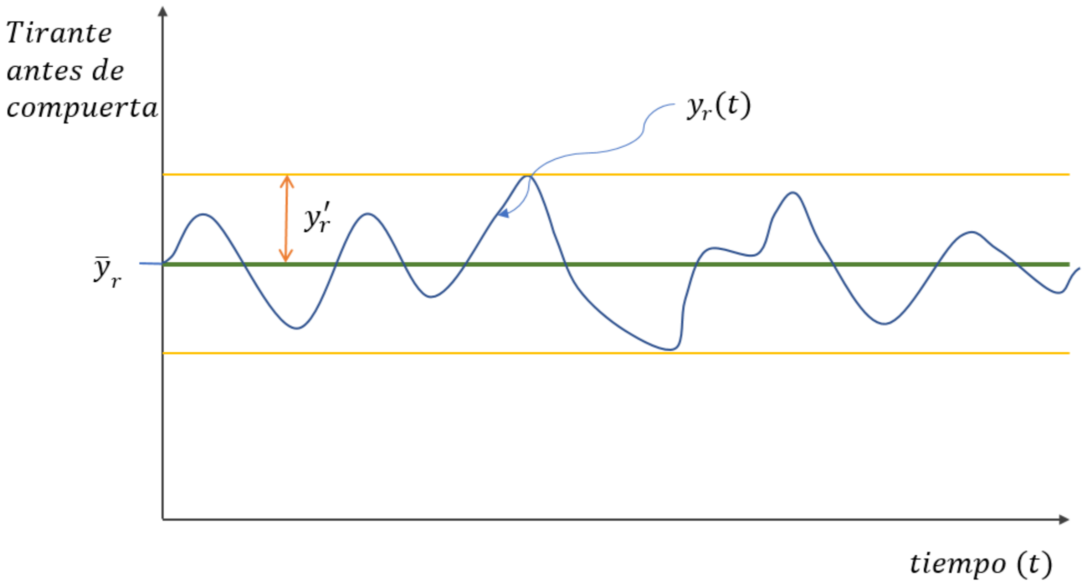


**Figure A1**. Variations of the water level above the gate.

Considering that the changes in the gate opening are $\Delta w = w(y_r) - w(\bar{y}_r)$. Furthermore, the derivatives are terms that incorporate the sensitivity effects of the aperture on the level, for which $K_{p_1} = \left.\frac{\partial w}{\partial y_r}\right|_{\bar{y}_r} = -\frac{1}{2}F_1 \cdot (y_r - y_3)^{-1.5}$ y $K_{p_2} = \frac{1}{2!}\left.\frac{\partial^2 w}{\partial y_r^2}\right|_{\bar{y}_r} = \frac{3}{8}F_1 \cdot (y_r - y_3)^{-2.5}$. Finally, the control of disturbances to direct the opening of the gate remains as:

$$w^{n+1} = w^n + y_r' K_{p_1} + {y_r'}^2 K_{p_2} \tag{A.4}$$

This algorithm requires that the time interval for which the new control action will be calculated ($T_{control}$) must be defined and the speed with which the gate can execute a maneuver ($T_{motion}$) must also be established. When applying this algorithm, it was observed that the disturbances can be smoothed by using a fraction of the derivative $K_{p_1}$, which was called $K_L$, and modifying the model as $w^{n+1} = w^n + K_L K_{p_1} y'_r$.

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