Control Methods in Automated Gravity Irrigation Systems: a review

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***Abstract*—Irrigation planning and management is vital in achieving food security. The water delivery to many small farms at varying times can be difficult to manage. Deviations between the predictive/control model and the reality can be caused by climatic variations or unscheduled demands by farmers. Furthermore, irrigation canals are large-scale systems, consisting of many interacting components, equipped with local controllers to modulate the flow of water by adjusting the settings of the gates. The available methodologies are mainly aimed at the optimal irrigation scheduling. This review provides the basis for the application of control methods to the irrigation systems.**

I. INTRODUCTION

An automated irrigation channel consists of a collection of interconnected pools (a pool is a portion of a canal, situated between two control devices). Each pool is equipped with gates, a communication system, sensors, actuators and a processing device (decision-maker) [1]. Optimum management of automated gravity irrigation systems is a fundamental objective to reduce water waste, trying to meet the demands of farmers and the real needs of crops as much as possible [2]. These suggest that irrigation systems improvements are strategic measures on the way to sustainable food security [3]. For this reason, the research activity is focusing on the development of algorithms that seek the best solution for channel management, trying to mediate between the possible objectives to be achieved [4],[5]. The hydraulic behaviors of irrigation canals show that these systems are complex, with a dynamic characterized by important time lags, strong nonlinearity and numerous interactions between different consecutive sub-systems [6]. One of the main problems in water management of irrigation systems is the control of the equitable distribution of water [7] especially in a context of limited water availability. A good knowledge of system dynamics is needed to design an automatic control of the irrigation canals. The controlled variables are mainly water level or flow by controlling locks and gates. In the light of the growing relevance of this topic, the scientific and technical literature have provided a plethora of approaches characterized by different degree of complexity that depends on the hydraulic network, purpose and level of automation of the system. The main objective of this paper is to present a review of methods to improve the management of gravity irrigation channels.

II. BACKGROUND AND TERMINOLOGY

Gravity-fed surface irrigation systems (Fig. 1) are used to distribute water to farms. Generally, irrigation networks take water from a branching point such as a river or a natural or artificial reservoir and distributes it through a series of channels (Fig .2).

The Saint Venant equations are used to describe dynamic behavior of the unsteady flow in an open canal. The first equation is the "Continuity Equation" and it is based on Conservation of the Mass (1), the second is the "Momentum Equation" and it is based on Conservation of Momentum (2):

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial (Q^2 / A)}{\partial x}+g\cdot A\cdot\frac{\partial z}{\partial x}=-g\cdot A\cdot S_f \tag{2}$$

where A is cross section area (m^2), t is the time (s), Q is the discharge (m^{2}s^{-1}), x is the longitudinal abscissa (m), in the direction of the flow, q is lateral inflow or outflow (m^{2}s^{-1}), g is 9.81 (ms^{-2}), z is water surface absolute elevation (m), S_f is the friction slope (3):

$$S_f=\frac{n^2\cdot Q^2}{A^2\cdot R^{4/3}} \tag{3}$$

where n is Manning coefficient and R is hydraulic radius (m). Saint Venant equations must be combined with boundary conditions at cross structure and initial conditions. In relation to the type and nature of the system, the equations describing the hydraulic behavior of the regulation structures might be different and some of them are shown below. The (4) and (5) concern the weir respectively free-flow and not submerged. The (6) and (7) concern the gate respectively free-flow and not submerged.

$$Q=c_{WF}\cdot L\cdot\sqrt{2\cdot g\cdot h_1^{3/2}} \tag{4}$$

$$Q=c_{WS}\cdot L\cdot\sqrt{2\cdot g\cdot (h_1-h_2)^{1/2}}\cdot h_2 \tag{5}$$

$$Q=c_{GF}\cdot L\cdot u\cdot\sqrt{2\cdot g\cdot (h_1-u/_{2}2)} \tag{6}$$

$$Q=c_{GS}\cdot L\cdot u\cdot\sqrt{2\cdot g\cdot (h_1-h\ )} \tag{7}$$

where L is device width (m), h_1 is upstream water depth (m), h_2 is downstream water depth (m), u is device opening (m), C_{ij} are discharge coefficients.

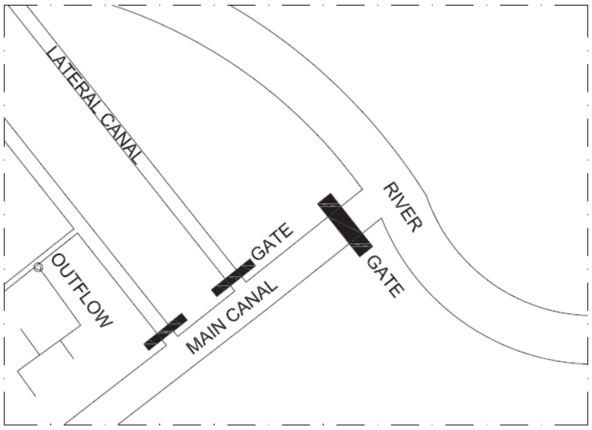

Fig. 1. Irrigation system

Considering the dynamic nature of the system, with devices that can, during its operation, change from one hydraulic condition to another, these equations are not sufficient, and the consideration of a continuous transition between hydraulic conditions is required.

Saint-Venant's equations have no known analytical solution in real geometry. Assuming some relevant simplifications concerning the geometry and the hydraulic characteristics of a system (e.g., zero slope, no friction, constant rectangular cross section), the hydraulic behavior of such scheme can be studied through the method of characteristics. But, for further tests on real systems, these equations have to be solved numerically. Several finite difference numerical schemes are used, either explicit or implicit (e.g., the well-known Preissmann implicit scheme [8].

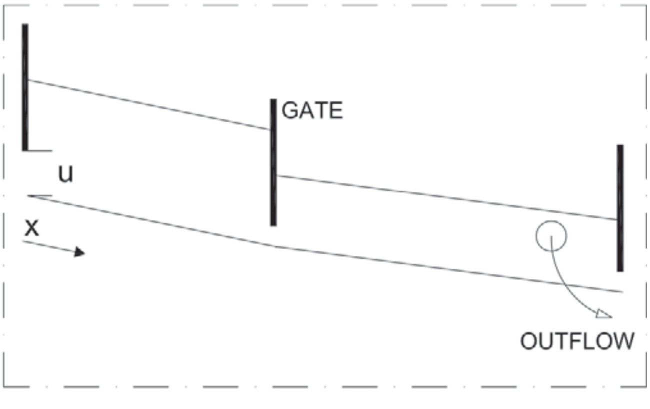

Fig. 2. Longitudinal section of an open channel

III. APPLICATION OF CONTROL METHODS FOR THE OPTIMIZATION OF IRRIGATION SYSTEMS

The application of control methods is mainly aimed at the optimal irrigation scheduling, thus to the control of the canals, gates and actuators that ensure the delivery of the water to farmers locations in agreement with their water needs. However, difficulties are due to deviations between the predictive/control model and the reality. The main disturbances can be caused by climatic variations or unscheduled demands by farmers who extract more or less water volume during the irrigation cycle. Following the approach of [9], it is possible to recognize two main approaches: (i) off-line analysis of the system, with the computation of the optimal irrigation scheduling and the definition of the reference trajectories that determines the positions of each gate; (ii) on-line predictive control which manages the scheduling and re-acts in case of deviations between the observed data and the desired behavior at the checkpoints during each regulation period (e.g., every 5 min), due to unknown perturbations. In literature, mathematical and heuristic algorithms are mainly used in off-line computation to obtain the optimal irrigation scheduling, while the most promising on-line methods suggest adopting model predictive control. In addition to these two main categories, a third one combines the off- and on-line analysis, performing first, off-line, the scheduling of the water requirements, and then acting on the actuators, on-line, for the management of possible deviations from the planned system conditions.

A. Mathematical algorithms

A feature that distinguishes the mathematical algorithms is the ease of introducing the constraints in the optimization problem and therefore, of finding suitable optimal solutions. In general, the non-linearity of the problem limits the application of programming optimization for large systems. For scheduling canals irrigation among a group of users, [10] applies a mixed-integer linear programming algorithm. The duration of flow of each outlet and a target start time is specified by users. Typically, the model does not consider the travel time. In [11] is implemented an integer program for flexible schedules based on users' requested start time, incorporating sequence dependent travel times. The method was applied on small problems due to the computational demand of the algorithm. Reference [12] uses MIQP (Mixed Integer Quadratic Programming). They consider three parameters as input to the problem: irrigation start time, duration of irrigation process and flow rate. These parameters represent the requests of the farmers. The problem is how to manage multiple irrigation requests, minimizing the differences between the required parameters and the actual availability to satisfy them. They also consider that the difference in types of crops creates different needs and for this, they insert priority coefficients. Another variable that is considered is the number of operations; in fact, the water is diverted to the farms through the gates that are often maneuvered manually, so to reduce the management cost, the number of operations must be minimize. To be able to keep track of the gatekeeper's trajectory, reference [13] considers also the propagation dynamics of flow by using hydraulic delay times. The optimization problem is solved with mixed integer linear programming (MILP). Three hypotheses are formulated to represent the dynamics of water: inflow variations are regulated only by the upstream gate and are not affected by the variations of the other sections; the water travel time from the upstream node to downstream node depends of the characteristics of the section, moreover, the time of delivery to the outlet placed in the stretch is assumed equal to the maximum time of distance of the stretch; the channel sections don't have storage capacity, so inflow must be equal at outflow. The authors propose three objective functions, the first is written with the aim to minimize the gap between scheduled and demanded time and duration, the second in order to minimize water losses (the ratio of supplied volume to diverted volume into the system), and the last in order to minimize the trip of gatekeeper. The final function is the sum of tree previous functions, each multiplied by a weight coefficient. In this problem the constrains concern the water delivery process, gate operation, gatekeeper trajectory, and water distribution policies.

B. Genetic algorithms

The main advantage offered by such approaches is the ability to deal with large problems. Theoretically, genetic algorithm are capable to find a sub optimal solution for an unlimited number of objectives within an unlimited number of hierarchical layers. Reference [14] proposes a genetic algorihm for lateral canals scheduling (Fig. 1). Multiobjectives genetic algorithm is applied by [15] to optimize the field inlet schedeling under conflicting objectives. The irrigation network components are modularized based on their physical connectivity. The channels system is hierarchized in several layers, from the first layer that is composed by the tertiary canal up to the main canal that distributes water to everyone else. Hydraulic model or travelling time are not explicity combined with the optimization algorithm. Actually, travel time play an important role to avoid delays in irrigation scheduling or shortened irrigation turns [11].

C. Model Predictive Control

Model predictive control (MPC) is an optimal control strategy based on the explicit use of a model to predict the process output at future time instant [16], [17]. Reference [5] analyzes and explains the application of MPC in irrigation systems according to main controlled variables: flow and water level. Reference [18] presents the differences between centralized and distributed MPC methods, both used to improve the performance of the overall system. The rationale underlying MPC is to transform the problem control into an optimization one, in such a way that at each instant of sampling time, a sequence of future control values is calculated by solving an optimal control problem of the finite horizon. The overall procedure is repeated at the next sampling time according to the receding horizon (or moving horizon) principle [19]. Reference [2] proposes a hierarchical distributed model predictive control approach applied to irrigation canal planning in order to have a system able to mitigate the risks. Two hierarchical levels of optimization are considered: a distributed model predictive controller optimizes, at lower level, the operation by manipulating flows and gate openings to follow the water level set-points; in the higher level a risk management strategy is implemented. This strategy has the objective to implement actions to mitigate the possible changes due to the considered risks (such as failure in reach or devices due to wear and tear, seepage loss, sensor theft). The goal is to optimize the cost of operation canal in order to mitigate the risks and if necessary change the setting of the lowest level. An overall control diagram to optimize the management of the canal is proposed by [9].The methodology presents both off-line and on-line operations. In the off-line operation, the desidered water level is calculated according to the needs of the crops and the desired flows for the canal outlet. Subsequently, it is calculated the level closest to the desired one so that guarantees the physical feasibility, and the degree of opening of the sluice gates to maintain it. The on-line control method is based on CSE (Canal Survey Estimation) algorithm developed in [7]. Comparing the water level measured at checkpoints with the desired water level, it stimates the disturbances. Finally, on-line predictive control calculates the new values in order to have the desired levels.

IV. CONCLUSION

The variables that contribute to defining the management of an irrigation system are numerous and characterized by significant temporal variability. This is one of the main reasons that constrained the application of off-line methods, such as irrigation scheduling, to real case studies. However, among these limited applications [12],[13] apply a mathematical approach to a secondary irrigation canal of the Gignac Canal for scheduling water user demands and show the potential of this optimization scheme. Despite off-line approaches are quite easy to be settled, they do not consider the temporal evolution of the boundary conditions, which may disturb the system from the hypothetical optimal operating conditions. In case this situation occurs, the optimization of the system would require a modification of the algorithm in the light of the real boundary conditions.

On-line approaches take into consideration these contingencies. The method proposed by [20] has been applied in a section of Tajo-Segura canals in the southeast of Spain, that distribute water, mainly used for irrigation. A numerical study on East Golburn-30 irrigation channel in Victoria, Australia was developed by [17]. They implemented a stochastic MPC approach to water level planning for irrigation of four automated pools. MPC models are more complex than others but result to be very flexible and able to drive the system to its optimum in relation to the real hydraulic condition of the network. However, a fully application of such models requires an adequate level of automation of canals and actuators, with sensors enabling a continuous monitoring of the overall irrigation network. Despite recent developments concerning IoT-based smart applications offer optimistic scenarios on the applicability of MPC approaches, the low automation level of current irrigation network represents the most relevant factor the currently constrains their practical diffusion.

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