# Classification of Canal Control Algorithms

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**Abstract:** Different control algorithms for the regulation of irrigation canals have been developed and applied throughout the world. Each of them can be characterized according to several criteria, among which are: the considered variables (controlled, measured, and control action variables), the logic of control (type and direction), and the design technique. This paper defines these terms and classifies the algorithms detailed in the literature. To summarize and compare algorithms, a structured table of the main published canal control algorithms is presented.

## INTRODUCTION

A control system is an elementary system (algorithm software + hardware) in charge of operating canal cross structures, based on information from the canal system. This information may include measured variables, operating conditions (e.g., predicted withdrawals) and objectives (e.g., hydraulic targets). Boundaries of the control system are output of the sensors placed on the canal system, and input to the actuators controlling the cross structures. This text presents definitions and a classification of canal control algorithms developed or used in the world.

The difficulty presented by the classification of canal control algorithms is due to the different ways of characterizing them (e.g., controlled variables, configuration of field implementation, communication management, design technique, alarm management, and location along a canal). Among all possible criteria, one wants to retain those, in minimum number, that allow characterization of the hydraulic behavior, the performance and the constraints of the various canal control algorithms. We choose to retain the following three essential criteria: considered variables, logic of control, and design technique. Subcriteria will be defined to refine them.

These different terms are defined, discussed, and illustrated in the following sections. The order of the three criteria is not linked to any priority of interest. Depending on technical background and areas of responsibility, different people may have different levels of interest in the three criteria. Civil and hydraulic engineers may be more concerned with the considered variables, while control engineers are more concerned with the design technique.

## CONSIDERED VARIABLES

The location of the considered variable is given in reference to a pool (a pool is a portion of a canal, situated between two control devices) and not to a structure (e.g., upstream, intermediate, or downstream end of a pool). This avoids confusion in the case of a multivariable control algorithm, where a variable can be controlled either by an upstream structure or by a downstream structure. Three types of variables are considered in control algorithms: controlled, measured, and control action variables.

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### Controlled Variables

Controlled variables are target variables controlled by the control algorithm. Examples are water level at the upstream end of a pool ($y_{up}$), water level at the downstream end of a pool ($y_{dn}$), flow rate at a structure ($Q$), volume of water in a pool ($V$), and weighted water level (e.g., $ay_{up} + by_{dn}$). Controlled variables are not necessarily directly measurable.

Control theory speaks of "tracking" when these target variables are time dependent. Some authors use the term "regulation" in a general sense, for all types of targets (constant or variable), while others use the term only in the case of a null constant target. In this article, the term "regulation" is used in a general sense and "tracking" refers to the time dependent feature of the target.

#### *Discharges*

The needs of irrigation canal users are defined mainly in terms of discharge. For example, agricultural needs are expressed in terms of given discharges delivered to a plot, to a secondary canal, or to a pumping station; environmental needs as tail end discharge, or minimal discharge; urban needs as discharges delivered to a house or to a city water filtration plant; and industrial needs as discharges delivered to a factory. Natural or artificial storage reservoirs are sometimes available (e.g., soil maximum water storage, lateral or on-line reservoir, basin of a water filtration plant, volume stored into the canal pools). Users' needs can then be defined in a more flexible way, in terms of volume distributed over a time period. In this case, the controlled variable is no longer a given value of discharge, but a volume, which is the integral of a discharge over a given time period. Discharge fluctuations are then authorized, and neutralized by the capacity of the storage reservoirs. However, these reservoirs are expensive and of limited sizes, and constraints of distribution never suppress needs expressed in terms of discharge.

Consequently, all free surface hydraulic systems must be managed, directly or indirectly, in order to satisfy users' demands in discharge. Considering the nature of the physical phenomenon at stake (gravity open-channel flow from upstream to downstream), these demands in discharge can be satisfied only from the source situated at the upstream end of the system, by draining the upstream reservoirs. Generalized Predictive Control (GPC) (Sawadogo 1992; Sawadogo et al. 1991a, 1991b, 1992a, 1992b; Rodellar et al. 1993), Compagnie d'Aménagement des Coteaux de Gascogne (CACG) (Piquereau and Villocel 1982; Piquereau et al. 1984; Grosclaude and Tardieu 1985; Verdier 1986; Tardieu 1988; Barbet 1990; Rey 1990; Trouvat 1991; Hurand and Kosuth 1993), and SIMBAK (Chevereau 1991) are examples of regulation methods controlling discharges.

#### *Water Levels*

Contrary to discharges, water levels can be easily measured in free surface canals and rivers. Furthermore, constraints of feeding gravity turnouts, stability of canal banks, efforts to reduce weed growth, constitution of intermediate water storage volumes, and risks of overflow are expressed in terms of water levels. Controlled water levels $y$ can be upstream ($y_{up}$, Fig. 1), downstream ($y_{dn}$, Fig. 2), or intermediate inside the pool ($y_{in}$, Fig. 3). The location of controlled variables in a pool is indicative of hydraulic behavior of the system (e.g., available storage volume) and structural constraints (e.g., bank slopes). In Figs. 1 and 2, controlled water level values are equal at null and maximum discharges. This is not always the case (e.g., GEC Alsthom Gates). The corresponding water level difference is called "decrement." Operational characteristics are very different depending on the location of $y$.

One of the advantages of controlling upstream water levels is that a storage volume $V$ is available between the null discharge volume and the maximum discharge volume. It allows for rapid response to unforeseen demands of turnouts or downstream reaches and for storing water in case of a consumption reduction. But canal banks have to be horizontal, which is expensive. AVIS and AVIO gates (*Notice* 1975–1979; *Gestion* 1981; Goussard 1993) and the LittleMan downstream controller (developed by the U.S. Bureau of Reclamation) (Zimbelman 1987) are examples of such methods.

When downstream water levels are controlled, canal banks can follow the field natural slope, which reduces construction costs. But, no storage volume is available between the null discharge volume and the maximum discharge volume. In fact, pool volumes change in the opposite direction from the direction that will help satisfy downstream demand changes. Therefore, the system cannot respond rapidly to unforeseen demands. The excess water cannot be stored locally and is "lost" in the downstream pools. Supply flow changes must overcompensate in order to match downstream demand changes and to establish new pool volumes. AMIL gates (*Notice 1975–1979; Gestion* 1981; Goussard 1993), EL-FLO (Electronic Filter Level Offset) (Shand 1971; Buyalski and Serfozo 1979), Canal Automation for Rapid Demand Deliveries (CARDD) (Burt 1983), the LittleMan upstream controller (Zimbelman 1987), the Proportional, Integral, "Retard" (i.e., Delay) controller (PIR) (Deltour 1992), the Proportional, Integral, Derivative controller (PID), used by UMA Engineering and applied at Imperial Valley, Calif.), PI (developed by Sogreah and applied at Kirkuk, Iraq), and Zimbelman (developed by Zimbelman in 1981; Zimbelman 1987) are examples of downstream water level control.

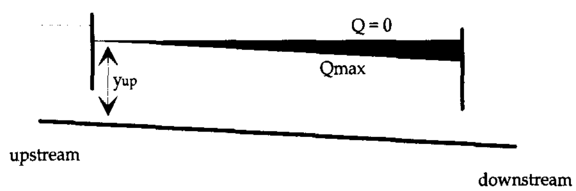


**FIG. 1. Control of Upstream Level of Pool**

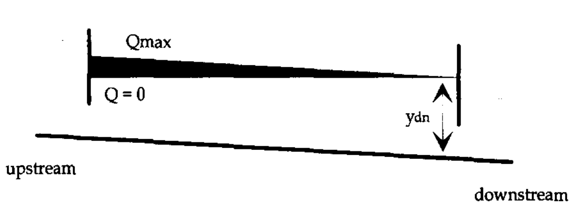


**FIG. 2. Control of Downstream Level of Pool**

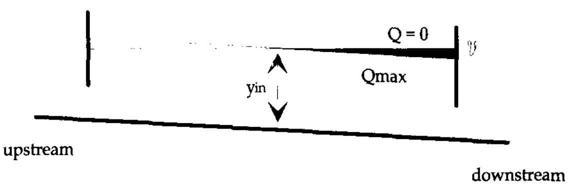


**FIG. 3. Control of Intermediate Water Level**

Controlling a particular intermediate water level, close to the middle of the pool, is equivalent to controlling the volume stored in the pool. This water level can be measured directly (no example has been found in the literature), or can be obtained as a linear combination of an upstream and a downstream water level (e.g., BIVAL). Controlling an intermediate water level is a compromise between the two previous options, in terms of construction cost and availability in storage volume $V$. Indeed, banks have to be horizontal only downstream from the controlled intermediate water level. But one or several distant water levels have to be measured, which increases measurement and telemetry requirements. BIVAL (developed by Sogreah) (Zimbelman 1987; Chevereau 1991) is the only example of such a method.

### *Volumes*

In the case of volumes, controllers are less sensitive to perturbations, but response times are increased (Framji and Verdier 1978). These methods are applicable to irrigation canals with important storage volumes, and equipped with turnouts whose feeding is not dependent on water levels in the main canal (e.g., pumping stations). Dynamic Regulation (Coeuret 1977; Lefebvre 1977; Deltour 1988), and Controlled Volumes (Buyalski et al. 1991) are examples of such methods.

## Measured Variables

Measured variables, also called inputs of the control algorithm, are the variables measured on the canal system. Examples are water level at the upstream end of a pool ($y_{up}$), water level at the downstream end of a pool ($y_{dn}$), water level at an intermediate point of a pool ($y_{in}$), flow rate at a structure ($Q$), and setting of a structure ($G$).

Measured variables on irrigation canals are generally water levels (e.g., EL-FLO, PIR). In some cases, measured variables can be discharges (e.g., CACG). Discharge can be measured with flow meters (based in general on the measure of one or several flow velocities, with a propeller or an ultrasonic or electromagnetic device); measurement flumes using water level measurement to compute $Q(z)$; a cross structure equation $Q(z_1, z_2, G)$; or a local control section rating curve $Q(z)$ with a sufficient precision. When such an equation exists, it is assumed that a discharge $Q$ is really measured, whatever the process used to obtain it, even if it is calculated from one or several water level measurements. Finally, measured variables can be volumes, evaluated by measuring several water levels along the canal, or by evaluating input-output discharge balance (e.g., Dynamic Regulation).

## Control Action Variables

Control action variables ($U$), also called outputs of the control algorithm, are issued from the control algorithm and supplied to the cross structures' actuators in order to move the controlled variables toward their established target values. They are either gate positions ($G$) or flow rates ($Q$). In this latter case, another algorithm transforms the flow rate into a gate position. The algorithm used to transform flow rate into a gate position is important from hydraulic and control points of view, and is considered as a control algorithm separate from those presented in this classification. Control action variables $G$ or $Q$ can be considered as absolute values, relative values (relative to a reference state) or as incremental values (to be added to the value of the previous time step).

Gate position ($G$) has the advantage of taking into account the complex dynamics linking this position with the local discharge and upstream and downstream water levels. These dynamics are important, and it can be hazardous not to take them into account [e.g., the Linear Quadratic Regulator (LQR Cemagref), also called Optimal Control and EL-FLO consider $G$ as the control action variable]. Considering discharge as the control action variable allows for decoupling of the different subsystems. This is interesting when monovariable controllers are used in series (e.g., Dynamic Regulation, PIR). However, the dynamics of the local controller linking the discharge (control action variable $Q$) to the gate position (control action variable $G$) are not taken into account in the global controller. Therefore, the quality of the behavior of the global controller cannot be assessed, because important dynamics are neglected in the design of the controller. If the control action variable ($U$) is a discharge ($Q$), it is necessary to convert it into gate position ($G$), applicable to the system. This conversion can be done through the inversion of the device static equation $Q(z_1, z_2, G)$, or by a local dynamic controller (e.g., PID controller).

For purposes of describing and classifying canal control algorithms, an I/O structure is used, consisting of the number of inputs and outputs considered by the control algorithm. The I/O structure of a control algorithm is described as "*n*I*m*O" when it has $n$ inputs (measured variables) and $m$ outputs (control action variables). Special names are given to the I/O structure in specific cases, for example: Single Input, Single Output (SISO), if $n = m = 1$; Multiple Inputs, Single Output (MISO), if $n > 1$ and $m = 1$; and Multiple Inputs, Multiple Outputs (MIMO), if $n$ and $m > 1$. This structure has an influence on the techniques that could be used for the design of the algorithm.

## LOGICS OF CONTROL

The logic of control refers to the type and direction of the links between controlled variables and control action variables.

### Type

The control algorithm uses either feedback control (FB, also called closed-loop control), feedforward control (FF, also called open-loop control) or a combination (FB + FF).

#### *Feedback Control*

In a feedback control algorithm, the controlled variables ($Y$) are measured or directly obtained from measurements. Any deviation from the target ($Y_c$) is fed back into the control algorithm in order to produce a corrective action $U$ that moves the controlled variables towards their target values (Fig. 4). Perturbations ($P$), even if unknown, are taken into account indirectly, through their effects on the output $Y$ of the system. In control theory, this concept is essential because it links a control action variable $U$ to a controlled variable $Y$.

Feedback control can be applied to all the controlled variables: discharge, water level and volume.

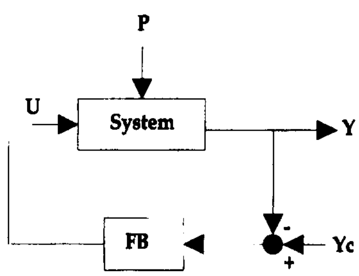


**FIG. 4. Feedback Control**

- Examples of feedback control in discharge are GPC (Sawadogo 1992; Rodellar et al. 1993), CACG (Piquereau and Villocel 1982), CARA (Compagnie d'Aménagement Rural d'Aquitaine) (Marzouki 1989; Roux 1992; Kosuth et al. 1992), Liu et al. (1994), CARAMBA (De Leon Mojarro 1986), and IMTA-Cemagref (De Leon Mojarro et al. 1992).
- Examples of feedback control in water level are AMIL, AVIS, AVIO gates, Little-Man, EL-FLO (Shand 1971), CARDD (Burt 1983), Zimbelman (1987), BIVAL, PI (developed by Sogreah), PID (Chevereau 1991), PID (developed by UMA Engineering), PIR (Deltour 1992), Liu et al. (1994), and Cemagref-IMTA (Chavez et al. 1994).
- Examples of feedback control in volume are Dynamic Regulation (SCP: Société du Canal de Provence) and Controlled Volumes (U.S. Bureau of Reclamation).

For complex processes, like dead time processes (processes with time delays; Kuanyi 1989), feedback control has limitations. In the case of irrigation canals, time delays between upstream control actions and downstream controlled variables are important (a few minutes to several hours). A single feedback control can function correctly only if important storage volumes are available. Indeed, control delay is, at least, equal to the system delay. But storage volumes imply high construction costs. The quality of the control can be considerably improved by adding a feedforward control component (Shinskey 1988).

#### *Feedforward Control*

In a feedforward control algorithm, the control action variables $U$ are computed from targeted variables $Y_c$, perturbation estimations $\hat{P}$, and process simulation (Fig. 5). Feedforward control usually improves control performance when few unknown perturbations occur in the canal system. The feedforward control can compensate inherent system time delays by anticipating users' needs. These needs have to be estimated as precisely as possible. They should take into account climatic, agronomic, and sociological data, as well as records of the water consumption of previous weeks or seasons (Perrin 1989).

Feedforward control can be applied to all the controlled variables: discharge, water level and volume. Some examples are quoted both in control of discharges and of water levels. For example, the dynamic wave model calculates simultaneously these two types of variables.

Examples of feedforward control in discharge are given depending on the calculation method used:

- By model inversion: kinematic wave or pure delay (CARA; Roux 1992), diffusive wave (CACG; Sawadogo 1992), dynamic wave [SIMBAK (Chevereau 1991); O'Loughlin 1972; Liu et al. 1992; and gate stroking (Falvey 1987)]. These different methods are studied and compared by Chevereau (1991).
- By optimization (Najim 1981; Sabet et al. 1985; Tomicic 1989; Khaladi 1992; Lin and Manz 1992).

Example of feedforward control in water level are:

- By inversion of the dynamic wave model (O'Loughlin 1972; Liu et al. 1992; Falvey 1987).

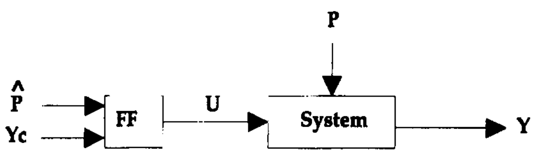


**FIG. 5. Feedforward Control**

- By optimization (Tomicic 1989; Khaladi 1992; Lin and Manz 1992).
- By simulation (Malaterre 1989; Baume et al. 1993).

Sabet et al. (1985) is an example of a feedforward control in volume.

Feedforward control is generally insufficient by itself, due to model errors, perturbation estimation errors, and unknown perturbations, and must be combined with feedback control to compensate for these errors.

*Combination*

Both feedback and feedforward control have advantages and limitations. For this reason, the combination of feedforward and feedback control is often used (Fig. 6). For a multivariable system (with several control action and controlled variables), several controllers with different logics of control can be combined. For example, discharges can be controlled in feedforward control and water levels in feedback control. Therefore, some regulation methods may appear in several categories.

## Direction

A structure can be operated to control a variable located further downstream, which is called downstream control (Fig. 7). All variables (discharge, level, or volume) can be controlled with downstream control. A structure can also be operated to control a variable located further upstream, which is called upstream control (Fig. 8). Only levels or volumes can be controlled with upstream control, when flow conditions are subcritical and under the limitations of the backwater effects. This limitation explains why downstream control is a very interesting method compared to upstream control.

Examples of downstream control methods are AVIS, AVIO gates, LittleMan downstream, EL-FLO (Shand 1971), CARDD (Burt 1983), Zimbelman (1987), CARA (Marzouki 1989), BIVAL, PI (developed by Sogreah), PID (Chevereau 1991), PIR (Deltour 1992), Liu et al. (1994), Dynamic Regulation (SCP), and Controlled Volumes (U.S. Bureau of Reclamation).

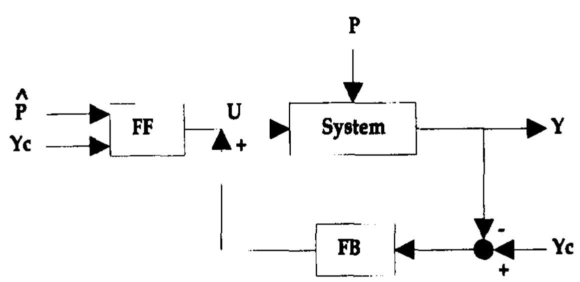


FIG. 6. Feedforward + Feedback Control

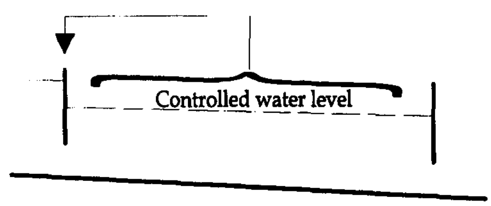


FIG. 7. Downstream Control

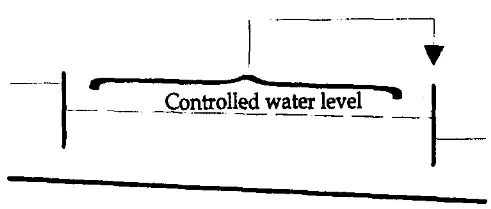


FIG. 8. Upstream Control

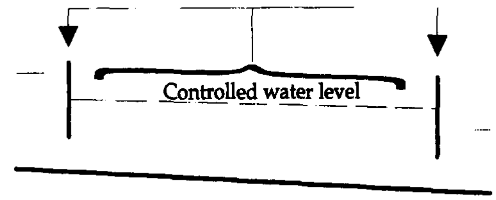


FIG. 9. Mixed Control

Examples of upstream control methods are AMIL gate, LittleMan upstream, P + PR (Buyalski 1977), and PID developed by UMA Engineering.

Some control methods combine upstream and downstream control logics (Fig. 9). They are sometimes called mixed controls. Because they benefit from the main advantages of downstream control methods, they are often simply called downstream control methods. Examples of such methods are LQR (Corriga et al. 1980, 1982a, 1982b, 1983; Balogun 1985; Balogun et al. 1988; Garcia 1988; Garcia et al. 1992; Hubbard et al. 1987; Reddy 1986, 1990, 1992; Reddy et al. 1992; Filipovic and Milosevic 1989; Florea and Popa; Malaterre 1994, 1995b; Sawadogo et al. 1995), and mixed gates [GEC Alsthom, used by the CNABRL (Compagnie Nationale d'Aménagement du Bas-Rhône Languedoc)]. The latter are sometimes designated as "associated levels gates" because, in certain hydraulic conditions, the purpose of the gate is to maintain a constant difference between its upstream and downstream water levels. We consider this gate as a "mixed control" gate, because modification of a water level in a pool implies the combined reaction of the two gates located upstream and downstream from this water level.

# DESIGN TECHNIQUES

Control theory implies a three-step process: (1) System modeling (i.e., the definition of a model); (2) system analysis (i.e., the study of the model behavior); and (3) controller design. The design technique is the algorithm or methodology used within the control algorithm in order to generate the control action variables from the measured variables. Examples of main design techniques are heuristic, three position, PID, pole placement, predictive control, optimal control, fuzzy control, neural network, backward simulation, linear optimization, and nonlinear optimization. A main technique can benefit from additional components that may improve control algorithm performance by accounting for canal system features. Examples are filter, decoupler, observer, Smith predictor, and autoadaptative tuning. Design techniques can be split into two main categories, usually requiring different mathematical backgrounds: monovariable and multivariable methods.

## Monovariable Methods

Heuristic monovariable methods have been developed based on hydraulics and not on control theory [e.g., Zimbelman (1987); CARDD (Burt 1983)]. Although quoted in the literature, these methods are too site specific and have not been implemented on operating canals. An empirical method used by CARA on river-pond systems (Marzouki 1989) is being modernized (Roux 1992). BIVAL and Little-Man (U.S. Bureau of Reclamation; Buyalski et al. 1991) are methods based on a three-position controller.

Most of the irrigation canal control methods based on control theory use the well-known linear monovariable PID controller. This PID controller can be tuned with the Ziegler-Nichols method or by pole placement (Larminat 1993; Aström and Häggland 1995). Examples of PID related methods are:

- P: AMIL, AVIS, AVIO
- PI: ELFLO, P + PR, Dynamic Regulation, PI Sogreah
- PID: PID UMA Engineering

Although very efficient in most cases, PID controllers do not explicitly take into account the characteristic canal time delays. Shand (1971) prospected the possibility to use a Smith predictor in order to overcome this problem, when studying the automation of Corning Canal, California. Developing an analog dead time model raised technological difficulties. Therefore, though less efficient, the EL-FLO method was eventually selected. Recently, the combination of a PI controller with a Smith predictor was further developed (Deltour 1992; Sanfilippo 1993). This controller is called PIR. Modern digital technology has solved problems faced by Shand.

Other linear controllers have been used on river systems with long time delays by CACG. High-order transfer functions are used, and tuned with the pole placement technique.

The generalized predictive control method (GPC), a monovariable optimization method, has been developed by Sawadogo (1992) and Rodellar et al. (1993). It is not based on the desired feedback control behavior, but on the minimization of a criterion $J$, pondering the control action variable and the error between the controlled variable and its targeted value. GPC method uses transfer function models (Chan and Yao 1990; Soeterboek 1990; Lee et al. 1990; Linkens and Mahfouf 1992). It naturally incorporates a feedforward and a feedback control.

Methods based on fuzzy control [e.g., CNABRL on the T2 and on the CPBS canals, Morocco (Bouillot 1994)], expert systems, or neural networks (e.g., Schaalje and Manz, personal communication, 1993; Toudeft et al. 1994) are being developed. The two latest methods are still prospective, and should be tested.

Monovariable methods require splitting the system into several subsystems without taking explicitly into account interactions between them. An irrigation canal is a multivariable system presenting strong interactions between subsystems. For example, the operation of a gate influences several upstream and downstream pools. The decoupler technique has been applied to the EL-FLO controller (Schuurmans 1992). It restrains, as far as possible, the influence of one control action

**TABLE 1. Classification of Canal Control Algorithms**

| Identification | | CHARACTERIZATION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Considered Variables | | | | Logic of Control | | | |
| Name (1) | Developer (2) | Controlled (3) | Measured (4) | Control action (5) | I/O structure (6) | Type (7) | Direction (8) | Design technique (9) | Applications or tests (10) |
| CARDD | Burt and Parrish | $y_{dn}$ | 3-5 $y_{in}$ | $G$ | 3-5ISO | FB | dn | Heuristic | CalPoly scale canal, U.S. |
| RTUQ | Rogers | $Q$ | $y_{up}$, $y_{dn}$, $G$ | $G$ | 3ISO | FB | dn | Heuristic | Dolores Project, U.S. |
| | Zimbelman | $y_{dn}$ | $y_{dn}$ | $G$ | SISO | FB | dn | Heuristic | Model |
| | Najim | $y$ | $y$ | $Q$ | ? | FB + FF | | Variable structure | — |
| BIVAL | Sogreah | $f(y_{up}, y_{dn})$ | $y_{up}$, $y_{dn}$ | $G$ | 2ISO | FB | dn | 3 position | Mali, Mexico, etc. |
| DACL | USWC Lab | $y_{dn}$ | $y_{dn}$ | $G$ | SISO | FB | up | 3 position | — |
| LittleMan | USBR and others | $y_{dn}$ | $y_{dn}$ | $G$ | SISO | FB | up | 3 position | Several in the U.S. |
| AMIL | GEC Alsthom | $y_{dn}$ | $y_{dn}$ | $G$ | SISO | FB | up | P | Several countries |
| AVIS, AVIO | GEC Alsthom | $y_{up}$ | $y_{up}$ | $G$ | SISO | FB | dn | P | Several countries |
| Danaidean system | — | $y_{dn}$ | $y_{dn}$ | $G$ | SISO | FB | up | P | Several in the U.S. |
| Mixed gates | GEC Alsthom | $f(y_{up}, y_{dn})$ | $y_{up}$, $y_{dn}$ | $G$ | 2ISO | FB | up + dn | P | Several countries |
| Dynamic Regulation | SCP-Gersar | $V$ | $y_{up}$, $y_{dn}$, $G$ | $Q$ | 3ISO | FB+ FF | dn | PI | France, Morocco |
| | IMTA-Cemagref | $y_{dn}$ | $y_{dn}$ | $Q$ | SISO | FB + FF | dn | PI | Begonia (Mexico) |
| | UMA Engineering | $y_{dn}$ | $y_{dn}$ | $G$ | SISO | FB | up | PI | Imperial Valley, Calif. |
| EL-FLO/P+PR | Buyalski, Serfozo | $y_{dn}$ | $y_{dn}$ and $G$ | $G$ | 2ISO | FB | dn/up | PI + filter | Several in the U.S. |
| | Sogreah | $y_{dn}$ | $y_{dn}$ | $G$ | SISO | FB + FF | dn | PI + filter | Kirkuk (Iraq) |
| | IMTA-Cemagref | $y_{dn}$ | $Q_{dn}$, $y_{up}$, $y_{dn}$ | $Q_{up}$ | 3ISO | FB + FF | dn | PID + pole placement | Yaqui (Mexico) |
| | CARA Cemagref | $Q_{dn}$ | $Q_{dn}$ | $Q_{up}$ | SISO | FB + FF | dn | PID + heuristic | Rivers, Southwest of France |
| EL-FLO + Decoupler | Schuurmans | $y_{dn}$ | $y_{dn}$ and $G$ | $G$ | 2-3ISO | FB | dn | PI + filter + decoupler | CalPoly scale canal |
| MODUVAR 32 | GEC Alsthom | $y_{up}$ or $y_{dn}$ | $y_{up}$ or $y_{dn}$ | $G$ | 1-2ISO | FB | up + dn | PID | France |
| PIR | SCP-Gersar | $y_{dn}$ | $y_{dn}$ | $Q$ | 2ISO | FB | dn | PI + Smith predictor | France (SCP) |
| | CACG Cemagref | $Q_{dn}$ | $Q_{dn}$ and $Q_{in}$ | $Q_{up}$ | 3ISO | FB + FF | dn | Pole placement | Rivers, southwest of France |
| CARAMBA | De Leon | $Q_{dn}$ | $Q_{dn}$ | $Q_{up}$ | SISO | FB + FF | dn | Pole placement | Model |
| | Sawadogo | $Q_{dn}$ | $Q_{dn}$ | $Q_{up}$ | SISO | FB + FF | dn | GPC | Nonlinear model |
| | Rodellar, Gomez | $Q_{dn}$ | $Q_{dn}$ | $Q_{up}$ | SISO | FB | dn | Predictive control | Nonlinear model |
| Model predictive control | Zagona and Clough | $Q$ and $y$ | $Q$ and $y$ | $G$ | MIMO | FB + FF | dn | Predictive control | Model |
| | Corriga | $y$ | $y_{up}$ and $y_{dn}$ | $G$ | MIMO | FB | up + dn | LQR + observer | Nonlinear model |
| | Davis U. | $Q$ and $y$ | $y_{up}$ and $y_{dn}$ | $Q$ and $G$ | MIMO | FB | up + dn | LQR + observer | Nonlinear model |
| PILOTE | Cemagref | $y_{dn}$ and $Q$ | $y_{up}$ and $y_{dn}$ | $Q_{up}$ and $G$ | MIMO | FB + FF | up + dn | LQR + observer | Nonlinear model |
| | Reddy | $Q$ and $y$ | $y_{up}$ and $y_{dn}$ | $G$ | MIMO | FB | up + dn | LQR + observer | Nonlinear model |
| FKBC | BRL-Gersar | $Q_{dn}$ | $Q_{dn}$ | $Q_{up}$ | SISO | FB + FF | dn | Fuzzy control | T2, CPBS (Morocco) |
| ANN | Schaalje and Manz | $y$ | $y$ | $G$ | MIMO | FB | up + dn | Neural network | Model |
| | Toudeft | $Q_{dn}$ | $Q_{dn}$ | $Q_{up}$ | SISO | FB | dn | Neural network | Model |
| ACS | CAP, USBR | $Q$ and $y$ | — | $G$ | MIMO | FF | dn | Model inversion | Central Arizona Project |
| CLIS | Liu | $Q$ and $y_{dn}$ | $y$ | $G$ | MIMO | FB + FF | dn | Model inversion | Nonlinear model |
| Controlled volumes | USBR, CSWP | $V$ | $y$ or $Q$ | $G$ | MIMO | FB + FF | dn | Model inversion | California Aqueduct |
| Gate stroking | Wylie, Falvey | $Q$ and $y_{dn}$ | — | $G$ | MIMO | FF | dn | Model inversion | Granite Reef Aqueduct CAP |
| | O'Laughlin | $Q$ and $y_{dn}$ | — | $Q$ and $G$ | MIMO | FF | dn | Model inversion | Scale model |
| SIMBAK | Chevereau | $Q_{dn}$ | — | $Q_{up}$ | SISO | FF | dn | Model inversion | Nonlinear model |
| DYN[2] | Filipovic | $V$ | $y$ | $Q$ | MIMO | FB + FF | dn | Linear optimization | Yugoslavia |
| | Sabet | $V$ | — | $Q$ | MIMO | FF | dn | Linear optimization | California State Water Project |
| | Cemagref | $Q$ and $y$ | — | $Q$ and $G$ | MIMO | FF | dn | Nonlinear optimization | Wateringues, France |
| NLP | Lin and Manz | $Q$ and $y$ | — | $Q$ and $G$ | MIMO | FF | dn | Nonlinear optimization | Nonlinear model |
| | Tomicic | $Q$ and $y$ | — | $Q$ and $G$ | MIMO | FF | dn | Nonlinear optimization | Nonlinear model |

on the unique regulator-controlled output. The global multivariable process can then be considered as a series of independent monovariable noninteractive processes evolving in parallel. This is possible if the number of inputs is greater than or equal to the number of outputs (Borne et al. 1990). Performance of a controller can be greatly improved through decoupling. Decoupling requires a linear model of the system. Its performance is therefore decreased due to unknown perturbations and model errors. Although PIR (Deltour 1992) and Dynamic Regulation do not consider coupling effects explicitly, they attempt to reduce these effects. The discharge and not the gate position is chosen as the control action variable, which is similar to decoupler II of Schuurmans (1992). Furthermore, part of the gate control action is transferred to the previous upstream controller, which is similar to decoupler I of Schuurmans (1992).

### Multivariable Methods

Control engineers have developed several multivariable methods. However, very few of them have been used on canals. For example, pole placement technique in state space and multivariable PID have never been applied to irrigation canal regulation.

Different model inversion methods are described in the literature, leading generally to feedforward controllers (Chevereau 1991; Liu et al. 1992), and more rarely to feedback controllers (Liu et al. 1994).

Optimization methods have also been developed. These methods are, in essence, multivariable. Different methods exist: linear optimization (Sabet et al. 1985), nonlinear optimization (Tomicic 1989; Khaladi 1992; Lin and Manz 1992), and LQR (Corriga et al. 1983; Florea and Popa; Balogun 1985; Hubbard 1987; Garcia 1988; Filipovic and Milosevic 1989; Reddy 1992; Malaterre 1994; Kosuth 1994; Sawadogo et al. 1995). The classical nonlinear optimization leads solely to a feedforward control, sensitive to errors and perturbations. In order to introduce a feedback control, the optimization has to be processed periodically (for example, at each time step). This complicates the method and limits its applications due to real-time constraints. Furthermore, the determination of real initial conditions, required for the optimization, is not easy. On the other hand, LQR methods, based on a state space representation, can incorporate, in essence, a feedforward control and a feedback control.

The implementation of multivariable methods is far more complex than that of monovariable methods.

## CONCLUSION

This paper presents a clear structure for characterizing each control algorithm according to a series of defined criteria (considered variables, logic of control, and design technique). The advantage of this structure is to allow the comparison of different algorithms' characteristics and to make possible the classification of them according to a selected criterion.

Canal control algorithms detailed in the literature are classified in Table 1. They are listed according to their main design technique (e.g., heuristic or PID). However, some data are missing owing to the lack of clarity of the available literature. In addition to information relative to the three criteria, the developer name and examples of application or test are given.

Complete references can be found in Zimbelman (1987), Goussard (1993) or Malaterre (1994, 1995a). Additional and updated information on canal regulation is available on the CANARI World Wide Web server at the Internet address: http://www.montpellier.cemagref.fr/~pom/canari.htm.

Such characterizations and classifications are useful to get a better understanding of the features and properties of each regulation method. Indeed, the characteristics of each regulation method will have corresponding advantages, disadvantages, performance, and constraints. Canal operators and engineers should find these classifications useful to determine appropriate regulation methods for specific installations.

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## APPENDIX II. NOTATION

*The following symbols are used in this paper:*

$G$ = regulator gate position;
$P$ = perturbation;
$\hat{P}$ = estimation of perturbations;
$Q$ = discharge in the canal;
$Q_{dn}$ = downstream discharge in the canal;
$Q_{in}$ = intermediate discharge in the canal;
$Q_{up}$ = upstream discharge in the canal;
$U$ = control action variable;
$V$ = volume in a canal pool;
$Y$ = controlled variable;
$Y_c$ = target controlled variable;
$y$ = water elevation;
$y_{dn}$ = downstream water elevation of the pool (therefore upstream of a regulator);
$y_{in}$ = intermediate water elevation in the pool;
$y_{up}$ = upstream water elevation of the pool (therefore downstream of a regulator); and
$Z$ = measured variable.

# Canal Control Algorithms Currently in Use

By David C. Rogers,[1] Member, ASCE, and Jean Goussard[2]

**Abstract:** Many canal control methods and algorithms have been developed, but only some of them are being used on operating canal projects. As a part of the ASCE task committee on canal automation algorithms, this paper discusses field application of automatic control algorithms. Based on available data, information is presented on the implementation of canal algorithms. These algorithms are categorized as implicit algorithms in self-regulating gates, local automatic feedback controllers, and supervisory control algorithms. For each algorithm, brief information is provided on water projects that are using the algorithm, the type of application, implementation history, and algorithm performance.

## INTRODUCTION

Canal automation has been evolving for several decades, to the point where most new canal designs and canal modernization projects include some level of automation. Numerous canal control algorithms have been developed, but how many of these algorithms have been implemented in the field? The practical implications, successes, and failures of control algorithms may be more important than theoretical performance. Additional information on the classification and comparison of canal control algorithms is in the paper by Malaterre et al. (1998). Discussions of control algorithm application can be found in recent books on canal automation (Buyalski et al. 1991; Goussard 1993; Rogers et al. 1995).

## CONTROL SYSTEMS VERSUS CONTROL ALGORITHMS

An algorithm is a step-by-step procedure for solving a problem or accomplishing some end. A canal control algorithm is the logical procedure that processes input, such as water levels, and outputs a control action, such as gate movement. Typically, control algorithms are expressed as a series of mathematical equations that are incorporated into software and implemented using computers. A control system can include both hardware and software. Canal control systems may include sensors, communication equipment, power supply, electromechanical devices, and human interface equipment.

Many existing control systems do not employ a control algorithm, because human operators provide the logic and decisions required for control actions (e.g., gate movements and flow changes). Supervisory manual control allows a watermaster to monitor system-wide conditions and to manipulate control structures from a headquarters office. Usually, control decisions are based on operator skill and experience rather than algorithms. (A control algorithm exists only within the operator's mind.) With an experienced watermaster at the controls, a canal can be operated with a high degree of flexibility and responsiveness.

Control systems without automatic control algorithms can be very practical and effective. However, a compilation of all such installations is beyond the scope of this paper.

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## IMPLICIT ALGORITHMS INTEGRATED IN SELF-REGULATING GATE DESIGN

### Neyrpic-Design Float-Operated Gates

Automatic, hydromechanical control gates are used successfully on many canal projects. Although they do not execute an algorithm in the customary sense, the performance of these devices could be described with mathematical equations if desired. Originally produced by Neyrpic, specially designed float-operated gates are marketed by GEC Alsthom, France, and licensees in many other countries (Goussard 1987). Gates are available to maintain the adjacent water level upstream from the gate (upstream control), downstream from the gate (downstream control), or a combination (mixed control).

The first operational constant upstream level gates (AMIL gates) were installed in Algeria (Oued Rhiou area) in 1937 for automatic upstream control in a main canal (10 $m^3/s$ maximum). Most of those gates are still working. By 1950, nearly 1,000 such gates had been installed, mainly in North Africa. They can now be found in virtually every irrigating country in the world. Fig. 1 shows two AMIL gates in parallel at Alpilles Septentrionales Canal in France. Among recent significant references are the North Jazirah 1 and 2 projects, Iraq (1987–1989, 30 $m^3/s$ maximum, 30 gates) and the Selangor project, Malaysia (1989, 20 $m^3/s$ maximum, three gates). AMIL gates also are used to control levels in drainage systems (Walt Disney World, Florida).

Constant downstream level gates (AVIS and AVIO gates) were developed and first applied in the late 1940s (over 400 gates installed before 1951, mainly in France and Algeria). Hundreds have been installed throughout the world since then, for downstream control in level-top canals. A recent reference (1989) is the Sidorejo area of the Kedung Ombo project, Indonesia, with four AVIS gates on the main canal (9.5 $m^3/s$ maximum) and four AVIO gates on turnouts to secondary canals. The flow (40 $m^3/s$ maximum) at the head of the Canal de Provence system, France, is automatically controlled according to downstream demand through two AVIS gates in parallel, as shown in Fig. 2.

Mixed gates were developed and first applied in the 1950s. In their basic operating mode they are used for related level control of reservoir pools. They also are used for mixed control, combining downstream level control with control of upstream lower and upper level limits. One of the earliest applications (1955–1961) has been the control of the reservoir pools forming the two main branches of the Bas-Rhône Canal in France (respectively, 61.5 and 13.5 $m^3/s$) through seven mixed gates, to compensate for the mismatch between the pumped head supply and the lateral on-demand deliveries (Fig. 3). The most recent reference (1993) is Canal T2, ORMVA Haouz, Morocco, with two mixed gates controlling a 20-km reservoir reach linking an upstream feeder section (53 km, 12 $m^3/s$ maximum) under upstream control to a downstream section of 20 km under downstream control.

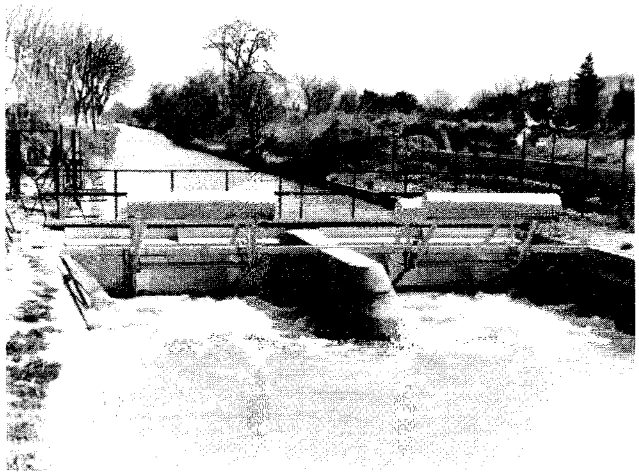

FIG. 1. AMIL Gates

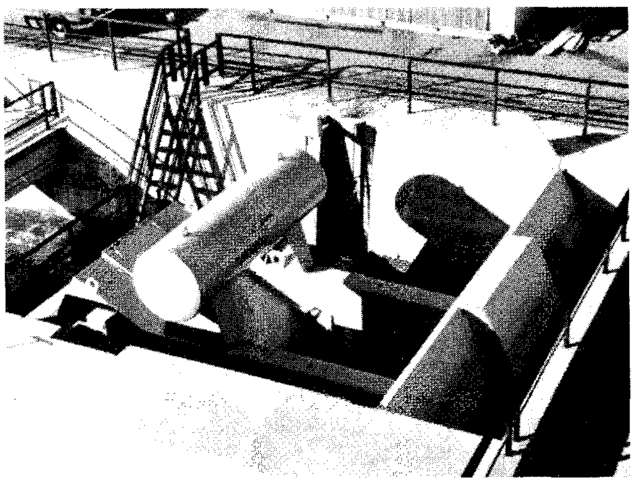

FIG. 2. AVIS Gates at Boutre Partition Works, France

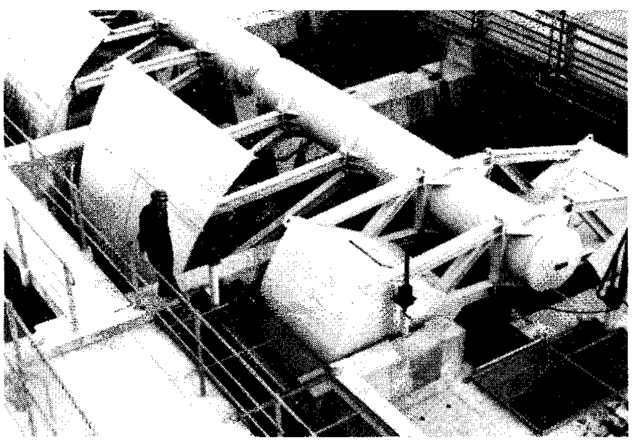

FIG. 3. Mixed Gates at Bas-Rhône Main Canal

The Neyrpic-design float-operated gates have benefited from 50 years of operating experience and improvements, and have shown their reliability and suitability in widely varied and difficult conditions. Though relatively simple, they can achieve effective automatic water level control where reliable electric power is not available. However, their application is subject to the following disadvantages:

- The specific structural requirements increase initial cost over conventional check structures.
- Because of the level-top pools required for downstream control, AVIS and AVIO gates often are not feasible for modernization projects.
- Except for mixed gates, the set point is fixed by design and can only be adjusted within a very restricted range.
- They are subject to possible interference from users, vandals, and debris.

### Controlled-Leak Systems

Controlled-leak methods use the hydraulic head across a structure to power a hydraulic piston, which moves the control gate (Clemmens and Replogle 1987). Controlled-leak systems include both single-acting (Danaidean) and dual-acting (DACL) systems. DACL was developed to overcome some of the limitations of the single-acting system, but the dual-acting system has been applied only to research studies.

The Danaidean controlled-leak system was developed in the 1930s and has been applied to canal control in several European, Asian, and American countries. Examples include Tranquility Irrigation District in California (maximum flow of 0.5 $m^3/s$); Welton-Mohawk Irrigation and Drainage District in Arizona, Northern Colorado Water Conservancy District in Colorado, and Imperial Irrigation District in California (maximum flow of 30 $m^3/s$).

Danaidean controlled-leak systems have performed reasonably well when applied to upstream control, maintaining the water level to within $\pm 25$ mm. For a variety of reasons, downstream control applications have been more problematic. Though simple and efficient, the system has not been more widely used because of the bulky additional structures required to provide buoyant counterweights and because the structural configuration offers little flexibility to change operations.

## LOCAL AUTOMATIC FEEDBACK CONTROLLERS

Local automatic control is accomplished with control equipment located at the site of the control gate using water level information from adjacent canal pools. Various types of algorithms and equipment have been used to accomplish local control in canal systems.

### Three-Position Controllers

Three-position control is a basic control mode that responds to a deviation from the set point water level by moving the control gate for a predetermined amount of time. The three controller states are:

1. Off—no corrective action
2. On, above setpoint—move the gate to lower the water level
3. On, below setpoint—move the gate to raise the water level

Two types of three-position controllers that have had widespread application are the Little-Man and the Colvin.

The first automatic gate controller in the United States was an electromechanical, three-position (floating, set-operate-time, set-rest-time) controller called the Little-Man, installed in 1952 by the U.S. Bureau of Reclamation (USBR). Little-Man controllers have been used to maintain a target water level adjacent to (either upstream or downstream from) the controlled gate. The Little-Man algorithm requires only a single water level input. The output is an incremental gate movement command. Performance is adjusted by setting the dead band, gate-operate-time, and gate-rest-time values. It is difficult to adjust the algorithm to be both stable during relatively constant flows and responsive to rapid flow changes. Two-stage Little-Man controllers—with a shorter rest time when water level goes beyond an outer dead band range—have been used to improve response to rapid changes.

Among numerous Little-Man installations, all located in the western United States, are:

- Columbia Basin project, Washington, where such controllers are used for automatic upstream level control of East Low Canal, Eltopia Branch Canal, Royal Branch Canal, Wahluke Branch Canal, and West Canal (a total of some 50 pools extending over 385 km, with maximum flows ranging from 16–144 $m^3/s$). (See Fig. 4.)
- Government Highline Canal near Grand Junction, Colo., where the Little-Man algorithm has been programmed into microprocessor canal controllers for upstream control at four check gate structures in series.
- Friant-Kern Canal (243 km, 113 $m^3/s$, 13 check structures), California, where Little-Man controllers have been used for upstream control of the upper section (nine check structures) and for close downstream control of the lower section (four check structures). (Recently, these electromechanical Little-Man controllers were replaced with new microprocessor controllers.)

The Colvin controller adds a rate control mode to the three-position mode to improve performance. Developed and improved by the USBR from 1971–1980, Colvin controllers have been applied to upstream control of diversion dam gates (North Poudre supply canal diversion dam, Colorado, and San Juan-Chama Project, New Mexico) and to downstream control of turnout or outlet gates (Loveland turnout from Hansen Feeder Canal, Colorado, and Flatiron afterbay outlet, Colo.).

Three-position controllers are most effective in applications with a single structure or a few isolated structures, because instability can develop when three-position controllers are installed on a series of check structures. An antihunt enhancement has improved performance in these applications. Antihunt is an element that disables the actuator when canal water level begins to return towards the set point.

Before microprocessors, three-position control was a feasible automatic control method using relays, timers, and other electromechanical devices. With modern, microprocessor-based equipment, more complex algorithms can improve control performance. However, because three-position control does not require a gate position indicator, it may still have application.

## PI and PID Controllers

PI controllers incorporate an algorithm that combines a proportional control mode with an integral (or reset) mode to perform the desired control action. PID controllers add a derivative (or rate) mode of control. A number of analog and microprocessor-based controllers integrating PI or PID algorithms have been developed and applied over the last two decades. They differ not only in hardware but also in their internal control logic and in their application. Some of these applications control the canal water level adjacent to the control gate (either upstream or downstream) while others control the water level at the far downstream end of the canal pool below the gate. Some typical references are briefly described here.

### *Control of Distant Downstream Level*

In the early 1970s, USBR developed the analog controller Electronic Filter Level Offset (EL-FLO) plus Rest from the results of a previous research program (HyFLO, then EL-FLO; see Buyalski and Serfozo 1979). EL-FLO has been implemented as a downstream controller to maintain water level at a canal pool's downstream end by controlling the gate at the pool's upstream end. The algorithm has proportional and integral (reset) components with a water level filter to accommodate the hydraulic lag time between the controlled gate and the water level sensor. Inputs are water level and gate position; output is desired gate position.

EL-FLO controllers were first installed in 1974 at two irrigation projects in California, Corning Canal (Fig. 5) and Coalinga Canal, and have since been used on other irrigation canals. Corning Canal is 34 km long with 12 single-gated check structures spaced an average of 2.6 km apart. Canal capacity varies from 14.2 $m^3/s$ to 2.5 $m^3/s$. The canal section is earth-lined with a 2:1 side slope, an average invert slope of 0.00019, a bottom width varying from 6.7 m to 3.0 m, and a normal water depth varying from 2.2 m to 1.1 m. Most canal deliveries are through turnouts with automatically controlled pumps serving pipeline distribution systems (Ploss 1987).

EL-FLO was implemented because flow changes were straining the capabilities of manual gate control. At Corning Canal, control performance is good at low flows but degrades as canal flow approaches design capacity. At high flows, canal operators switch controllers into an upstream mode (constant level close upstream).

In recent years, commercially available PID controllers have been used in USBR applications rather than custom-built EL-FLO controllers.

The Sogreah PID controller by Sogreah, France, was installed in the 1970s to control the level at the downstream end of the 37-km head reach (278 $m^3/s$ maximum) of the Kirkuk-Adhaim main canal in Iraq. Similar controllers are currently being installed on the Cupatitzio-Tepalcatepec Project in Mexico (five check structures on a secondary canal of the right bank system and a dam outlet to the left bank system).

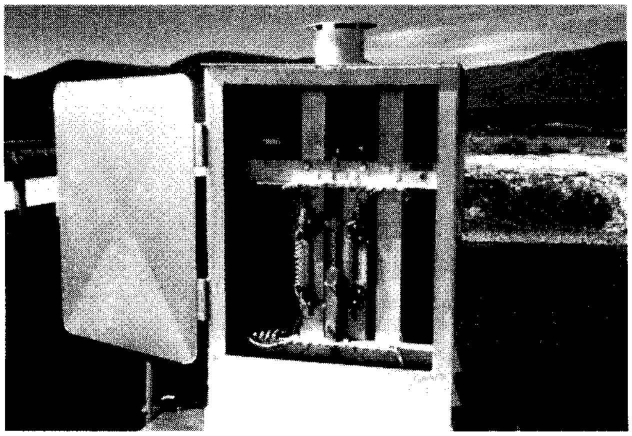

**FIG. 4. Electromechanical Little-Man Controller at Columbia Basin Project**

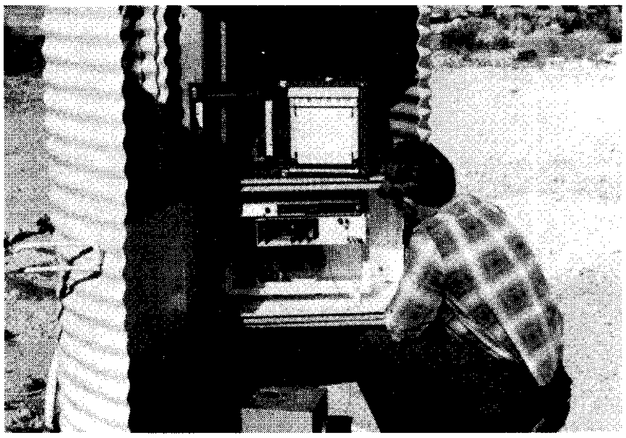

**FIG. 5. EL-FLO Controller at Corning Canal, California**

*Control of Constant Level Close Upstream or Downstream*

The Proportional plus Proportional Reset (P + PR) algorithm is essentially the same as EL-FLO, but applied in an upstream (supply-oriented) mode (Buyalski 1977). P + PR has been implemented at the Yuma Desalting Plant Bypass Drain Canal (Arizona), Umatilla Basin (Washington), Closed Basin Canal (Colorado), and Dolores Project (Colorado). In each of these applications, controllers are installed at several canal check structures in series to route flow changes downstream through the canal while maintaining a constant water level upstream from each check.

In general, P + PR is more responsive to flow changes than Little-Man and more stable for multiple gates in series. Because of the hydraulic advantages of supply-oriented operations and because the water level sensor is near the controlled gate, P + PR control performs better than EL-FLO for large flow changes and at high flows. As with EL-FLO, the P + PR algorithm contains three coefficients (proportionality constant, reset constant, and filter constant) that must be "tuned" to optimize performance. Unlike EL-FLO, the filter does not have to account for lag time from gate to sensor. The filter element in a P + PR element is used to reduce high frequency fluctuations in the water level input signal, such as those from wind waves and inconsistent water level sensor output.

UMA Engineering, Canada, in collaboration with Armtec, has developed a system combining drop-leaf (overshot) gates and programmable local controllers (Modicon or TeleSafe). This system is installed on the St. Mary River Irrigation District main canal, Alberta, Canada (280 km, 91 $m^3/s$ maximum, upstream level control at check structures, indirect flow control via downstream level control at outlet gates) and at the South San Joaquin Irrigation District main canal, California (1989, 40 km, 26 $m^3/s$ maximum, upstream control of 10 check structures, and flow control via downstream level control for two check structures).

To our knowledge, the only controllers using related level control logic are those installed in the 1970s by Sogreah, France, to control the two reservoir-reaches (22 km each, 232 and 130 $m^3/s$, respectively) of the Kirkuk-Adhaim main canal in Iraq, to maintain a constant difference between the level just upstream from each regulator and the level at the far end of the pool downstream from the same regulator.

Constant volume (BIVAL) control logic, developed by Sogreah, has been applied to two reaches (62 km each, 75 $m^3/s$) of the Sahel canal in the Fala de Modolo system in Mali, since 1983 (Chevereau and Schwartz-Benezeth 1987). Because infrequent gate adjustments are required, the regulators are operated manually using level readings and charts. An automated BIVAL control system is currently under implementation on the right bank of the Cupatitzio-Tepalcatepec Project, Mexico.

The PIR algorithm was developed by Société du Canal de Provence in 1992–1993 and has been satisfactorily controlling a branch of the Canal de Provence system since 1994. For this first operational application, the PIR software has been integrated into the Dynamic Regulation system to maintain water level downstream from the controlled gate (downstream control). No specific hardware has yet been developed or selected for a possible canalside PIR controller.

### Heuristic Controllers

The Remote Terminal Unit flow control (RTUQ) algorithm was developed by USBR in 1992 ("Programmable" 1988). The algorithm uses a feedback loop to maintain a target flow through a gated check structure. Inputs are upstream water level, downstream water level, and gate position(s) at the check. Using these input data and empirically developed gate coefficients (Buyalski 1983), actual gate flow is computed and compared to target flow. Algorithm output is the gate movement required to produce the target flow.

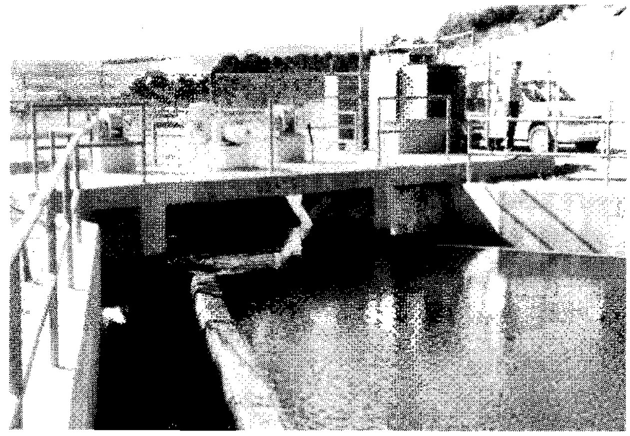

**FIG. 6. Check Structure and RTU at Dolores Project, Colorado**

RTUQ is being used at the Dolores Project, Colorado (125 km, 11 $m^3/s$ maximum, 60 check gate structures) as part of a supervisory control system (see Fig. 6). A schedule of target flows is sent to each check structure RTU based on system-wide operating needs, and RTUQ adjusts gates as necessary to maintain the prescribed flow. Because turnout flows are pumped from the canal into pipe distribution systems, constant water level in the canal is not required (Rogers 1995).

To be accurate, RTUQ requires complete data on check structure dimensions, water levels, and gate positions. The algorithm has performed well when all these data are accurate. Enhancements have been added to improve control stability when the water level on the downstream side of the gate is in the transition zone between free and submerged gate flow.

## SUPERVISORY (OR CENTRALIZED) CONTROL ALGORITHMS

Supervisory control involves monitoring canal conditions and controlling structures from a centrally located master station. Supervisory control algorithms use system-wide (global) information to manage the canal system's operation by controlling multiple sites. In recent years, supervisory monitoring with manual control has become more prevalent on smaller canal projects. Automatic control using global algorithms has been limited to large projects because of the cost and complexity involved.

Dynamic Regulation was developed by the Société du Canal de Provence, France, for application on the Canal de Provence system (Rogier et al. 1987). Initiated in 1971 for application to a branch canal, dynamic regulation was extended to the entire Canal de Provence system by 1986. The conveyance system, which supplies agricultural, municipal, and industrial users, includes 105 km of main and branch canals (40 $m^3/s$ maximum) and 130 km of pressure pipes and tunnels. The Dynamic Regulation system controls and monitors the operation of 33 regulating gates, 24 emergency gates, four pumping stations, and two in-line hydropower plants. The system has shown a high degree of efficiency and reliability: error on daily demand forecasts is less than 15%, actual demand is met with no operational spillage, and master station availability exceeds 99%. Only one operator supervises the system during daytime and the master station is unmanned at night.

Dynamic Regulation also has been successfully applied to complex systems in Greece (Athens water supply), Macedonian Republic (Stretzevo Irrigation Project), and Morocco (Rocade Canal, 127 km, 20 $m^3/s$, seven check structures, two main turnouts, 15 RTUs).

Aqueduct control software (ACS) was developed by USBR in the 1980s to control the Central Arizona Project (CAP) canal system (Gooch and Graves 1985). The CAP is a 540-km-long series of open canals, inverted siphons, and tunnels with 14 in-line pumping plants and 36 check structures. The project is demand-oriented, delivering a maximum of 85 $m^3/s$ for irrigation and municipal use without any wasteways to spill excess water.

ACS is a centralized, feedforward algorithm that generates pumping plant flow schedules and check structure gate position schedules to control water volumes throughout the canal system while minimizing pump starts. Pump and gate operation schedules are based on predicted demand and real-time water level data, using model inversion (backwards simulation) to solve canal hydraulics. Inputs are upstream and downstream water levels for 40 canal pools, pumping plant flows, turnout flows, gate positions and predicted flow schedules. ACS outputs gate position setpoints for check structures and suggested gate openings for turnout structures.

ACS executes on a master station computer and sends control schedules to microprocessor RTU equipment at pumping plants, check structures, and turnouts (see Fig. 7). It has been operating successfully for more than 10 years and has been upgraded numerous times. Enhancements to the original software have included improved data error checking plus extensive calibration of gate flow coefficients and pump curves.

The controlled volume control method was developed in the 1970s for the California Aqueduct (710 km, 290 $m^3/s$ maximum, 242 turnouts, and some 90 aqueduct pools with tunnels, siphons, 66 gated check structures, and 27 pumping and power plants). The centralized algorithm controls pool volumes to satisfy scheduled water demand while minimizing pumping power costs and avoiding overloading the power supply network. Although the system was designed to respond to delivery changes on relatively short notice, farmers (30% of the yearly deliveries) sometimes complain that the system lacks flexibility.

The CACG method was originated in the mid-1960s and has been continuously improved since then by Compagnie d'Aménagement des Coteaux de Gascongne (CACG), France. CACG was developed for central management of flows and reservoirs in a system of rivers in which the discharges are regulated by supplementary supply from off-line sources and releases from in-line storage dams. Reservoir releases are centrally controlled according to automatically generated demand forecasts and the current status of the system. No gated structures are used on the rivers, and accurate control of water levels is not a concern because irrigation deliveries are pumped.

The main reference for CACG is the Neste system, France, for which the method was devised (17 rivers totaling 1300 km, four in-line dams with a total storage capacity of 52 million $m^3$, additional supply from eight mountain reservoirs totaling 48 million $m^3$ storage capacity, and a 29-km, 14-$m^3/s$ feeder canal). The objectives of the project—satisfying user demand, maintaining minimum flows required for water quality, and improving the conveyance efficiency (now about 90%) by reducing operational losses—are considered to be fully met.

**FIG. 7. Supervisory Control Room at Central Arizona Project**

The Fuzzy knowledge-based controller (FKBC) has been developed very recently by BRL-Ingénierie (a division of Compagnie Nationale d'Aménagement de la Région du Bas-Rhône et du Languedoc, France). A first FKBC was installed and put into operation at the beginning of 1995, as a part of the supervisory control system of Canal T2 in Morocco. FKBC determines the optimal flow set point for the two radial head gates, based on demand forecasts, current system-wide status, a rule base, and a database.

## CONCLUSIONS

Although this paper summarizes canal control algorithm implementation, it is not an all-inclusive compilation. Because the use of modern control technology on water projects is constantly expanding, many cases of control algorithm implementation exist beyond those mentioned in this paper. The writers welcome additional information on canal projects where control algorithms are being used, especially cases where a new algorithm has been implemented for the first time.

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