

# Design, implementation and tuning of an irrigation canal system SCADA

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**Abstract:** The paper presents the design, implementation and field tuning of the (SCADA) system of a Portuguese irrigation canal network upstream controlled by AMIL radial gates and equipped with other Neyrpic devices. In addition to the irrigation district and its main hydraulic system, the paper also presents SCADA architecture, including two synoptics, and their remote terminal units (monitoring and controlling as well as monitoring units). The SCADA manual controllers – direct, gate position and gate flow controllers - are defined for the intakes of main canals and main distributors, in order to permit a pre-defined flow value or a daily flow schedule achievement. SCADA also monitors outflows from the main canals and main distributors - the most important canal-top-side weirs and terminal weirs of the canal. The developed manual gate flow controllers were tuned in the field using collected data readings from two types of acoustic Doppler flow meters. The field procedures for tuning the flow controllers and the obtained parameter values are also presented.

**Keywords:** canal control, flow controller, flow equations, irrigation canal, local upstream control, SCADA system

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## 1 Introduction

Irrigation is the largest water user in the world, using up to 85% of the available fresh water in the developing countries (Plusquellec et al., 1994). The same issue happens in Portugal, where 87% of the available fresh water volumes are used in the agriculture, only with an efficiency of 58% (the ratio of the useful water volumes to the used water volumes) (INAG, 2001).

The established user-payer principle in the European Union begins to press the agriculture and the irrigation water prices begin to rise. Nowadays, in Portugal, all the water users have to pay a water resource tax, considering the used water volume. The immediate consequence for irrigation is that present water use efficiencies have to increase drastically and the water management must be

moved rigorously. The agriculture has to be developed and intelligent management and operation of the irrigation systems have to be implemented, in order to achieve higher water savings and desirably better water delivery service within a short period of time.

Due to technical and economical reasons, the large untreated water conveyance and delivery networks are usually open-channel systems. In Portugal, 95% of the governmental irrigation projects were built between the 40's and the 70's of the last century. In these irrigation districts, the water is conveyed and delivered through an open concrete-lined canal system and the canals are upstream controlled by AMIL gates or duckbill weirs (Kraatz and Mahajan, 1975).

Upstream control (Buyalski et al., 1991) provides a water supply system which have to be operated on a scheduled delivery basis. Flow rates out of each turnout are computed in advance. The deliveries have to precisely match the amount of water which is turned into the system (Clemmens, 1987). However, in the field, this method is rarely implemented and, if unannounced flow

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rate changes are made at turnouts, the system will end up with an excess or deficit of water, especially at downstream end of canals (Rijo, 2010).

In Portugal, all these canals operate on an arranged delivery schedule basis (Clemmens, 1987), with flow rate adjustments being approved in advance by the water-master. Water delivery gained flexibility, but the daily operation of the canals became much more complex, difficult and inefficient in the water use. Operational and controlling water losses in the canals (all of them concrete-lined, as mentioned) became significant, reaching values of 50% of the inflow water volumes (Rijo and Almeida, 1993). Most of these systems are still empirically operated according to personal judgments.

Operating a conventional upstream controlled canal system is a difficult and demanding task. Control, reporting, historical data, rising costs of energy, limited water supplies and labour represent only a few management concerns. To overcome some of these problems, a few irrigation districts are considering replacing manual and outdated telemetry systems by Supervisory Control and Data Acquisition (SCADA) systems which are based on state-of-the-art computer.

There are probably three major reasons why irrigation districts are investing in SCADA systems: i) to retire “art” and to shift to an industrial control process, in which real-time information at a central location is constantly used to make appropriate decisions; reducing “art” from the process fulfils the need and desire to reduce inflow; to provide better customer service (adding more flexibility to water delivery); to reduce pumping costs; to conserve water; to remove the mystery of operation details, so that new employees can be easily trained, and so that managers can establish clear and measurable performance guidelines for canal/ pipeline operators; to improve water delivery to farm turnouts which contributes to better on-farm efficiency; ii) there is often a need for automation that requires computers at remote locations; because it is the nature of computers, electronics, sensors and software to have occasional problems, it is prudent to remotely monitor their performance at such sites (Burt, 2005); iii) some districts have key trouble spots where water levels historically get too high, or flow rates get too

low or high; SCADA provides a mean to remotely monitor those sites in real-time, eliminating tremendous labour, distractions, vehicle mileage, dust, etc. (Burt, 2005).

On the other hand, remote monitoring and control systems are becoming cost-effective water management tools because of the constant cost breakthrough in computers, software, controllers, remote terminal units, communication equipment and sensors.

SCADA allows the water manager to continuously compare actual hydraulic state of the canals with their optimal hydraulic state, and to take appropriate corrective steps as required. These innovations allow the manager to react rapidly and effectively to the changing conditions, thereby accommodating both high and low flow conditions and reducing canal spillage and seepage.

The paper presents the SCADA system designed for the Idanha-a-Nova Irrigation District (INID), a Portuguese governmental irrigation district built in the 40's of the last century, and the corresponding implementation and field tuning.

The paper begins with a brief presentation of the INID and its main and secondary canal system and, after that, makes a general presentation of the developed and implemented SCADA system, including field stations, two of the developed synoptics, monitoring flows and manual controllers. An especial attention is paid to the remote manual gate flow controllers installed at the main canals and main distributors. The general algorithm used for the gate flow controllers was tuned in the field, using two types of acoustic Doppler flow meters. The paper also presents the used flow meters, the obtained results and the calibration methodology of flow gate controllers.

## 2 Idanha-a-Nova irrigation district

INID is located at the center of Portugal, in the valley of the Ponsul river, a tributary of the Tejo River, the main river of the country. The total area equipped and gravity dominated by the canal system is 8200 ha (Figure 1) and the customers are around 950.

The entire irrigation district is supplied by the Marechal Carmona Dam, of which the reservoir has a useful capacity of  $77.3 \times 10^6 \text{ m}^3$ . The main canals and

main distributors are open concrete-lined canals and are upstream controlled by AMIL radial gates (Kraatz and Mahajan, 1975) that provide adequate operation conditions for the Neyrpic orifice module (Kraatz and Mahajan, 1975), which equip customers with the great majority of the canal intakes and turnouts.

The irrigation district is composed of two irrigation blocks (Figure 1) – Campina Block, with a surface of 5700 ha, supplied by the Main Canal, by the Distributors 1 to 21 and by the Ladoeiro Pumping Station (Ladoeiro PS); Aravil Block, with a surface of 2500 ha, supplied by the Aravil Main Canal, Canal Direito and Canal Esquerdo, which is with the Distributors 1 to 5, and by the Aravil Pumping Station (Aravil PS), which supplies the Aravil Main Canal.

The main canal system is the water conveyor to the two irrigation blocks and consists of (Figure 1):

- MC – Main Canal – with the intake at the Marechal Carmona Dam and the end section at the Ladoeiro PS; it is designed for  $7.38 \text{ m}^3 \text{ s}^{-1}$  and has a length of 23701 m;
- MCcont – Main Canal of continuation – It is the direct continuation of the MC; it develops between the Ladoeiro PS and Distributor 19 (D19) intake, near the Management Centre of the irrigation district and also of the installed SCADA system; it is designed for  $1.58 \text{ m}^3 \text{ s}^{-1}$  and has a length of 2614 m;
- MCa – Aravil Main Canal – with the intake at the Aravil PS, it ends at the diversion node of the Canal Direito (CD) and Canal Esquerdo (CE); it is designed for  $2.275 \text{ m}^3 \text{ s}^{-1}$  and has a length of 808 m.

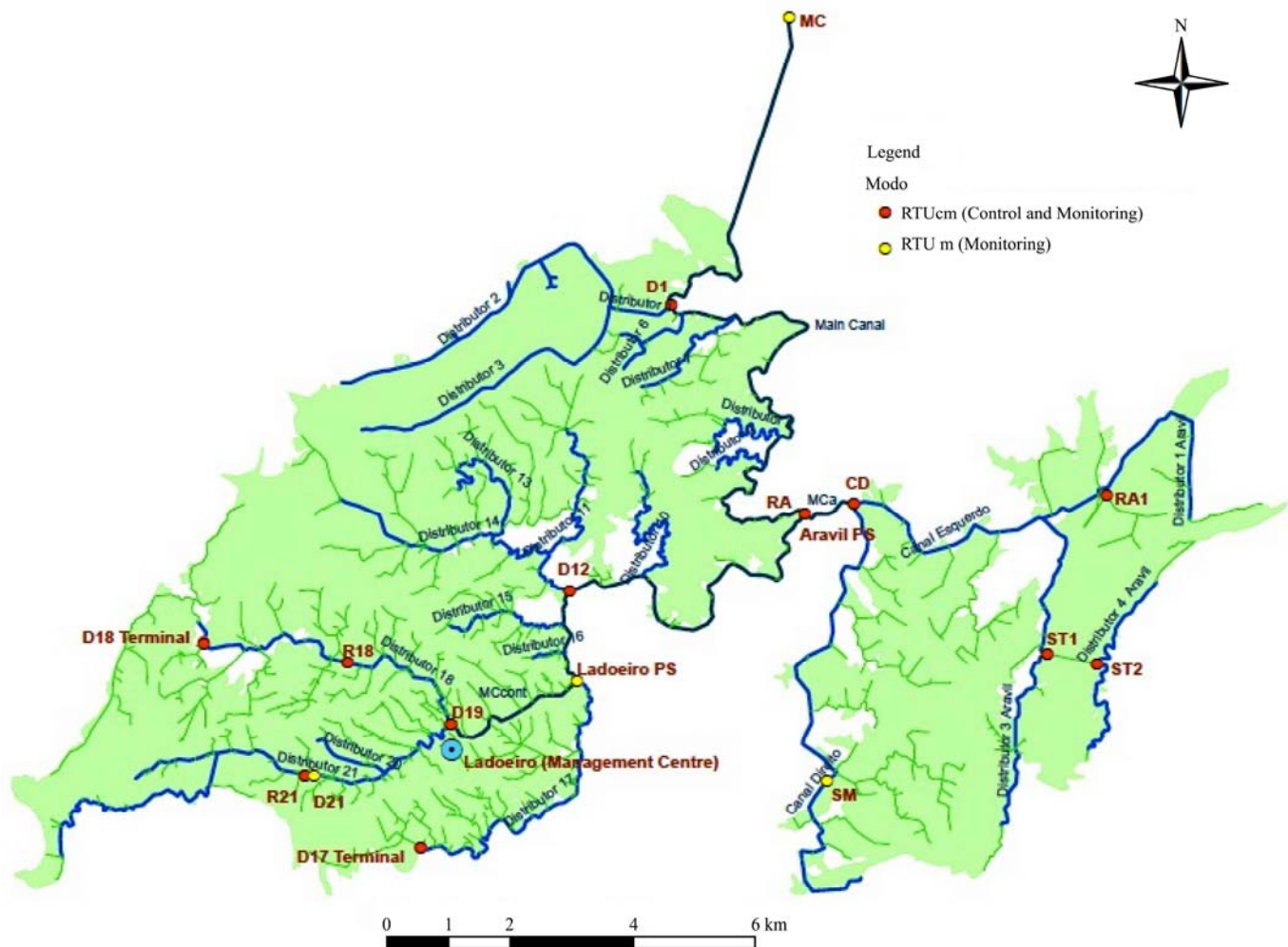


Figure 1 INID scheme and the location of SCADA field stations

The secondary canal network, beginning at the main canal system, in addition to the water conveyance, already has a significant water delivery function to the customers and is constituted by the distributors (Figure 1):

- MC – Distributors one to 17 (D1 to D17);
- MCcont – Distributors 18 to 21 (D18 to D21);
- MCa – Distributor one, distributor two, distributor three, distributor four, canal CD and canal CE.

### 3 INID canal system SCADA

#### 3.1 General presentation

Upstream local control can be manual or automatic for water depths. In the present case is automatic, with AMIL radial gates being the controllers. However, with upstream control, all the flows are, always, manual controlled, the inflows at canal (or distributors) intakes and the outflows at turnouts to customers or to the drainage system.

The main goal of a SCADA system is to optimize these manual procedures and, in this way, to improve the traditional manual canal operation.

The central manual control of a canal system is only appropriate and efficient when reliable information exists about the real-time hydraulic state of the system. Therefore, a canal SCADA system usually involves (Rijo, 2008):

- a real-time remote monitoring action in order to keep abreast of the hydraulic conditions or in order to obtain actual hydraulic state; this action is guaranteed by the SCADA;
- a real-time control action in order to lead the system to the desired state – manual flow control at canal intakes and turnouts (eventually, also at a few outlets to drainage system), guaranteed locally or remotely by the SCADA;
- a management action to support operational decisions and correction actions, ensuring the desired service performance, regarding the real and expected demands, the available water storage volumes and economic factors – a watermaster decision.

The SCADA should be robust to local failures, in order not to compromise the functioning of the entire system, and modular and flexible to permit an easy expansion. So, in the present study, the adopted solution was to choose a distributed system by opposition to a centralized system with all the decisions concentrated in one central computer. The distributed control system guarantees flexibility and modularity, since for each new extension, the existing controllers do not need to be altered and also guarantee robustness, as a failure in one of the controllers or in the communication system that links the controllers to the hydraulic structures and

sensors affects just a part of the system.

Basically, the SCADA system involves: a central computer or an Human Machine Interface (HMI), remote terminal units (RTU) and a communication system connecting the central unit to the RTU's. RTU's are, basically, small computers that can be programmed for specific requirements at individual sites (Programmable Logic Computers, PLC). The RTU's are also the points to which sensors are connected and constitute the interfaces between the SCADA and the hydraulic system. For safety, they are located inside field stations (Sta).

#### 3.2 Remote terminal units

RTU's main purposes are: controlling inputs and outputs of field devices (gates); monitoring water levels, flow rates, gate positions and log alarms; reporting to the management centre and carrying out the commands set they receive from the management centre.

With the implemented SCADA, two functions are guaranteed:

- remote monitoring – through the HMI of the management centre, to receive and plot, depending on needs and functional requirements, the direct information of the sensors (water levels, gate positions and flow rates) of each RTU or the corresponding computed values;
- remote manual control – it is the same as supervisory control and is the historical foundation of the SCADA systems; the operator can raise or lower gates and send flow orders or setpoints to each RTU and thereby effect the canal operation from the central computer directly; this is called remote manual because gate movements are implemented or ordered by the canal company staff just as if they were at the gate or check, but the gate adjustments can be made much more frequently and therefore canal operations, overall, can become more real time.

SCADA canal systems can also have automatic control functions, which is not the case of the implemented version. Canal automatic control or canal automation can be defined, for example, as the closed-loop control in which a gate changes its position/setting in response to a water level (or flow rate) and close-loop means by which the action is performed without human intervention (Wahlin and Zimbelman, 2014).

Table 1 presents the main features of the selected locations to be monitored and controlled by the SCADA. These locations were selected in the field in collaboration

with the water master and ditch riders, in order to take into account their experience and knowledge about canals dynamics and operation.

**Table 1 Brief characterization of the locations chosen for the INID SCADA field stations installation**

Location	Flow				Intake			Comments
	Intake, $m^3 s^{-1}$	Canal, $m^3 s^{-1}$	Useful width, m	Total width, m	Structures	Structure height <sup>(*)</sup> , m	Canal height <sup>(**)</sup> , m	
MC intake	7.38	7.38	5.50	---	two gates	---	1.23	Free/subm. flow <sup>(***)</sup> ; EDP power
D1 intake	---	0.784	1.40	1.75	five gates	---	1.07	Free/subm. flow; no power
RA- Aravil PS	---	2.275	1.50	1.68	one gate	---	2.30	Free/subm. reverse flow; no power
D12 intake	---	1.134	1.95	2.12	three orifices with gates	---	1.45	Free/subm. flow; no power
Ladoeiro PS	---	---	---	---	---	---	---	EDP power
D17 terminal	0.065	0.065	0.065	0.067	XX <sub>1</sub> -M3-65	0.58	0.42	Free flow; no power
R18 intake	2.30	2.30	2×0.80	2.0	two gates	---	1.80	Free/subm. flow; no power
R18 turnout	1.10-0.66	---	---	---	gate Ø800 mm	---	---	Pipe flow; no power
D18 terminal	1.025	1.025	0.94	1.05	two gates	---	1.05	Free/subm. flow; no power
D19 terminal	0.288	0.288	1.00	1.87	one orifice with two gates	---	1.50	Free/subm. flow; no power
D21	---	0.111	---	---	---	---	0.75	No power
R21 turnout	0.19-0.16	---	---	---	gate Ø400 mm	---	---	Pipe flow; no power
CD intake	0.608	0.608	---	---	Weir with gates	---	1.50	Free/ subm. flow; no power
SM	---	0.608	---	---	---	---	1.40	No power
RA1 intake	1.265	1.265	1.00	1.0	one gate	---	2.50	Free/subm. flow; no power
RA1 downstream	1.265	1.265	2×1.00	2.90	two gates	---	1.35	Free flow; no power
RA1 turnout	0.30	---	---	---	gate Ø700 mm	---	---	Pipe flow; no power
ST1	0.493	0.493	1.04	1.34	one gate	---	---	Free flow; no power
ST2-D4 intake	0.203	0.203	1.32	1.94	two gates	---	0.75	Free/subm. flow; no power
ST2-D5 intake	0.121	0.121	0.80	1.40	two gates	---	0.67	Free/subm. flow; no power

Note: (\*) From the weir crest to the top of the Neyptic module; (\*\*) From the canal bottom or weir crest to the canal top; (\*\*\*) Free or submerged hydraulic jump downstream the gates.

They were defined as two different RTU's types, one with monitoring functions and the other with control and monitoring functions:

- **Field Stations with Control and Monitoring Units (RTUcm)**- There are 12 field stations with RTUcm; these RTU's can include the functions – flow gates control,  $Q$ ; remote monitoring of upstream gate (or other hydraulic structure) water levels,  $h_1$ ; remote monitoring of downstream gate (or other hydraulic structure) water levels,  $h_2$ ; remote monitoring of gate openings,  $w$ ; flow computations over weir ( $s$ ),  $Q_1$ ; and flow meter monitoring sensor,  $Q_2$  (Figure 1 and Table 2).

- **Field Stations with Monitoring Units (RTUm)** – There are four field stations with RTUm, equalling to the RTUcm, but without flow gates controllers,  $Q$  (Figure 1 and Table 2).

The different developed controllers were programmed inside each PLC with control functions. The algorithms to monitor water levels and gate openings and to compute

flow over weirs were also programmed inside the PLC's. The different programmed algorithms are activated by the operator, locally or at the central unit.

The installed PLC's are industrial devices that use standard Ladder programming language.

### 3.3 Management centre

The management centre is located at the Water Users Association Building (Ladoeiro, Figure 1) and its main functions are the control and monitoring of the canal system. It coordinates the RTU's through the central HMI, sending orders or target values and receiving information about the general state of the hydraulic system.

The central unit is a computer based system and an interface software is used to communicate with remote sites. The software that provides an umbrella over everything (human-machine interface or HMI) is a general SCADA software and the application for the INID was developed within the modernization project here presented.

**Table 2 INID SCADA field stations**

Field station (Sta)	Location	RTU type	Gates nber	Hydraulic jump	Monitoring	Weirs	Flow sensors	Controllers	Power
MC-Main Canal									
MC	MC intake	RTUm	---	---	(3*)	---	---	---	EDP
D1	Distributor one intake	RTUcm	1	Free/subm.	$h_1, h_2, w$	---	---	$D, P, Q$	Solar
RA-Aravit PS	Aravit PS	RTUcm	1(*)	Free/subm.	$h_1, h_2, w, Q_1, Q_2$	2	1	$D, P, Q$ (5*)	EDP
D12	Distributor 12 intake	RTUcm	2	Free/subm.	$h_1, h_2, w$	---	---	$D, P, Q$	EDP
Ladoeiro PS	Ladoeiro PS	RTUm	---	---	$h_1, h_2, Q_1, Q_2$	2	1	---	EDP
D17 Terminal	Distributor 17 terminal	RTUcm	1	Free	$h_1, w, Q_1$	2	---	$D, P, Q$	Solar
MCcont-Main Canal continuation									
R18	Reservoir 18	RTUcm	2(*)+1(*)(**)	Free/subm.	$h_1, h_2, w, Q_1, Q_2$	1	1+1(4*)	$D, P, Q$	EDP
D18 Terminal	Distributor 18 terminal	RTUcm	1	Free/subm.	$h_1, h_2, w$	1	---	$D, P, Q$	Solar
D19	Distributor 19	RTUcm	1	Free/subm.	$h_1, h_2, w, Q_2$	---	1	$D, P, Q$	EDP
D21	Distributor 21	RTUm	---	---	$h_1, Q_2$	---	1	---	Solar
R21	Reservoir 21	RTUcm	1(*)(**)	---	$h_1, Q_1$	1	---	$D, P, Q$	EDP
MCA-Aravit Main Canal									
CD	Canal Direito intake	RTUcm	2	Free/subm.	$h_1, h_2, w$	---	---	$D, P, Q$	EDP
SM	Mascarenha siphon	RTUm	---	---	$h_1, Q_1, Q_2$	1	1	---	Solar
RA1	Aravit reservoir one	RTUcm	3(*)+1(*)(**)	Free/subm.	$h_1, h_2, w, Q_2$	1	---	$D, P, Q$	EDP
ST1	Toula siphon intake	RTUcm	1	Free	$h_1, w, Q_1$	1	---	$D, P, Q$	Solar
ST2	Toula siphon end	RTUcm	1+1	Free/subm.	$h_1, h_2, w$	---	---	$D, P, Q$	Solar

Note: (\*) Already installed; (\*\*) Turnout wall gate; pipe flow; (3\*) Signal readings of the already existing SCADA; (4\*) Electromagnetic flow meter in the water intake pipe; (5\*) Eventual reversal flow.

### 3.4 Communications

The communications between the RTU's and the central unit is guaranteed by a mobile phone operator and supported by GPRS/UMTS. It is a two-ways communication, in which the central can call a selected RTU or all the RTU's, according a pre-defined sequence after a central decision or automatically according a pre-defined time interval, or the RTU's can call the central system to report alarms. The alarms appear at the central computer but also are transmitted to pre-defined cell phones.

The communications are supported by the IEC60870-5-104 protocol. With this protocol, it is not necessary that a permanent data is reading by the SCADA. There is only data transmission to the SCADA when alarm situations appear at one or more field stations, being always possible to connect RTU's, if required or desired.

### 3.5 Power supply

The RTU's are supplied by the national electrical power network (EDP, Table 2) or by solar panels (Solar, Table 2).

### 3.6 Alarms

The SCADA alarms processing has an important role, making possible the information about verified damages, suggesting the corresponding actions and, in extreme

conditions, making pre-defined automatic decisions (open or close gates, for example).

The main alarms of the SCADA are: water depths inside canal pools – in order to prevent the canal emptying or overtopping; the operational state of the control devices (gates, water level and gate sensors and controllers).

## 4 Examples of SCADA synoptics

Figure 2 and Figure 3 represent examples of synoptics of the developed SCADA application.

Figure 2 presents the SCADA main synoptic, a general overview of all canals. Clicking on a specific canal, we can access the canal synoptic. The main menu is divided into four parts: the title bar (top bar); navigation bar (left bar), which permits navigating among the several SCADA pages; information bar (bottom bar), with the display of the alarms occurred that have not been recognized; main area, with the selected synoptic menu, as it is the case of the Sta D19 synoptic presented in Figure 3, which presents, namely, the flow and water depth values of the upstream gate, values of the upstream and downstream gate water depth sensors, gate opening (%) and flow under the gate. In Figure 3, it is also visible that a small table with the controllers can be selected and the flow calendar for the gate is visible, too.



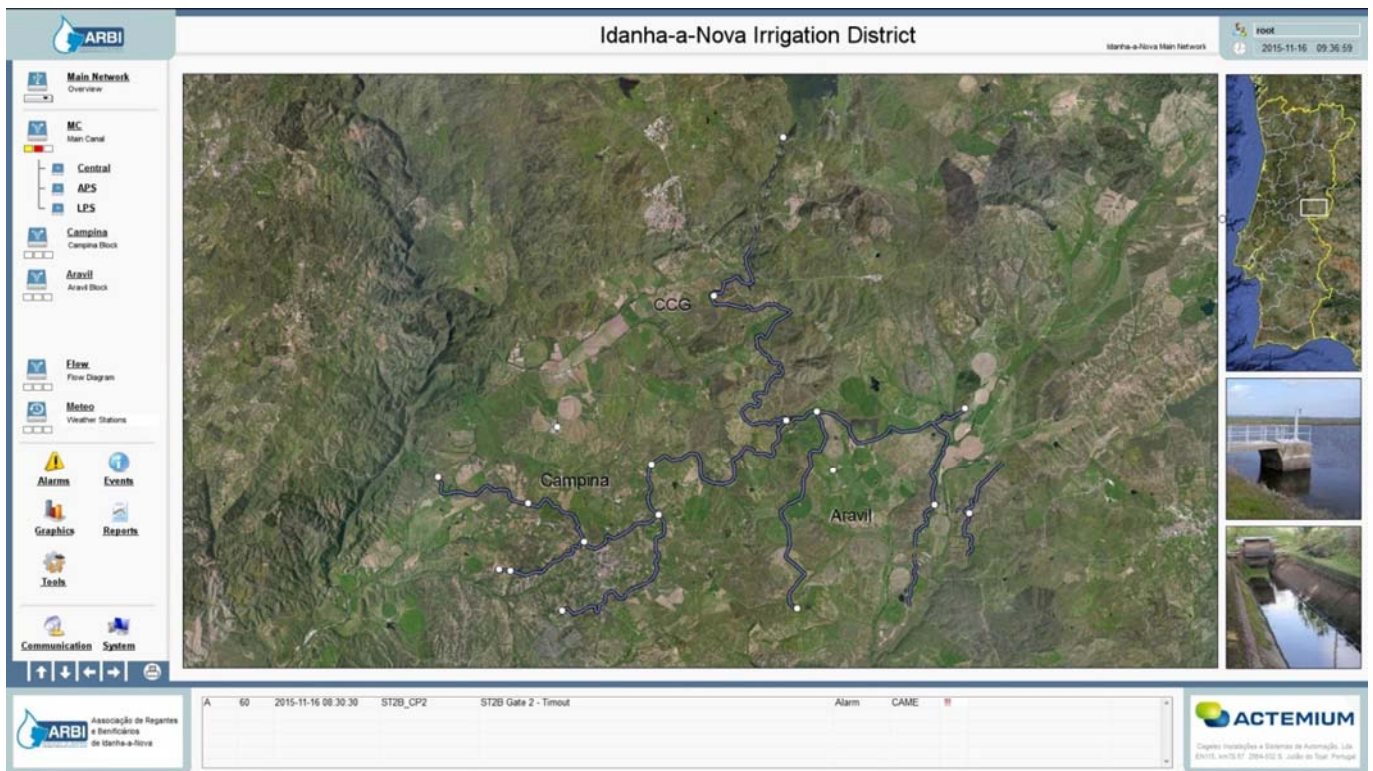


Figure 2 Main synoptic of the INID SCADA

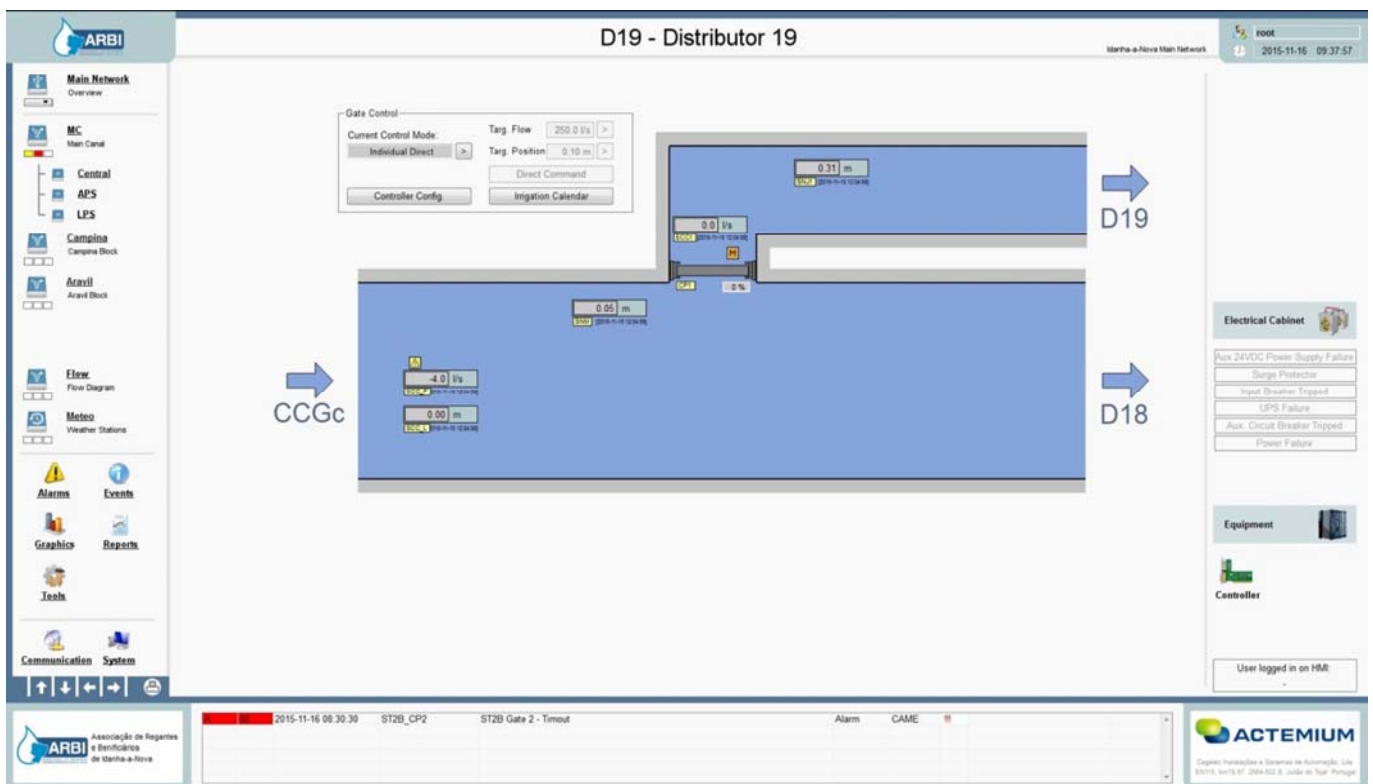


Figure 3 Sta D19 SCADA synoptic

## 5 Installed controllers

### 5.1 Gate flow controller ( $Q$ )

The main goal of the flow controller is to obtain and maintain a pre-defined flow (or a flow calendar) for the selected gates. Figure 4 shows the control algorithm for

two independent gates at the same installation, the implemented solution for a few field stations (Table 2).

In Figure 4, the presented variables mean:

- COMMAND  $G1$ , COMMAND  $G2$ , respectively, operation order for the gates  $G1$  and  $G2$  (Open/ Close/ Stop);

- $G1_{status}$ ,  $G2_{status}$ , respectively, gates  $G1$  and  $G2$  states (Open/ Closed / Failure / Manual);
- $h_1$ ,  $h_2$ , respectively, water depths at the upstream and downstream gates;
- $Q$ , global flow for the two gates computed by the flow controller;
- $Q_{ref}$ , target flow for the two gates;
- $w1_{me}$ ,  $w2_{me}$ , respectively, the measured values of the gate  $G1$  and  $G2$  openings;
- $w1_{ref}$ ,  $w2_{ref}$ , respectively, the target values for the openings of the gates  $G1$  and  $G2$ ;
- $\Delta Q$ , inside the dead band filter, is the error dead band ( $2\text{-}5\text{ Ls}^{-1}$ , defined for each location);
- $\Delta T1_{OFF}$ ,  $\Delta T2_{OFF}$ , respectively, minimum stop time required by the servomotors of the gates  $G1$  and  $G2$ .

The error,  $e = Q_{ref} - Q$ , is compared with the pre-defined value of  $\Delta Q$  and the actuators will open the gate (s) when  $e > \Delta Q$  and close the gate (s) if  $e < \Delta Q$ .

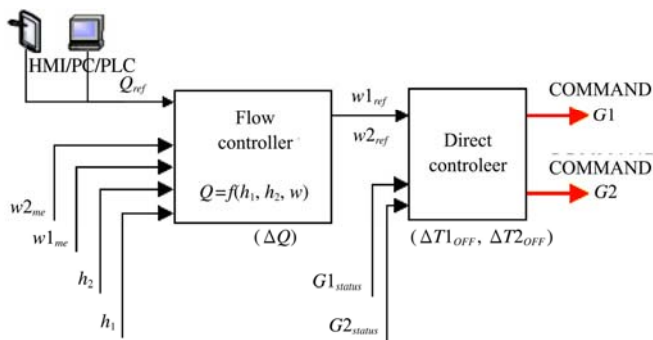


Figure 4 Remote/local flow controller algorithm scheme for two gates (Rijo and Arranja, 2010)

#### Flow $Q$ computation

In order to program a digital flow controller, it is very important to have a general flow algorithm that guarantees the solution continuity for the entire operation domain of the hydraulic structure under study (gate or weir controlled or not by gates), without numerical discontinuities.

There are several flow equations, but, usually, they are only valid for a certain flow condition – weir or gate free flow (free hydraulic jump downstream, Figure 5) or weir or gate submerged flow (submerged hydraulic jump downstream, Figure 5). The combination of these well-known flow equations usually fails in the transition of the free to submerged condition, in one way or another, and makes no difference between totally or partially

submerged flow (Baume et al., 2008; Brunner, 2010).

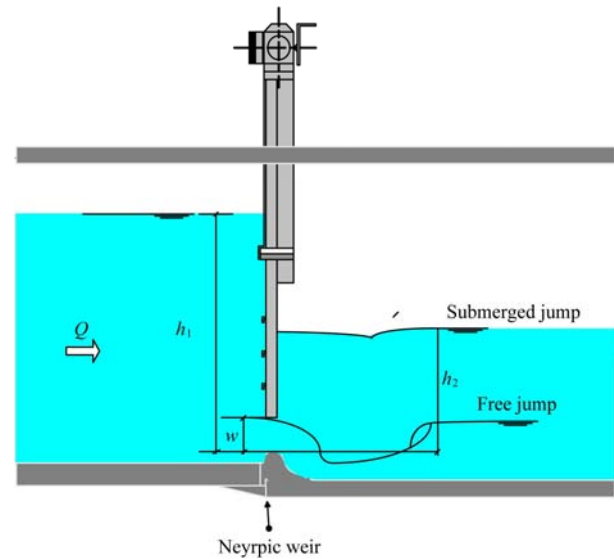


Figure 5 Sluice gate associated with a Neyrpic weir (Rijo, 2008)

Baume et al. (2008) presents a general flow algorithm that guarantees the continuity of the numerical solution for the entire domain of operation of these hydraulic structures. For this reason, this was the flow algorithm chosen for the present study and its general definition is as follows.

Figure 5 presents a low weir ( $p_1 \rightarrow 0$  and  $p_2 \rightarrow 0$ ) controlled by a sluice gate, whose general flow equation is

$$Q = L\sqrt{2g}[k_a h_1^{3/2} - k_b (h_1 - w)^{3/2}] \quad (1)$$

where,  $L$  is the weir length;  $g$  is the acceleration of gravity,  $k_a = k_F \mu$  and  $k_b = k_{F1} \mu_1$ , being  $k_F$  and  $k_{F1}$  reduction factors and  $\mu$  e  $\mu_1$  coefficients of discharge for free flow conditions.

- Weir flow situation ( $w \geq h_1$  and  $k_b = 0$ ) – the flow is only controlled by the weir and the reduction factor  $k_F$  is computed according to Baume et al. (2008) algorithm and, when the downstream water depth  $h_2$  does not affect the discharge over the weir (free hydraulic jump, Figure 5), Equation (1) is the well-known flow weir Bazin equation ( $k_F = 1$ );  $\mu$  is a function of  $\mu_0 = 2/3 C_G$ , where  $C_G$  is the theoretical (0.6) or calibrated in the field value of the coefficient of discharge for the situation of free flow over the weir; in the present study, the  $C_G$  value was obtained by trial and error, which considers several flow computations for each installation in different steady flow situations and is supported by flow meter readings in the field;



- Flow gate situation ( $w < h_1$ ) – for free flow (free hydraulic jump, Figure 5), and  $\mu$  and  $\mu_1$  are functions of  $\mu_0$ ,  $h_1$  and  $\mu$ , with  $\mu_0$  with the already presented value; for submerged conditions, the used algorithm considers two situations – total submersion, where  $k_F$  and  $k_{F1}$  are functions of  $h_1$ ,  $h_2$  and  $w$  and  $\mu$  and  $\mu_1$  are computed as already mentioned; partial submersion, considering the same variables computed in the same ways, but with  $k_{F1}=1$  (Baume et al., 2008).

*Calibration of flow Q algorithm*

In recent years, Doppler technology has been adapted to accurate water flow measurement. Acoustic pulses sent and received by transducers at a fixed frequency colliding with particles in the water, allowing for a determination of flow velocity. The flow rate for an open channel is then computed using an algorithm based on the measured velocity and the water depth in the channel.

In the present project, two types of acoustic flow meters were used, based on the physical principle called the Doppler shift. One, fixed on the canal bottom in chosen locations, is the SonTek IQ Plus (SIQ) (SonTek, 2012) and the other is the SonTek River Surveyor S5 (SRS5) (SonTek, 2010), which is mounted on a small moving floating platform and is used to verify SIQ accuracy and for tuning the gate flow controllers.

SIQ uses four independent pulsed Doppler velocity beams that work to map the cross-section flow velocity, two along-axis beams and two skew beams, and feeds back this data to a flow computation algorithm. Additionally, the equipment also has a vertical beam and a pressure sensor to measure the water stage, which permits computing the flow area. Flow rate is computed as a product of the flow area and the mean cross-section flow velocity.

SIQ uses the velocity index (SonTek, 2012), an empirical relationship between the measured velocity and the mean cross-section flow velocity, based on a series of measurements over time for different flow rates. The velocity index is very accurate, with an accuracy within  $\pm 2\%$  (Styles, 2001).

As presented in Table 2, were installed SIQ devices at the Sta’s RA-Aravil PS, Ladoeiro PS, R18, D19 and SM.

SRS5 base system, an acoustic Doppler profiler (ADP), consists of four transducers for velocity

measurement and one vertical acoustic beam for water depth. The ADP measures velocities of the water up to 128 cells for the entire cross section, with “swept” being regarded as the profiler moves of a margin for the other. With the SIQ, it is only possible to estimate the water velocity along one vertical profile (with up to 100 points along the profile). The remote communication between the ADP and a PC or the ADP and a Mobile device via radio link, where a specific software runs, permits the computation and the integration of the computed discharge along the canal width in real time. The device is also equipped with a GPS. Manufacturers indicate an accuracy of 0.25% of the measured velocity (SonTek, 2010).

Table 3 presents flow computations comparison between flow meters SIQ and SRS5 for the field stations equipped with SIQ (without Sta D21, because the SIQ device was out of service), always in steady flow situations. The obtained results permit the following conclusions:

- For both devices, the results are relatively consistent; the standard deviation (SD) is always relatively small;
- The SRS5 gives bigger mean values than SIQ for three situations (+10%; +2%; 1.5%) and less values for two situations (–2%; –10%);
- Considering the field situations, without readings exactly for the same instant in both equipment, with readings in neighbouring but not at the same cross sections and knowing that the results depend on the passage or not of debris in suspension and also of the cleanliness of the SIQ sensors head (fixed on the canal bottom), it is thought that differences of up to 10% are acceptable;
- In conclusion, the index velocity equation used for SIQ tuning gives acceptable accuracy and its results can be used for real time management through the SCADA.

**Table 3 Field flow computations with flow meters SIQ and SRS5**

Field Station (Sta)	SIQ			SRS5		
	Mean, m <sup>3</sup> s-1	SD, m <sup>3</sup> s-1	Comp. Number	Mean, m <sup>3</sup> s-1	SD, m <sup>3</sup> s-1	Comp. Number
RA-Aravil PS	1.016	0.068	52	1.120	0.020	6
Ladoeiro PS	0.858	0.036	22	0.839	0.016	6
R18	0.419	0.011	64	0.428	0.010	5
D19	0.773	0.016	22	0.784	0.013	9
SM	0.137	0.008	22	0.123	0.003	5

Figure 6 presents a picture of the estimation of flow with SRS5 at the Sta R18, with the visible profiler mounted on a small floating platform moved very carefully by two operators along the canal width and the third operator controlling in the real-time flow computation in a PC, where the specific software runs.

Table 4 presents the adjustment of the theoretical value 0.60 for the coefficient  $C_G$  introduced into the flow gate controllers, considering the two flow estimations for different steady flow conditions in each installation, using the flow meter SRS5. The adjusted value for the coefficient  $C_G$  (last column of Table 4) was obtained by

trial and error, running the flow algorithm and comparing the obtained flow with the estimated flow by the SRS5.



Figure 6 Flow estimation with SRS5 at Sta R18

**Table 4 Field adjustment of the theoretical coefficient  $C_G$  for the flow gate controllers**

Field Station (Sta)	Gate, m			Hydraulic Jump	Flow, $Q$ , $m^3 s^{-1}$		$C_G$ adjustment
	$h_1$	$W$	$h_2$		$C_G = 0.60$	SRS5	
D1	0.395	0.117	0.277	Subm.	0.22	--- (*)	None
	0.4	0.118	0.355	Subm.	0.123	---	
RA-Aravil PS	1.38	0.865		Subm.	1.112	0.927	$C_G = 0.5$ ; passing flow rates to be 0.925 and $0.953 m^3 s^{-1}$ , respectively.
	1.4	0.755		Subm.	1.15	0.912	
D12	0.98	0.063	0.737	Subm.	0.203	0.213	None; SRS5 results very close of the controller
	0.99	0.144	0.74	Subm.	0.46	0.422	
D17 Terminal	0.27	0.066	--- (**)	Free	0.054	0.053	None; SRS5 results very close of the controller
	0.25	0.068	--- (**)	Free	0.055	0.058	
R18	1.293	0.095	0.41	Subm.	0.226	$0.277^{(3*)}$	$C_G = 0.75$ ; passing flow rates to be $0.280$ and $0.240 m^3 s^{-1}$ , respectively
	1.367	0.095	1.015	Subm.	0.2	0.283	
D18 Terminal	1.077	0.138	0.75	Subm.	0.28	0.186	$C_G = 0.50$ ; passing flow rates to be $0.231$ and $0.292 m^3 s^{-1}$ , respectively
	1.07	0.255	0.86	Subm.	0.356	0.312	
D19	0.963	0.102	0.82	Subm.	0.141	0.085	$C_G = 0.45$ ; passing flow rates to be $0.096$ and $0.332 m^3 s^{-1}$ , respectively
	0.968	0.377	0.85	Subm.	0.435	0.336	
CD	1.48	0.2	1.05	Subm.	0.369	0.274	$C_G = 0.5$ ; passing flow rates to be $0.288$ and $0.160 m^3 s^{-1}$ , respectively
	1.44	0.118	1.035	Subm.	0.212	0.153	
RA1	1.14	0.05	1.02	Subm.	0.108	$0.188^{(4*)}$	$C_G = 0.7$ ; passing flow rates to be $0.186 m^3 s^{-1}$
ST1	0.35	0.233	--- (**)	Free	0.222	0.171	$C_G = 0.45$ ; passing flow rates to be $0.166$ and $0.132 m^3 s^{-1}$ , respectively.
	0.27	0.233	--- (**)	Free	0.177	0.115	
ST2 - D4	0.6	$0.700^{(5*)}$	0.6	No jump	---	0.115	---
	0.7	0.08	0.55	Subm.	0.152	0.091	$C_G = 0.35$ ; passing flow rates to be $0.091 m^3 s^{-1}$
- D5	0.6	0.154	0.53	Subm.	0.121	0.064	$C_G = 0.35$ ; passing flow rates to be $0.071 m^3 s^{-1}$

Note: (\*) Canal covered downstream – not possible to use SRS5; (\*\*) Always free hydraulic jump at the downstream gate; (3\*) Diversion gate to reservoir R18; difference between the values obtained by SRS5 and SIQ, inside the Distributor 18 that supplies R18, respectively, at the upstream and downstream diversion to R18; (4\*) Diversion gate to reservoir RA1; difference between the values obtained by SRS5 inside the Canal Direito that supplies RA1, respectively, at the upstream and downstream diversion to RA1; (5\*) Gate above water surface; flow that is not controlled by the gate or weir.

## 5.2 Direct gate controller (D)

The direct controller block is responsible for the control orders sent to the actuators of the gates (Open/Close/Stop). In Figure 4, it appears as the final block of the flow controller, but it is also available for

remote or local manual operation of the gates (operator, HMI). All the gates were equipped with this controller (Table 2).

## 5.3 Gate position controller (P)

The gate position controller ensures that a pre-defined

gate position is established. The gate positions are controlled by a *Bang-Off-Bang* controller with a deadband (Ogata, 1997). In this controller, the direct controller appears as the final block of the algorithm. All the gates were also equipped with this controller (Table 2).

## 6 Flow monitoring ( $Q_1$ , $Q_2$ )

Table 2 presents the field stations equipped with flow monitoring over weir ( $Q_i$ ). The computation of the flow is done considering the simplification of the Equation (1) for weirs. All the weirs operate in free flow conditions (not submerged from the downstream).

Table 2 also presents the field stations equipped with SIQ flow meters ( $Q_2$ ).

## 7 Final considerations

Hardware and software is increasing in capacity and decreasing in cost, becoming much more affordable for irrigation districts to use SCADA technologies. Today, real-time monitoring and control are within the cost range of most water user groups, including irrigation districts. SCADA system allows reducing water losses and waste, to increase the ability of meeting real-time water demands and to reduce operation, power and labor costs.

The total cost of the presented SCADA was around 1.4 million euros, including designing project, equipment, software, installation and field calibration.

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