Water and Energy Balances in Collective Irrigation Systems

A new approach to hybrid systems

Henrique Machado Correia da Cunha
Instituto Superior Técnico, Lisboa, Portugal, 2018
henrique.correia.da.cunha@tecnico.ulisboa.pt

Abstract: The main purpose of the current thesis is the development and application of a methodology to perform systematic evaluation of water and energy use in collective irrigation systems including pressurized pipelines and open canals. The work presented addresses the current gaps in the diagnosis of water losses and energy inefficiencies in these systems. Existing approaches to collective irrigation systems focus on assessing the water resources use efficiency in different components of the system, without a system-wide approach.

The proposed methodology to calculate the water balance outcomes from the adaptation of the existing approaches developed for urban water supply systems to collective irrigation systems. Similar to the water balance proposed by Alegre *et al.* (2004), the system input volume is divided into authorized consumption and water losses. Additional sub-components are considered in the input volume, related to the entry of water by precipitation, by runoff and from storage in intermediate reservoirs. In open canal conveyance and distribution systems, a new sub-component of authorized consumption, related to volumes required for the canals operation, is taken into account. Water losses include apparent losses, evaporation losses and real losses.

The methodology was applied to a case study, known as "Aproveitamento Hidroagrícola do Vale do Sorraia". Obtained results were validated with the experience of all the stakeholders, having reviewed alternative methodologies to estimate some sub-components. The application of the simplified energy balance developed for urban systems to collective irrigation systems led to the need to account for an additional component related with the volume variation in the intermediate reservoir.

Keywords: Water balance, energy balance, water supply systems, collective irrigation systems

1 Introduction

Nowadays, the irrigation sector is the one with the largest water consumers, representing *ca.* 80% of the total consumption nationwide (APA, 2012).

The National Plan for the Use of Water Resources (PNUEA) establishes as an objective for 2020 water use efficiencies for the agricultural sector in the order of 65% (APA, 2012). The achievement of this goal depends on the conveyance and distribution, storage and use within the fields, stressing the need for an inclusive approach.

Recently, the Strategy for the Public Irrigation estimates irrigation efficiencies at around 60-65%, which can be partly explained with the aging of the irrigation networks and the high demand of human resources to operate these systems. The higher the water losses are, the larger the pumped volumes are, increasing the energy consumption.

Cabrera et al. (2013) indicate that in urban water supply systems the energy savings potential is are higher than 30% and, in irrigation systems, this may reach up to 50%.

The goal of the current work is the development and application of a methodology for the systematic evaluation of water and energy use in collective irrigation systems.

2 State of the art

2.1 Water balance approach

In order to evaluate water losses in a system, water balances are calculated. These balances account for the water flows throw the system boundaries during a reference period. This period corresponds to the time that the systems operates, which in urban water supply systems is usually one year (Alegre *et al.*, 2004).

The water balance calculation starts with the estimation of the total input volume taking in to account collected and imported water volumes. Therefore, the input volume is divided in authorized consumption and water losses.

The next component to calculated is the authorized consumption, which accounts for the water volumes that are related with the users of the system (consumptions of the water utility and volumes used for cleaning and maintenance purposes are included).

Water losses result from the difference between the input volume and the authorized consumption. Losses can be distinguished in apparent and real losses (Thornton *et al.*, 2008). Apparent losses are divided in metering inaccuracies and unauthorized uses. Real losses are physical water losses (e.g., leaks and overflows) that occur until the consumer meter.

2.2 Energy balance approach

The energy balance calculation allows management entities to analyze the effects that the implementation of certain measures have at the energy related to water consumption. This approach enables preliminary diagnosis and to identify areas of the network with a lower energy efficiencies (Mamade *et al.*, 2014).

The development of a mathematical model of the systems is necessary. To overcome this difficulty, Mamade *et al.* (2017) proposed a simplified energy balance that only considers components that do not require mathematical modelling.

Reference period and systems boundaries should match the ones considered in the water balance. Knowing the systems boundaries, it is possible to identify elements that supply energy to the system and elements that store and dissipate energy. The total system input energy has two components: natural input energy (*e.g.*, potential energy supplied by tanks and reservoirs) and shaft input energy (energy supplied by pumping stations).

Total system input energy is calculated and then divided in energy associated with authorized consumption and energy associated with water losses, according to the percentage of authorized consumption and water losses obtained in the water balance (Mamade *et al.*, 2017). In the simplified analysis, the total system input energy is divided in minimum energy required to supply consumers, energy dissipated in pumping stations and turbines and recovered energy.

2.3 Collective Irrigation Systems

In order to promote the agricultural activity, collective irrigation systems include catchment, storage, conveyance and distribution infrastructures. At a national level, these systems represent around 35% of the total area occupied by irrigation systems (DGADR, 2014).

The distribution method depends on the freedom that is given to the farmer concerning the flow rate, frequency and duration of the irrigation period. Rijo (2010) identified the following distribution methods, organized from the most flexible to the most rigid method, as the most typical: distribution on request, with prior agreement and rotation.

The canal operation is carried out based on a water levels control system, so the water intakes are fed, the stability of the canal is guaranteed, and overflows do not occur (Rijo, 2010). Worldwide the control system mostly used is the upstream control, meaning that the controlled variable is the water level upstream the control equipment. As it is shown in Figure 1, from the point of view of the canal stretch, it is the water level downstream.

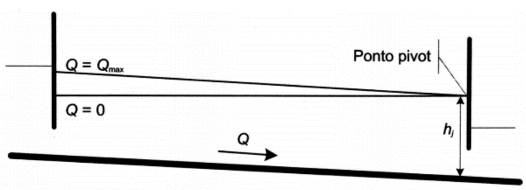

Figure 1- Water level control downstream the canal stretch (Rijo, 2010)

This control system allows an optimized design of the canals and cheaper control structures. On the contrary, it is not efficient in water use and it's demanding in terms of manpower. The control structures are gates that allow to maintain the free surface level upstream the structure (AMP gates) or downstream (AVIO gates). In Portugal, the latter ones are more used in water intakes, since the control system adopted is the upstream one.

The most common water intakes in collective irrigation systems with a canal network is the Neyrpic module. This module is characterized by allowing a certain flow to go through if the required shutters are opened and the upstream water level is the required one.

3 Methodology

3.1 Water balance proposed approach

Contrarily to urban water supply systems, that usually operate 365 days per year, collective irrigation systems operate only during the irrigation periods which can have different time lengths depending on the water needs.

For the input volume calculation, besides the volume collected and imported, there is also the need to account for the water that enters in the system by precipitation, surface run-off and from intermediate water reservoirs/tanks.

To calculate the volume entered by precipitation, data from the nearby weather station should be collected. An association between each work element or intermediate reservoir and the closest station is made, matching the water height precipitated in the structure to the one registered in the weather station. The area subjected to precipitation is the surface area of the canal, neglecting eventual water losses in side slopes of trapezoidal cross section canals. At intermediate reservoirs, the flooded area at full storage level should be obtained, assuming, again, no precipitation losses in the reservoir surface.

The runoff affluent to artificial canals is not considered since it is assumed that these structures have a surface drainage network, illustrated in Figure 2, which prevents the water from getting into the canal.

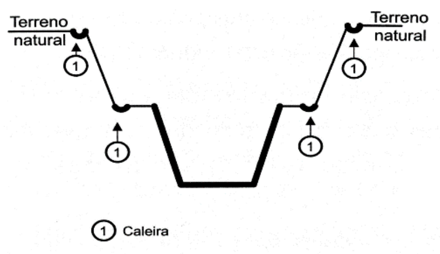

Figure 2- Surface drainage in canals (Rijo, 2010)

In case there are natural canals or intermediate reservoirs that allow the inflow of water by surface runoff, it is recommended that such inflows are estimated based on the monthly sequential hydrological balance. Considering several simplifications of the hydrological phenomena. The complexity and the heterogeneity of the physical processes taking place in the basin are aspects that the calculation does not take into account. The required data are the monthly precipitation, the average monthly temperature and the soil capacity. Evapotranspiration is then calculated using Thornthwaite formula, since it only depends on the temperature. The hydrological balance returns the surface runoff height, value that should be multiplied by the basin area to get the runoff in terms of volume.

An alternative to this method is the use or the development of statistical regression curves that relate the precipitation to the surface flow.

To evaluate the contribution of intermediate reservoirs, the water balance should be carried out considering all water entries and exits from the reservoir:

$$\Delta V = (V_{in} + V_p + V_{run\ off}) - (V_{out} + V_{evap} + V_{leak} + V_d)$$

In the calculation of the water balance a positive volume variation is counted with a negative signal, since this corresponds to water that actually enters into the system and is stored in the intermediate reservoir. Otherwise, when there is a decrease in stored volume in the intermediate reservoir, it means that the volume of water leaving the reservoir is higher than the volume of water entering. Thus, in the calculation of the water balance, this variation is positive, since it is a volume of water that enters into the system.

When calculating the authorized consumption, a new sub-component in unbilled authorized consumption should be considered. This sub-component arises from the characteristics of the infrastructure that require a minimum volume to start supplying. It is necessary that, along the water intakes, the water level is higher than the level of the water intake responsible for the supplying the flow rates to the consumers. The volume needed to reach a water level equal to the last water intake in each stretch is called minimum operation volume in canals. This volume is delimited by the canal track and the horizontal free surface line defined according to the downstream water level.

To obtain this volume, three methods can be applied, which led to a sensitivity analysis based on a canal section from the case study. The options studied were considering the downstream water level equal to the design level (h_u) and considering the downstream level given by the difference between the water level fixed by the control structure and the water intake nominal head. Results point out to an underestimation of the volume of around 20% if the first option is chosen, making option number two the one adopted in the presented methodology. In Figure 3 it is presented a sketch of the minimum operation volume and the water levels involved in its determination.

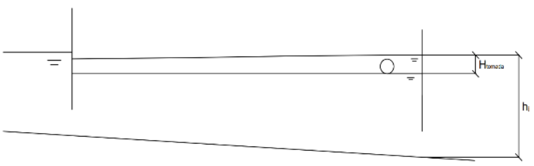

Figure 3- Minimum operation volume sketch

As for water losses, evaporation losses in canal and intermediate reservoirs should be addressed. Having ET_p already calculated, it was studied if it was reasonable to estimate the water losses by evaporation using the Thornthwaite formula, since Rodrigues (2009) considers this an excellent option to estimate monthly evaporation values.

Contrary to the calculation of the precipitated volume, in which the area to be considered is the surface area of the infrastructure, in the calculation of the evaporated volume, the area considered is the one corresponding to the free surface level in the canal section under study. One possible way to calculate the area subject to evaporation in the canals would be to determine the flow curve for each section. This would be a demanding and time-consuming calculation, thus simpler methods were analyzed to estimate the value of this area. A possible solution is to calculate the area subject to evaporation based on a constant flow level and given by the uniform water level. Another solution, in which a level is assumed along the constant stretch, is to consider the water level downstream of the stretch imposed by the water level control structure. In Figure 4 both solutions are presented.

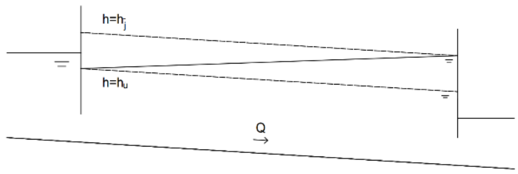

Figure 4- Evaporation losses solutions

An intermediate solution (upstream level equal to h_u and downstream level equal to h_j) is the one chosen for the methodology presented, since it was considered as the best compromise solution.

Apparent losses depend on the metering equipment installed and the percentage of non-authorized uses. In order to correctly measure the water loss component associated to measurement errors, it is necessary to carry out an inventory survey of the measuring devices. The equipment should be grouped in categories according to the type and age of the equipment. Measurement tests should be performed for each group of meters in order to determine measurement error curves that may be associated with each defined category.

In this approach, the real losses contemplate two new components related with the canals: leaks and discharges.

One of the ways of estimating the leakage component of water losses would be to carry out leakage tests on representative sections of the canal. When performing these tests, it is essential to ensure the control of the volumes entered and exited during the time interval of the test. The control of such entrances and exits presents increased difficulty, mainly because the floodgates do not completely block the cross-section, due to this such tests become impracticable. In the bibliography consulted, it is accepted that canals in good operating conditions present infiltration losses between 25 and 50 L/(m^2/day) (Montañés, 2006).

In order to obtain the volumes of water discharged from the canals and from intermediate reservoirs, it is necessary to use measuring equipment at the points where discharges from the system can occur.

To calculate all the variables relevant to the calculation of the water and energy balance, a calculation tool was implemented in MS Excel. The tool is organized into tabs for entering data on water volumes and the characterization of the infrastructures. Looking for a greater discretization of each component, the tool produces a list of the components of the water balance in which each component is disaggregated into sub-components.

A scheme of the tool layout is presented in Figure 5.

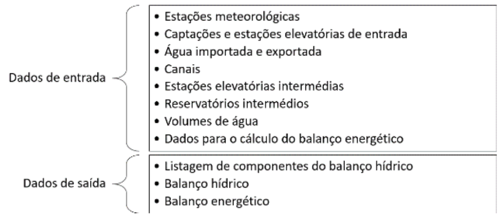

Figure 5- MS Excel tool layout

Table 1 shows the proposed water balance, in which new components are marked in gray and distinctive component, when compared to the urban water balance, are marked with "(*)".

Table 1- Proposed water balance

System input volume (*)	Authorized consumption	Billed authorized consumption	Billed metered consumption
			Billed unmetered consumption
		Unbilled authorized consumption	Unbilled metered consumption
			Unbilled unmetered consumption (*)
	Water losses	Evaporation losses	Evaporation losses in canal
			Evaporations losses in intermediate reservoirs
		Apparent losses	Unauthorized uses
			Metering inaccuracies
		Real losses	Leaks in pipes
			Leaks in canals
			Leaks in intermediate reservoirs
			Discharges in canals
			Overflows in intermediate reservoirs

4 Case study

4.1 Preliminary characterization

The methodology presented was applied to a collective irrigation system named “AHVS” in two reference periods (2016 and 2017). The system is composed of two irrigation networks that are hydraulic independent and only operates during the irrigation period. Farmers must request water 24 hours in advance, so the utility manager operates the system to supply the flow rate at the requested time. It is prior agreement distribution method.

The main water sources are three reservoirs, located at the upstream part of the system, along with pumping stations that pump directly from the river to the canal network. There is also an intermediate water reservoir that stores surpluses flows from the canal and supplies water to on time water requests. A schematic representation of the system is presented in Figure 6.

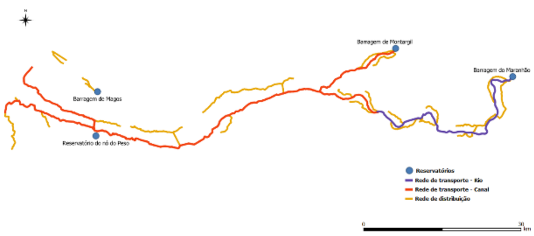

Figure 6- System layout

It should be noted that, between Maranhão dam and Furadouro weir, the water is transported in a natural canal.

In Furadouro weir it is installed a SCADA remote station that monitors the volumes discharged to the river and to the conveaync canal.

4.2 Proposed methodology application

4.2.1 Water balance calculation

The proposed methodology for the water balance calculation was applied to the irrigation periods that took place in 2016 and 2017.

First of all, the assessment of the total input volume was carried out which involved not only accounting for the water that came from the utility catchments (dam and entry pumping stations), but also water entry due to precipitation in canals and intermediate reservoirs and from runoff until the Furadouro weir.

A sensitivity analysis to a set of methods for estimating the runoff was carried out in order to achieve which one was closer to the reality, according to the utility managers. A volume balance applied to the sub-system upstream the Furadouro weir, seems to be the most reliable estimate.

The authorized consumption was calculated by summing the billed authorized consumption with the minimum operational volume. The calculation tool was used for the determination of the minimum volumes in a work element of the conveyance network and in another work element of the distribution network. These two elements were considered as representative of the conveyance and distribution network and the minimum operational volume was extrapolated from the value calculated for these two work elements.

For the estimation of the evaporation losses in canal, the mean values of ET_p were estimated for each reference period. Based on this average value and with information from the “Furadouro-Couço” canal and the “Franzina” distributor introduced in the calculation tool, the volumes of water lost by evaporation in these two building elements were estimated.

The calculation of the evaporated volume in the network, similar to the hypothesis adopted in the calculation of the minimum operational volume, resulted from the extrapolation of these values to the canal network.

As for the apparent losses, to estimate the non-authorized uses, the results of the iPerdas project were used, having adopted the highest value among the participating management entities. For the specific case study, the value in question was reduced by 80% given the daily scan carried out by the utility people.

For the metering errors, it was adopted the highest percentage from the utilities involved in iPerdas. Despite of the measurement of authorized consumption billed by means of mechanical counters and hour counters installed in Neyrpic modules differing from the equipment used to measure consumption in urban systems, this value was considered as the first approximation.

Lastly, real losses should be estimated.

For the estimation of leaks in conduits, a reference value from urban water supply systems was used.

In order to estimate the leakage losses in canals, an estimation based on observed phenomena was carried out. It was seen that the canal was receiving a certain amount of water and leaking some through the gates. The estimation was based on the estimation of the wet area that was obtained with the calculation tool. This value obtained from the “field” is the one used for the water balance calculation.

4.2.2 Energy balance calculation

In order to start the calculation of the energy balance, it was necessary to determine the reference level of the system. Only the levels of the conveyance and distribution networks and the pump stations were considered, as it is not possible to obtain the minimum supply level due to the lack of knowledge. Reference level corresponds to the level of the water intake located at the minimum level.

For the minimum required energy, it was assumed that the pressures in each block were homogeneous and of equal value between blocks, considering a minimum required pressure value of 2.5 m, by ARBVS indication, since there are no pressure data at points of consumption. The average terrain level of each block was estimated by overlapping the blocks' areas in topographic charts.

The calculation procedure adopted is the same as originally proposed by Mamade *et al.* (2017).

4.3 Intermediate reservoirs

When the contribution of the intermediate reservoir is considered null, the subcomponent has no implications for the calculation of the water balance and energy balance. However, it was sought to determine the influence that the consideration of this subcomponent would have on the level of the energy balance.

Thus, two possible scenarios for the water balance in the reservoir during the irrigation campaign were tested: supply of water from the reservoir or accumulation of water in the reservoir.

Results confirmed that the calculated energy balances are well calculated as long as there is an energy component associated with the contribution of the intermediate. Table 2 presents a proposal for the calculation of the energy balance in collective irrigation systems.

Table 2- Proposed energy balance

<table>
<tr><td rowspan="6">Total system input energy</td><td rowspan="3">Energy associated with authorized consumption</td><td>Energy associated with water supplied to consumers</td></tr>
<tr><td>Dissipated energy associated with authorized consumption</td></tr>
<tr><td rowspan="2">Energy recovered</td></tr>
<tr><td rowspan="2">Energy associated with water losses</td></tr>
<tr><td>Dissipated energy associated with water losses</td></tr>
<tr><td colspan="2">Energy associated to intermediate reservoirs contribution</td></tr>
</table>

5 Conclusions

The current work proposes a methodology for calculating the water balance in collective irrigation systems. This water balance is a procedure for diagnosis of water losses adapted to the characteristics of these systems with new additional components that do not exist in urban water systems. As for the energy balance, the need to access the energetic contribution from the intermediate reservoir came across, leading to a discussion about the component. It was found that the contribution should not be neglected. A n enhanced energy balance for collective irrigation system was proposed.

Concerning the results of the application of the proposed methodology to the case study, sensitivity analyses were carried out to find the most appropriate calculus methodology. The largest component in the system input volume was the water that came from the utility catchments (more than 90%), followed up by the runoff volume that has a larger expression (up to 10%) when the precipitation is higher. In terms of non-revenue water, the estimations obtained point out to values between 35 and 40% of the total input volume. Real losses represent more than 70% of the total losses, being discharges in canals responsible for more than 50% of the total non-revenue water.

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