# Evaluation of energy and water efficiency in Collective Irrigation systems: contribution to the sectorial diagnosis and study of intervention solutions

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**Abstract:** This paper focuses on the analysis of water and energy efficiency in collective irrigation systems aiming at the system and network area diagnosis. A novel energy balance methodology specific for irrigation systems is developed and applied to two case studies of a different nature, a supply system predominantly in canals and a fully pressurized system. The system diagnosis requires the calculation of water and energy balances. The proposed approach for carrying out the water balance in irrigation systems is based on previous work[1]. It is presented a reformulation of the calculation of some water balance components (i.e., system input volume due to surface runoff, minimum operational volume, evaporation, real and apparent losses). Regarding the energy balance, a specific approach is developed, based on the energy balance applicable to urban water systems[2]. The results showed that, in systems composed predominantly of canals, the main problem in terms of water losses is discharges in canals that represent 28% of system input volume. In pressurized systems, the main problems are leaks and pipe bursts, which represent losses around 7% of the volume of water entered. In terms of energy, the systems composed predominantly of canals show a great potential for recovery energy. The main energy inefficiency in this type systems are the dissipated energy due to water losses (33% of the input energy) and the dissipated energy due to layout problems (30% of the input energy), while in the pressurized system the main inefficiencies are due to equipment inefficiency and problems in layout which represents 22% and 14% of the input energy respectively. Priority subsystems are also identified for the two case studies and improvement solutions are prioritized for one of them. Solutions for the priority subsystem can reduce water losses by 38% and increase the recovery of excess energy by 25%.
**Keywords:** collective irrigation systems, energy efficiency, energy balance, water balance,

## 1. Introduction

The agriculture sector faces significant challenges nowadays, namely producing in quantity with quality and safety, while ensuring efficient use of water and energy resources. In the Mediterranean climate, irrigation is crucial to minimize the impact of irregularity and unpredictability of precipitation in agricultural production. Irrigated agriculture is seen as fundamental support in the fight against food shortages, as it can guarantee a high rate of productivity throughout the year[3], and it is expected to intensify due to population growth worldwide. This population growth will raise water consumption by 30% and the energy consumption in 45%[4], that is why it is so crucial to ensure excellent water management and the enhancement of energy efficiency.

The irrigation system is divided into two subgroups, namely the collective irrigation system, which represents the infrastructure for abstraction, transport and distribution of water to farmers, and the irrigation plot which include a specific infrastructure and equipment culture irrigation. The overall irrigation water efficiency (plot and collective) is between 60-65%[5], this efficiency being dependent on the catchment system, distribution, and the adopted irrigation method. In some irrigation systems, the energy costs represent around 70% of the operational costs[6]. In some pumping stations, there is a considerable potential to reduce the energy intensity in order 20 to 30%[6]. To improve the energy efficiency in irrigation systems it is very important to reduce the water losses and to increase equipment efficiency. Measures to improve the energy efficiency in irrigation systems can be divided into two groups: interventions in the infrastructure and intervention in the electromechanical equipment[7]. For the second group, it is imperative to ensure the pumped flow rate is as close as possible to the optimal operating point, to reduce or recover topographic energy through the installation of turbines[8] and to use more efficient pumps, preferably with variable speed drives[9].

Until now, several limitations in the analyses of the irrigations systems water efficiency existed, due to the lack of knowledge on this field, namely the importance of system input volume due to precipitation, due to surface runoff and evaporation losses[10], the illiteracy about apparent losses due to metering inaccuracies and the nescience of experimental tests about irrigation water meters errors and canal and pipe leakage[11].

This paper will contribute to overcome those gaps of knowledge, minimizing the limitations found so far in the water efficiency assessment in collective irrigation systems. Firstly, it will be tested the hydrologic mathematical modelling using the Thorntwaite and Penman-Monteith formulas for potential evapotranspiration in order to estimate the surface runoff, and it will be done a sensitive analyses to see which give a better estimation of the input volume due to surface runoff; a new calculation approach for the minimum operation volume is proposed (i.e., the volume necessary to ensure the water level needed at water intake[1]) which takes into account the canal slope; the Penman (1948) method is proposed herein to estimate evaporation in surface water, since it has proven to provide a good estimation of the evaporation[12]. Previously, the Thornthwaite formula was used, but this paper will demonstrate why this method is not accurate enough in the evaporation estimation; ponding tests were carried out to better assess the leakage volumes in rehabilitated canals and pipe system from those non-rehabilitated. Experience has shown that ponding tests lead to very accurate results[13], so with this is expected to improve water losses estimates; the water flowmeters were tested, and the metering inaccuracies have shown that apparent losses have a relevant contribution in total losses. The most important novelty presented herein is the development and demonstration of an energy balance approach tailored to collective irrigation system characteristics with canal and pressurized pipes, since previous energy balance was specific for urban water supply systems. That is why it is proposed a methodology to estimate the input energy due to precipitation, surface runoff; the energy associated with the minimum operation volume, and the energy associated with leakages and evaporation. The development of this paper was based on the previous work concerning the water balance methodology for collective irrigation systems[1], energy efficiency in irrigation distribution networks[8] and energy balance proposed for urban water supply systems[14]. It contains an approach for water and energy balance calculation for a collective irrigation system that is applied in two case study at the global and sectorial level whose results are presented and discussed.

## 2. Propose Approach

### *2.1. Approach for water balance calculation*

Recently, a water balance proposal for collective irrigation systems was developed (*Table 1*), based on the water balance for urban systems proposed by the International Water Association (IWA). The main difference between both approaches is that transport, storage, and distribution in collective irrigation systems is mostly carried through canals and intermediate reservoirs with a free surface. The provision of service through this infrastructures implies the consideration of new components, namely in the system input volume (e.g., due to precipitation, due surface runoff in intermediate reservoirs), the authorized consumption (i.e., minimum operational volume) and water losses (e.g., evaporation and canal leaks), which do not exist in pressurized systems[1]. The components for which changes were introduced in the current work are highlighted in grey in *Table 1*.    .

*Table 1 – Water balance components for collective irrigation systems.*

| | | | | |
|---|---|---|---|---|
| System input volume | Authorized consumption | Billed authorized consumption | Billed metered consumption | Revenue water |
| | | | Billed unmetered consumption | |
| | | Unbilled authorized consumption | Unbilled metered consumption | Non-revenue water |
| | | | Unbilled unmetered consumption | |
| | Water losses | Evaporation losses | Evaporation losses in canals | |
| | | | Evaporation losses in intermediate reservoirs | |
| | | Apparent losses | Unauthorized consumption | |
| | | | Metering inaccuracies | |
| | | Real losses | Leakage on pipe network | |
| | | | Leakage in canals | |
| | | | Leakage in intermediate reservoirs | |
| | | | Discharges in intermediate reservoirs | |
| | | | Discharges in canals | |

▢components reformulated in the current paper

***Input volume***

In general, input volume includes the abstracted volume from reservoirs, water lines or underground sources and the volume imported from other systems. When water transport carried out in canals, the input volume also includes the input volume due to precipitation on the surface area (reservoirs and canals) and due to surface runoff entered through the transport and distribution network or intermediate reservoirs. The estimation of system input volume due to precipitation requires the knowledge of the physical characteristics of the canals and intermediate reservoirs, as well as data about precipitation measured at the meteorological stations in the wide area[1]. The calculation of the volume entered due to surface runoff can be carried out based on the calculation of water balance in subsystems[15], or based on the hydrologic mathematical modelling, namely the Thorntwaite-Mather model or the Temez model [16], both models require precipitation and potential evapotranspiration data. The potential evapotranspiration can be calculated by Thorntwaite formula, which assumes that the temperature is the only variable that imply evapotranspiration[16], or based on Penman-Monteith formula which requires more data (i.e, temperature, humidity and radiation)[17]. The Penman-Monteith formula is recommended since it considers more parameters that can lead to better results.

***Authorized consumption***

Authorized consumption represents the volume of water, billed and unbilled, consumed by users, or by those who are implicitly or explicitly authorized to consume, namely for social commitments or legitimate use in fighting fires[1]. The water supply by canals requires a minimum operational volume (*unbilled unmetered consumption*), which is defined as the volume of water in the canal from which the water supply starts through the various water intakes. Therefore, it is necessary that, near the water inlets, the flow height in the canal is higher than the dimensions of the thresholds of the water inlets responsible for the derivation of flow rates for supply. This study showed that it is important to reformulate the calculation of this volume, because on the previous work, it was said that the minimum operational volume depends only on the length and the cross-section areas upstream and downstream of a stretch of the canal [15]. Taking this into account, this work proves that the minimum operational volume is also dependent on the slope of the canal. Therefore, two calculation approaches have been proposed, referring to canals with low and high slopes.

The subsystems can be hydraulically independent, that is they do not have any hydraulic connection between them. In the case of existing hydraulic dependency between subsystems (Figure 1), the water component entered in the subsystem B also includes the imported volume. In the case of the originating subsystem A belonging to the same entity as the water-receiving subsystem B, the imported volume is a measured consumption unbilled in the source subsystem A, since this volume is billed to the downstream subsystem B; otherwise, it is a measured consumption volume billed and the input water in A is given by the difference between total volume captured with the volume transferred to B.

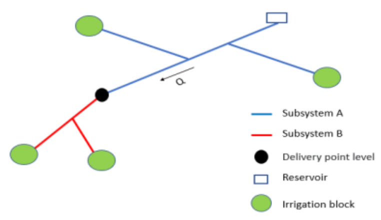


*Figure 1 – Schematic of transferred volumes and energies between subsystems.*

***Water losses***

Water losses are defined as the volume of water, which, having been introduced into the system, is never delivered, or billed to the final customer. Water losses in collective irrigation systems with free surface flow include three subcomponents: evaporation, real losses, and apparent losses. The apparent losses include the unauthorized consumption (i.e., illicit connections, bypass connections, water meter manipulation) and metering inaccuracies. The unauthorized consumption is considered to represent a small fraction of authorized consumption, according to feedback collected from water users associations (≈ 1%). For the estimation of *metering inaccuracies,* tests must be carried out on some existing water meters, by installing a reference flowmeter downstream to see the difference in the measured volumes. These tests allow to evaluate the error associated with the water meters, that typically lead to under-measurement that tends to worsen with their age[18]. A new Woltman water meter (used in the analysed projects), well installed, operating in nominal flow has an average error lower than 2%[18]. Considering this value and the rate of degradation of meters obtained through the tests performed on other system meters, $t_d$, it is possible to estimate the meter relative error, $E_R$, as a function of its age, $y$, and of the initial error, $i$, by:

$$E_R = i - t_d Y \quad (1)$$

with, $E_R$, $i$, $t_d$ expressed in % and $y$ in years.
After the estimation of the relative error, it is possible to estimate the unmeasured volume by:

$$V_{NM} = V_M \left(1 - \frac{1}{1 + E_R}\right) \quad (2)$$

where $V_{NM}$ is the unmeasured volume due to metering error (m$^3$) and $V_M$ is the measured volume (m$^3$). If the volume not measured is higher than zero, it means that the water meter is measuring the volume by excess, and if it is less than zero, it is measuring the volume by default.
Regarding real losses, for the estimation of leakages, tests (ponding tests preferably) must be carried out to estimate the reference values to be used in rehabilitated, non-rehabilitated and impermeabilized canals. In the lack of tests, values from the literature or tests carried out in similar systems should be used. The following reference values for canal leakage should be considered: 25 l/(m$^2$.day) in rehabilitated canals and 50 l /(m$^2$.day) in not rehabilitated canals[19], in pipes if tests are not done 5 l/(km.dia) can be used which represents the worst scenario[1]. In this study, ponding tests were used, through which it was concluded that rehabilitated infrastructures canal leakage is 14 l/(m$^2$.day) and non-rehabilitated canals is 25 l/(m$^2$.day). In contrast, rehabilitated pipes leakage is 1.5 m$^3$/(km.day) and non-rehabilitated is 7 m$^3$/(km.day).
For the estimation of evaporation there was a lack of knowledge that is why in the previous work it was used the potential evapotranspiration as evaporation which is not a good approach since this method consider that just temperature can induce the evaporation, which is not true, because it is known that this component varies according to the radiation that hits the water surface, the wind speed, humidity and atmosphere pressure. That is why in this work it is propose to use the Penman (1948) formula to estimate the evaporation [20]. In order to prove why the Penman formula should be used, a sensitive analysis was done based on comparison of the evaporation volume given by the two formulas.

### *2.2. Proposed approach for energy balance calculation*

Previously, no methodology existed to calculate the energy balance in irrigation systems, including canals and pressurized pipes. For this reason, the energy balance developed for urban water supply systems [21] was the basis of the current development. A novel energy balance specifically tailored for collective irrigation systems is presented in *Table 2* where components in which changes have been introduced are marked in grey. For the energy balance, new components were considered for the calculation total energy input: energy associated with precipitation volume, surface runoff volume. Energy associated with authorized consumption was reformulated to include energy associated with the minimum operational volume and with the volume transferred) and the energy associated with leakage and evaporation losses was estimated.

*Table 2 − Energy balance components for collective irrigation systems.*

<table>
<tr><td rowspan="6">Natural input energy</td><td rowspan="13">Total energy input</td><td rowspan="7">Energy associated with authorized consumption</td><td rowspan="2">Energy associated water delivered to consumers</td><td>Minimum energy</td></tr>
<tr><td>Surplus energy*</td></tr>
<tr><td rowspan="4">Energy dissipated</td><td>Headlosses in pipes and canals*</td></tr>
<tr><td>Headlosses in gates and valves *</td></tr>
<tr><td>Pump inefficiency</td></tr>
<tr><td>Turbine inefficiency</td></tr>
<tr><td rowspan="7">Shaft input energy</td><td rowspan="2">Energy recover</td><td>From authorized consumption</td></tr>
<tr><td rowspan="6">Energy associated with water losses</td><td>From water losses</td></tr>
<tr><td rowspan="5">Energy dissipated due to water losses</td><td>Energy in nodes where losses occur*</td></tr>
<tr><td>Headlosses in pipes and canals*</td></tr>
<tr><td>Headlosses in gates and valves *</td></tr>
<tr><td>Pump inefficiency</td></tr>
<tr><td>Turbine inefficiency</td></tr>
</table>

*Components that require mathematical modelling; ▢ reformulated in the current paper

***Total energy input***

The first step is to define the calculation period for the energy balance and the system boundaries, which must agree with those adopted in the water balance for the same system. The reference elevation, $Z_{ref}$, must also be defined, from which the energy components associated with the flow are calculated; this may be the minimum hydrodynamic level of a catchment (i.e., underground catchment) or the elevation of the consumer located at the minimum level [2]. This component is given by the sum of natural energy (e.g. existing in reservoirs or water lines that are at a higher elevation, volume of precipitation, runoff and the volume imported) with the shaft energy (the electrical energy used for pumping), given by the Eq.*(3)*. There are two types of pumping stations: system inlet stations (include natural energy) and the intermediate stations.

$$E_{In} = E_N + E_p \tag{3}$$

where $E_{In}$ is the input energy (kWh); $E_N$ is the natural input energy (kWh), calculated based on *Eq. (4)*; $E_p$ is the shaft energy input (kWh) given by *Eq. (5)*.

$$E_N = \frac{\gamma}{3600}\sum_{i=0}^{n} V_i\left(H_i - Z_{ref}\right) \tag{4}$$

$$E_p = \sum_{j=1}^{n1} E_j^F + \frac{\gamma}{3600}\left[V_j^B \times \left(H_I^B - Z_{ref}\right)\right] + \sum_{k=1}^{n2} E_k^F \tag{5}$$

where $\gamma$ is specific weight of water (9.8 kN/m³); *n, n1 and n2* are the total number of reservoirs, of inlet pumping stations and of intermediate pumping stations, respectively; $V_i$ is the volume abstracted in reservoir *i* (m³); $H_i$ is the hydraulic head in reservoir *i* (m) calculated based on Eq. *(6)*; $Z_{ref}$ is the reference elevation (m); *j* is the number of entering pump station; $E_j^F$ electrical energy consumed in pumping station *j* (kWh); $V_j^B$ is the volume pumped in station *j* (m³); $H_I^B$ is the hydraulic head downstream of the pump (m); $E_k^F$ is the electrical energy consumed in the intermediate pumping station k (kWh);

$$H = z + h + \frac{v^2}{2g} \tag{6}$$

where H is the hydraulic head (m); z is the elevation of the canal bottom above the datum level (m); $h$ is the water height in canals (m); $\frac{v^2}{2g}$ is the kinetic head (≈ 0 m).

The energy associated with the volume of water entering the system due to surface runoff in the reservoir or section *i* as well as in the canal surface area *j* is given by:

$$E^{SR} = \frac{\gamma}{3600}\sum_{i=1}^{n} V_i^{SR} \times \left(H_i^R - Z_{ref}\right) + \sum_{j=1}^{n} V_j^{SR} \times \left(H_j^c - Z_{ref}\right) \tag{7}$$

where $E^{SR}$ is the energy associated with the runoff surface volume (kWh); $V_i^{SR}$ is the volume entered due to surface runoff in intermediate reservoir *i* (m³); $H_i^R$ is the water average level in the intermediate reservoir *j* (m); $V_j^{SR}$ is the volume entered due to surface runoff in canal *j* (m³); $H_j^c$ is the water level downstream of the canal *j* (m).

The input energy due to precipitation entered in the intermediate reservoir *j* and in the canal *i* is calculated by:

$$E^p = \frac{\gamma}{3600}\sum_{i=1}^{n} V_p^{C\,i} \times \left(\frac{H_i^{up} + H_i^{dw}}{2} - Z_{ref}\right) + \frac{\gamma}{3600}\sum_{j=1}^{n} V_p^{R\,j} \times \left(NPA_j^R - Z_{ref}\right) \tag{8}$$

where $E^p$ is the input energy due to precipitation (kWh); $V_p^{C\,i}$ is the volume precipitation entered in canal section *i* (m³); $H_i^{up}$and $H_i^{dw}$ are the water level downstream and upstream of canal *i* (m); $V_p^{R\,j}$ is the volume entered due to precipitation in the intermediate reservoir *j* (m³); $NPA_j^R$ is the water level of full storage of the intermediate reservoir *j* (m).

If there is hydraulic dependence between subsystems as showed in *Figure 1,* it is important to estimate the input energy due to volume importation. For this purpose, Eq. *(9)* must be applied.

$$E_{Imp}^{A\to B} = \frac{\gamma}{3600}\sum_{i=1}^{n} V_{Imp\,i}^{A\to B}\left(H_I^E - Z_{ref}^B\right) \tag{9}$$

where $E_{Imp}^{A\to B}$ is the energy imported from subsystem B in A (kWh); *n* is the number of import point; $V_{Imp\,i}^{A\to B}$ is the imported volume from subsystem B in A delivered in point *i* (m³); $H_I^E$ is the hydraulic head in the delivery point (m); $Z_{ref}^B$ is the reference elevation in subsystem B (m);

***Energy from authorized consumption***

The energy associated with authorized consumption is calculated based on the approach presented in the previous work[14]. However, a new approach to estimate the minimum required energy, $E_{min}$, is proposed being given by Eq. (10). It includes the energy needed to ensure direct consumption in the irrigation blocks, $E_{min}^{R}$, the energy associated to the minimum volume operation, $E_{min}^{V}$, and if there is volume transfer, it includes also the energy required to export volume, $E_{Exp}^{A\rightarrow B}$:

$$E_{min} = E_{min}^{R} + E_{Exp}^{A\rightarrow B} + E_{min}^{V} \tag{10}$$

The energy associated with the minimum operational volume is given by Eq.*(11)*, the energy required to transfer water between subsystems is given by Eq.(12) and the minimum energy required tom ensure consumption is calculated based on Eq.(13). The energy associated with the minimum operational volume corresponds to new components in the energy balance (*Table 2*), since it is a specific component for irrigation systems. However, the minimum volume has a minor contribution to the water balance, so that is why the energy associated was included in the minimum energy required to guarantee consumption, instead of creating a new box in *Table 2*.

$$E_{min}^{V} = \frac{\gamma}{3600}\sum_{i=1}^{n} V_j^{min}\left(Z_j^{ph} - Z_{ref}\right) \tag{11}$$

where $V_j^{min}$ is the minimum volume required in canal *i*; $Z_j^{ph}$ is the canal *i* downstream water level (m).

$$E_{Exp}^{A\rightarrow B} = \frac{\gamma}{3600}\sum_{p=1}^{n} V_{Exp\,p}^{A\rightarrow B}\left(H_I^{E} - Z_{ref}^{A}\right) \tag{12}$$

where $V_{Exp\,p}^{A\rightarrow B}$ is the volume transferred to subsystem B from A delivered in point *p Figure 1* (m$^3$); $Z_{ref}^{A}$ is the reference elevation in subsystem A (m). The minimum energy required to ensure water to the farmers is given by:

$$E_{min}^{R} = \frac{\gamma}{3600}\times\sum_{i=1}^{n} V_i^{R}\times\left(Z_i + \frac{p_i^{min}}{\gamma} - Z_{ref}\right) \tag{13}$$

where $V_i^{R}$ is the volume delivered in the irrigation block *i* (m$^3$); $Z_i$ is the level of irrigation block mean sea level (m); $p_i^{min}/\gamma$ is the minimum pressure required in irrigation block *i* (m).

*Energy from water losses*

The energy from water losses is calculated based on the equations presented in previous work[14]. In this study, a new approach to estimate the energy losses due to leakage in canals (Eq.(13)) and evaporation, specific of irrigation system, is proposed (Eq. (15)).

$$E^{L} = \frac{\gamma}{3600}\sum_{i=1}^{n} V_i^{L}\left(\frac{H_i^{Up} + H_i^{dw}}{2} - Z_{ref}\right) \tag{14}$$

$$E^{EVP\,C} = \frac{\gamma}{3600}\sum_{i=1}^{n} V_I^{EVP\,C}\left(\frac{H_i^{up} + H_i^{dw}}{2} - Z_{ref}\right) + \frac{\gamma}{3600}\sum_{j=1}^{n} V_j^{EVP\,R}\left(N_j^{m} - Z_{ref}\right) \tag{15}$$

where $E^{L}$ is the energy associated with leakage in canals (kWh); $V_i^{L}$ is the leakage volume in canal *i* (m$^3$); $V_I^{EVP\,C}$and $V_I^{EVP\,R}$are the volumes lost due to evaporation in canal *i* and intermediate reservoir *j* (m$^3$); $N_j^{m}$ is the average water level in the intermediate reservoir *j* (m).

***2.2.1 Methodology for application for energy balance***

The water balance should be carried out before the calculation of the energy balance**.** The first step to implement the energy balance proposed is the definition of the reference elevation, typically, defined as the minimum level of the systems[14]. In this study, different reference elevation will be analysed to assess the robustness of the results. To implement this approach at the system level, the reference elevation can be the minimum elevation, the weighted average elevation of consumption delivery points or the minimum system elevation of the consumption delivery points. The same alternatives of reference elevation can be applied to the subsystems or each subsystem can have their specific reference elevation (e.g., minimum subsystem elevation, weighted average elevation or minimum elevation at delivery points of consumption).

A sensitivity analysis can be carried out to the effect of the reference elevation on the results by comparing two energy performance indicators, E2 (Energy in excess) and E3 (Supplied energy)[2], expecting to have the same answer in both (i.e the system/subsystem with higher E2 must also have the higher E3).

Regarding the energy transferred between subsystems (*Figure 1*), two approaches are proposed.

**Approach 1:** It is applied when the energy transferred is exclusively natural energy. In this case, the energy transferred to the subsystem B *(Figure 1*) is given based on Eq. (12). The energy available to be used in subsystem A is given by:

$$E^{A} = E_{in}^{A} - E_{Exp}^{A\rightarrow B} \tag{16}$$

where $E^A$ is the energy available to be used in subsystem A (kWh); $E_{in}^A$ is the total energy input in subsystem A (kWh).

To estimate the energy transferred, $E_{Exp}^{A\to B}$, given by Eq.(12), it is necessary to know the hydraulic head in the delivery point; in case this is unknown, the energy transferred is given by Eq.(17), but it is important to know that this approach should be applied only when there is no data on topographic elevation.

$$E_{EXp}^{B} = \frac{V_{A\to B}^{Exp}}{V_{AE}^{A}} E_{in}^{A} \tag{17}$$

**Approach 2:** This is applied when the energy transferred is provided by natural input and shaft input. It happens when the system input volume requires natural energy, but it is also necessary to use shaft energy until the delivery point. In this case, the natural energy transferred, and shaft energy is given by the weighted sum (in energy Eq.(18)). Notice that the energy transferred from pumping includes the energy effectively transferred and the inefficiencies associated with the pumping stations in the same proportion of volume or energy transferred.

$$E_{Exp}^{B} = \frac{E_{Exp}^{A\to B}}{E_{in}^{A}} \left( \sum_{i=1}^{n} E_{N\,i}^{A} + \sum_{j=1}^{p} E_{P\,i}^{A} \right) \tag{18}$$

where $E_B^{Exp}$ is the energy transferred to subsystem B from A (kWh); $E_{Exp}^{A\to B}$ is the energy transferred from A to B given by Eq. (12) (kWh); $E_{in}^A$ is the input energy in subsystem A that is transferrable (kWh); $n$ is the number of gravity source that contribute to the transfer of the volume, $E_{N\,i}^A$ is the natural energy associated with component $i$ of water entering system A which is transferable (kWh); $p$ is the number of pumping stations (PS) that contribute to the transfer of the volume; $E_{P\,i}^A$ is the electrical energy associated with PS $j$ in the transport of the transferred volume (kWh).

The imported energy also can be calculated based on these two approaches: according to Approach 1, it is given by Eq. (9) which means the volume is transferred due to the height difference. If the transferred volume requires shaft energy it is important to differentiate the natural and shaft energy transferred, to do that the following equations should be applied:

$$E_{N}^{Imp} = E_{B}^{Imp} - \frac{E_{Exp}^{A\to B}}{E_{in}^{A}} \sum_{j=1}^{n} E_{P\,i}^{A} \tag{19}$$

where $E_N^{Imp}$ is the natural energy imported by subsystem B (kWh); $E_B^{Imp}$ is the imported energy (kWh) given by Eq.(9).

## 3. Results

### *3.1. Cases studies description*

The approach presented here is applied in two different collective irrigation systems, which the main difference is the flow type. *Table 3* shows the main features for each one of them.

*Table 3 – Case studies description.*

| | System 1 | System 2 |
|---|---|---|
| Number of Meteorological stations | 6 | 1 |
| Pipes (km) | 193.3 | 41.3 |
| Canals (km) | 208.5 | - |
| Irrigated area (km$^2$) | 163.6 | 15.0 |
| Number of intermediate reservoirs (-) | 3 | - |
| Number of pumping stations (-) | 13 | 1 |
| Number of subsystems (-) | 5 | 2 |
| Minimum pressure head (m) | 1 | 50 |

### *3.2. Sensitivity analysis to the proposed methodology for the calculation of water balance components*

Relatively to water balance components, *Figure 2*, shows the results obtained for system input volume due to surface runoff and water losses due to evaporation in canals and intermediate reservoirs, using the different methods proposed (see 2.1) for irrigation season in 2016, 2017 and 2018. The results obtained for volume entered due to surface runoff *Figure 2 a)* prove that the calculation of this component based on the hydrologic mathematical modelling, should be based on the potential evapotranspiration given by the Penman-Monteith formula (*Vsr(PM)*). The water balance (*Vsr(WB))* proposed in previous work presents promising results, so when it is not possible to apply hydrologic mathematical modelling, it is advisable to use the water balance in subsystems to estimate surface runoff. The results given based on potential evapotranspiration based on

Thorntwaite *(Vsr(TW))* formula using the hydrologic mathematical modelling are inconclusive, since it appears to overestimate the input volume due to surface runoff when there is a high precipitation rate and underestimate when the precipitation rate is low (e.g 2016: P= 214 mm $V_{SR}$= 50 hm³; 2017: P=58 mm $V_{SR}$= 0 hm³). *Figure* 2b) shows the evaporation component given by the Thorntwaite formula for potential evapotranspiration (*Vevp(TW))* and the evaporation given by the Penman formula (*Vevp(P))* in irrigation season in 2016, 2017 and 2018, with this was concluded that the Thorntwaite formula is underestimating the evaporation losses, that is why it is advised to use the Penman formula for evaporation calculation since it consider more parameters that can induce evaporation instead of using the Thorntwaite formula which consider only temperature.

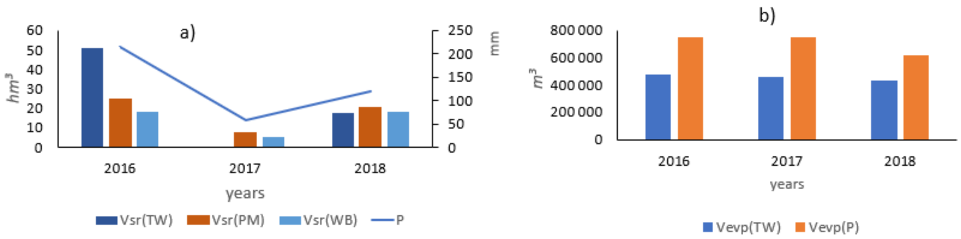


*Figure 2 – Water balance components between 2016 and 2018 for case study 1: a) System volume due to surface runnof b) Water losses due to evaporation in canals and intermediate reservoirs.*

### 3.3. *Sensitivity analysis to the proposed methodology for application of energy balance*

In this paper, sensitivity analysis has focused on the reference elevation adopted for calculation of energy balance components and performance indicators proposed in this study, and a comparative analysis was carried between the Supplied energy (E3) and Energy in excess (E2) performance indicators. Sensitivity analysis was carried out for *case study 1*, which is composed by five subsystems (S1 to S5). The four firsts subsystems are connected (S1 to S4) and S5 is independent but very close to the others, and a connection might be possible. At the system level, the results for both performance indicators were consistent, along the three years, when the adopted reference elevation was the minimum system elevation or the minimum elevation of the delivery point of consumption. Therefore, the minimum system elevation, 0.23 m (which corresponds to upstream level of one pump station) was adopted for calculation of system energy balance. Yet, when comparing the minimum reference elevation of the system with those of the other subsystems, there was a significant difference between them (e.g., the reference elevation of S1 is 59.9 m), so using the minimum level of the system would overestimate the energy components and influence the calculation of performance indicators, that is why this analyse was applied to see which reference elevation should be applied at subsystems level based on E2, (*Figure 3a)* and E3, (*Figure 3b).* These results show that E3 is very sensitive to the variation of the reference elevation. Therefore, is important to use the reference elevation that gives the same answer for the other performance indicator as E3, since this indicator has the advantage of being easy to understand and being widely used in gender studies. The results show that the reference elevation that leads to the most coherent results of E2 and E3 is the minimum elevation of points of delivery of consumption for each subsystem. Taking this into accounting at system level it was considered the minimum absolute elevation point as the reference elevation, and in subsystem level it was used the minimum elevation of consumption.

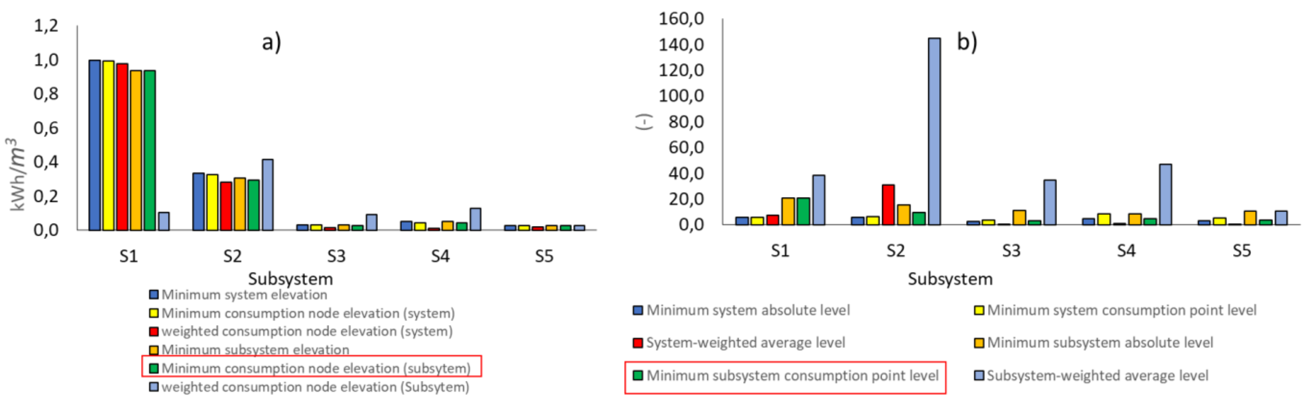


*Figure 3-Sensitive analyses of the reference elevation based on the value of proposed performance indicators: a) E2; b) E3.*

### 3.3. Energy efficiency assessment for case study 1

To calculate the energy balance first it is important to calculate the water balance in the analysis period and always respecting the system boundary. In 2018 irrigation season this case study used 61.31% of the entered water to ensure the authorized consumption (60.98% billed and 0.33% unbilled) and 38.69% of the entered water was lost in the supply process (the main component losses component is the water discharges in canals). This water balance was very important to make diagnosis of water losses, and the sectorial analyse prove that those losses occurred mainly in subsystem S2 due to extension and quality of the canals network and S4 due to terminal discharges. With the water balance it can be concluded that 61.31% of the total input energy was used to ensure authorized consumption and 38.69% was dissipated due to water losses in 2018.

To estimate the energy transferred between subsystems, *Approach 2* was used because intermediate pumps are required to deliver water to other subsystems. Therefore, the energy transferred include natural energy (i.e associated with precipitation, surface runoff and abstracted in reservoirs) and shaft energy (i.e electrical energy consumed in PS used to transfer the volume).

The results of the energy balance are shown in *Figure 4.* The main global energy inefficiencies are due to dissipation of energy in the network (30% of the input energy) and the dissipated energy due to water losses (33% of the input energy). The subsystem S1 seems to have a considerable potential to reduce the energy in excess since just 4% of the total input energy represent the energy required to ensure consumption. The subsystem S5 dissipated 30% of the total input energy in equipment due to inefficiencies in pumping stations, but it is dissipating a small part of the input energy due to water losses because in this year the water losses represent 9% of the water entered in this subsystem, being this low percentage of water losses related to the physical characteristics of this subsystem (i.e small extension, fully rehabilitated*).*

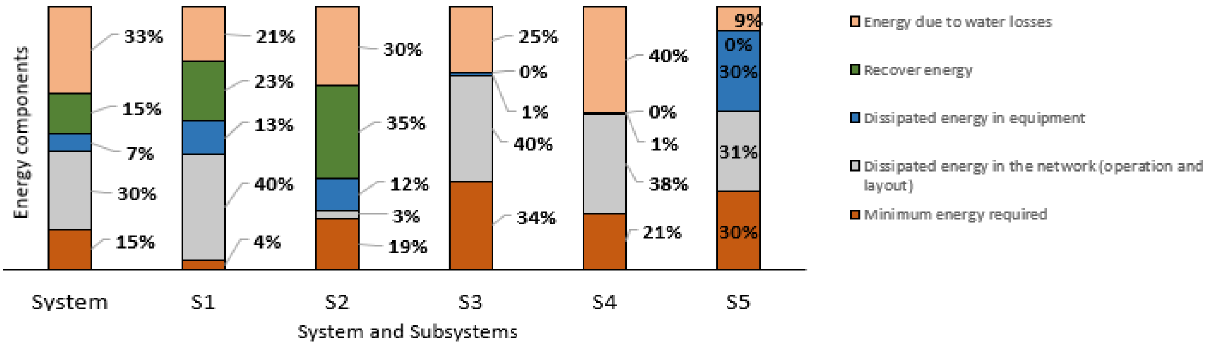


*Figure 4 – Energy balance components as a percentage of the input energy for the case study 1.*

To improve the water and energy efficiency in this case study it is important to improve the operational condition in subsystem S2 (priority). That is why an intervention proposal is suggested for this subsystem which consists in the rehabilitation of the supply network, replacement of water flows meters that have already exceeded their useful life and turbine rehabilitation. The implementation of this proposal may lead to reduce water losses by 38% and increase the recovery of excess energy by 25%, thus contributing to better economic and environmental sustainability

### 3.2. Energy efficiency assessment for case study 2

This case study is composed of pressurized systems and it is divided in two subsystems, C1 and C2. In 2018, the water losses represented only 9% of the system input volume, and those losses occurred mainly in subsystem C1 due to leaks and pipe bursts. Concerning the reference elevation for the systems analysis, it was considered the minimum consumption point elevation of the system, and, for the subsystems analysis, the minimum consumption point elevation for each subsystem was used. The energy balance components as a percentage of the input energy for the system, and the two subsystems is presented in *Figure 5*. The main efficiency problem in this case study is the efficiency of the pumping equipment that contribute to the dissipation of 22% of system input energy in 2018. Unlike the previous case study, the minimum energy required represent 55% of the input energy. Subsystem C2 seems to have lower efficiency, since only 47% of the input energy is used to ensure consumption and 26% of the input energy is dissipated in the network layout & operation. The results are different from subsystem C1, where the most significant component of dissipated is due to inefficiency in pumping stations (21%), followed by dissipated energy due to water losses, 13% (subsystems with a pipe network in asbestos cement, with a high occurrence of pipe burst). In subsystem C1, energy dissipated due to layout & operation represents only 5%.

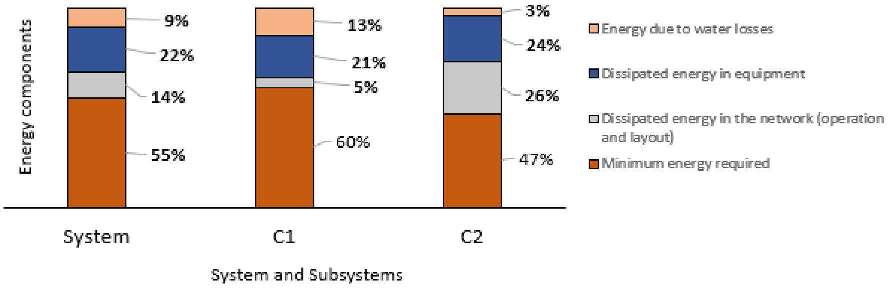


*Figure 5– Distribution of the energy balance components as a percentage of the input energy.*

The sectorial analyse done in this case study demonstrated that the subsystem C1 is priority to receive interventions, being the main problems related to leaks, bursts in pipes and efficiency of the pumps.

**4. Conclusions and future developments**

This study showed that the implementation of water and energy balances in collective irrigation systems is essential to assess water losses and energy efficiency. For this purpose, a novel methodology was developed and applied in two case studies of a different nature, a supply system composed predominantly of canals and a fully pressurized system. The proposed methodology consists of (i) data collection and processing, (ii) water and energy balances and performance indicators calculation; (iii) final diagnoses and recommendations.

Comparing the two case studies in terms of water losses, it was concluded that the supply systems in canals is the one with the highest water losses, being the main problem discharges in canals that represent about 28% of the volume entered in the system. In the pressurized collective irrigation systems, the main problem is related to leaks and ruptures in the pipes that contribute to the loss of 7% of the volume of water entering in the system. In terms of energy efficiency, the obtained results for the *case study 1* show that most of the input energy was dissipated due to problems in the layout and water losses. On average 30% of the input energy was dissipated in the network, due to layout problems, on the other hand, water losses contributed, on average, to the dissipation of 32% of the input energy. The sectorial analysis carried out in this case study shows that there are subsystems with a lot of excess energy, for example the subsystem S1 in which only 4% of the input energy is used to ensure consumption. On the other hand, *case study 2* presents a better energy efficient, since 57.6% of the input energy were used to guarantee consumption, 22% dissipated in equipment, 14% it was dissipated due to the layout and operation of the network and just 9% were dissipated due to water losses.

Several *recommendations* can be made for *the water balance* application *in collective irrigation systems*, namely *:* *(i)* the calculation of surface run-off based on hydrologic mathematical modelling, namely the Thorntwaite-Mather model in order to include the crop evapotranspiration; (ii) the identification of the canals with high extension or steeps slopes in order to have better estimation of the minimum operational volume; (iii) the use of the Penman formula to calculate evaporation; (iii) the testing of the flow meters in order to have a better estimation of the metering inaccuracies; (iv) carrying out ponding tests to assess leaks in canals and pipes.

Concerning the *energy balance* calculation, the following suggestions are made: (i) to carry out sensitivity analyses to the reference elevation to be adopted at system and at subsystem level; (ii) to use the performance indicator E3 to assess the energy efficiency, as it allows obtaining the same response as other energy efficiency indicators, with the advantage of being easy to understand; (iii) inclusion of the energy associated with the minimum operational volume in the component of the minimum energy required for consumption.

The next steps in the future research concerning the water and energy balances in irrigation systems are the hydraulic modelling of water supply system with canals for better operational control of discharges, the study of low-head energy recovery solutions in canals, such as the Archimedes screws turbine and the development of a methodology to assess the physical condition of canals to support their rehabilitation.

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