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# A comprehensive performance assessment system for diagnosis and decision-support to improve water and energy efficiency and its demonstration in Portuguese collective irrigation systems

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A R T I C L E I N F O

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A B S T R A C T

In regions with a strong seasonal or interannual asymmetry in the distribution of precipitation and higher frequency of droughts, collective irrigation systems are vital infrastructures for agricultural activity. Although operating for decades, several systems have ageing infrastructures, with relevant water losses and pumping energy inefficiencies. Consequently, the systems are not adequately designed or operated to meet current and future water demand. Therefore, rehabilitation to improve water and energy efficiency while ensuring infrastructure, economic sustainability and service quality is crucial. In this sense, comprehensive approaches using performance assessment to support the planning process or benchmarking between water users associations play an essential role in improving efficiency in collective irrigation systems. However, few methodologies assess interdependencies between water losses, energy efficiency, infrastructure condition, service quality, economic and operational dimensions. Additionally, these approaches rarely were applied to the different stages of the planning process (diagnosis, planning, monitoring, and reviewing the impact of measures) and to different types of collective irrigation systems (gravity, pressurised, combined) for comparative analysis. This paper presents a comprehensive performance assessment system (PAS) for diagnosis and decision support about measures to improve water and energy efficiency in collective irrigation systems. Afterwards, the PAS is applied for diagnosis and prioritisation of alternatives to enhance the efficiency of a gravity system. The results indicate significant water losses due to the canal and intermediate reservoirs discharges and leakage in canals and low-pressure pipes, related to network ageing and insufficient flow monitoring and control for the gravity system. Ranking allowed identifying the gravity network area with high priority of intervention due to poor performance in non-revenue water, water losses due to discharges, energy efficiency of pumping stations and system energy in excess. Several alternatives were studied for this network area, and infrastructural solutions involving canal rehabilitation and water discharge control significantly impact global performance improvement besides the substantial investment associated. Subsequently, the PAS is used for comparing gravity and pressurised systems. In opposition to gravity, the pressurised system, with efficient use of water resources, presents a poor performance in pumping energy efficiency. Furthermore, the significant energy costs indicate the importance of energy improvement measures for the pressurised system. Besides assessing water and energy efficiency, the novel PAS may help managers and policymakers identify every system's best practices and weak points.

## 1. Introduction and review

Agriculture and public urban water supply are the primary sources of pressure on freshwater resources. Over 40% of the EU's water use is on agriculture irrigation (EPRS, 2019), and global demand for agricultural products is foreseen to increase by 15% by 2028 worldwide (OECD-FAO, 2021), which might intensify irrigation.

Portugal, whose water demand represents between 40% and 80% of

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its average annual water availability, presents high exposure to water stress in the future due to recurrent drought events and increased water consumption (Gassert et al., 2013). According to the National Water Plan (Decree-law No. 76/2016 in DR, 2016), the agriculture and livestock sector used 3390 $hm^3$/year, corresponding to 74% of the available water volume, between 2012 and 2016. Moreover, climate scenarios for the next decades indicate a reduction in precipitation, which might reach between 15% and 30% in the southern region (FCG, 2020). A decrease in precipitation and an increase in temperature leads to an increase in evapotranspiration and higher demand for irrigation. Therefore, problems related to water scarcity due to environmental challenges and climate variability, and ageing irrigation infrastructures highlight the need to improve efficiency in water and energy use in collective irrigation systems (CISs) and private irrigation systems, as identified by the Common Agricultural Policy Strategic Plan (GPP, 2020) and the national strategy for irrigation until 2050 (Fenareg, 2019). In Portugal, the equipped area for irrigation corresponds to 626 820 ha (5% of the national territory). The equipped area in public CISs, private CISs and private systems represent 40%, 10% and 50% of the total equipped area, respectively (GPP, 2020). Public CISs correspond to national infrastructures for abstraction, transport and water distribution to users (*e.g.*, irrigators, industry users), owned by the national authority for irrigation and managed by Water Users Associations (WUAs). In contrast, private CISs are owned and managed by privates. Private systems correspond to water distribution systems for crops owned and operated by the irrigators. The average water consumption in Portugal for irrigation decreased from 15 000 $m^3$/(ha.year) to 4 000 $m^3$/(ha.year) in the last 60 years (70% of water consumption reduction) (EDIA, 2021). However, in the same period, the energy consumption for irrigation increased from 200 kWh/(ha.year) to 1 750 kWh/(ha.year) (more than eight times the initial energy consumption) (Fenareg, 2022). The modernisation from gravity to pressurised systems without a comprehensive assessment of the impact of improvement measures ought to contribute to the observed energy increase.

In recent decades, WUAs and the end-users, namely the irrigators, have focused on irrigation systems modernisation to improve water use efficiency and ensure on-demand service without a relevant concern for energy consumption and efficiency (Rocamora et al., 2013; Levidow et al., 2014; Tarjuelo et al., 2015). Furthermore, main efforts to improve efficiency in water use have been focused on the farmer level (Bjornlund et al., 2009; Speelman et al., 2008; Benouniche et al., 2014). Thereby, it is essential to efficiently manage CISs for higher water and energy savings in abstraction, storage, transport, and water distribution to end-users. However, unlike the urban water systems, there is a lack of integrated approaches that systematically quantify water and energy inefficiencies, identify network areas with high priority for intervention, and support planning and monitoring improvement measures in those infrastructures. For instance, Speelman et al. (2008), Nam et al. (2016), and Zema et al. (2019) focus on the water use-related aspects, namely the water delivery, quantification, and low-cost measures, neglecting the importance of integrated quantification of the water and energy inefficiencies. In addition, isolated and decoupled solutions may conflict with WUAs' objectives (*e.g.*, like-for-like pump replacement without reducing downstream water losses may lead to high investment and operation costs compared to an alternative involving water loss control and adequate pump design and replacement).

WUAs benchmarking focusing on service performance comprises a step forward for modern irrigation systems (Malano and Burton, 2001). Moreover, performance assessment for diagnosis, planning, monitoring, and revising the impact of implementing measures in WUAs constitutes a step forward.

A performance assessment system (PAS) is driven by the service objectives of WUAs, criteria for assessing the fulfilment of each objective, performance indicators (PIs) – the core elements of a PAS, and context information, following the principles of the ISO 24500 standards (ISO, 2007a, 2007b, 2007c). Aligned with these standards and Alegre et al. (2017), assessment criteria correspond to points of view that allow the assessment of the objectives. PIs are expressed by the ratio between two variables of the same nature. In essence, the numerator expresses the objective of the indicator (*e.g.*, real losses, network failures), and the denominator represents a related system scale (*e.g.*, network length) (Loureiro et al., 2020). The PIs are calculated for a reference period, generally one year, and the value found does not issue judges, requiring comparison with a reference. Reference values can be proposed based on legislation, recommendations from regulatory entities, literature, or historical data.

Previous studies have successfully adopted PAS for evaluating and monitoring water utilities in different contexts (ERSAR and LNEC, 2021). The PAS application to support diagnosis and decision-making represents a common practice across the urban water sector, identifying adequate measures and prioritising interventions. In line with the need to provide adequate service levels, a structured PAS for strategic infrastructure assessment management was developed by Alegre and Coelho (2012) and Alegre et al. (2013). In addition, different PAS were developed for the diagnosis of water losses and energy inefficiencies in drinking water systems (Mamade et al., 2017), undue inflows and systems' functioning aspects in wastewater and stormwater systems (Almeida et al., 2017; Santos, 2021) and energy inefficiencies in urban water systems (Loureiro et al., 2020).

In irrigation, performance assessment in water and energy use has been proposed in some studies (Malano and Burton, 2001; Malano et al., 2004; Córcoles et al., 2010; Borgia et al., 2013, 2020). However, some are focused only on the irrigator level (Rodriguez-Diaz et al., 2011; Parra et al., 2020). Even when specific PIs to evaluate water and energy use have been developed in CISs (Córcoles et al., 2010; Rodriguez-Diaz et al., 2011, Fernández-Pacheco et al., 2015, Zema et al., 2018), the impact of water losses, network layout and operation on energy efficiency was not assessed, disregarding the water and energy nexus. Existing PIs for CISs do not consider water loss components (*e.g.*, evaporation, real losses due to discharges and leakage, metering errors) and the energy inefficiency components (*e.g.*, pump and hydropower inefficiencies, energy dissipated due to water and head losses) that occur throughout the network until the water intakes (*i.e.*, point of delivery to users). Recent contributions to water and energy balance for collective irrigation systems allow estimating these components during the irrigation period and enable the calculation of new PIs (Cunha et al., 2019a, 2019b). The water balance (Cunha et al., 2019a) estimates billed authorised consumption and non-revenue components (*i.e.*, the volume associated with unbilled authorised consumption, evaporation losses, apparent losses, and real losses) relative to system input volume. Apparent losses include inaccuracies related to users' metering and unauthorised consumption, whereas real losses include canal and pipe leakage and discharges in canals and intermediate reservoirs. The energy balance (Cunha et al., 2019b; Mamade et al., 2017) allows for estimating the minimum required energy to ensure the service to users and energy supplied in excess relative to system input energy (*i.e.*, natural, shaft input energy). The energy supplied in excess may be associated with water losses, dissipated due to head losses or energy inefficiencies in pumping stations or hydraulic turbines. First steps were given to establish a PAS for CISs (Córcoles et al., 2010; Rodríguez Díaz et al., 2011; Zema et al., 2018). These studies also performed useful statistical analysis to reduce the number of PIs and group WUAs. These studies constitute important steps for developing a PAS with essential information and defining reference values. However, besides the economic impact of water and energy inefficiencies, the relations with other dimensions should also be assessed, namely, on operation and infrastructure, resources efficiency, and quality of service. Thus, a comprehensive PAS to support planning in WUAs, or comparative analysis between utilities of CIS from different contexts, is still missing.

This paper presents and tests a PAS for water and energy efficiency assessment based on trustworthy and well-organised information for collective irrigation systems. The PAS was developed under a co-production environment of researchers, irrigation systems managers, and irrigators, in the scope of a research project. Aligned with the objectives of WUAs, this PAS integrates a water utility profile, a CIS profile, a set of criteria, and a set of new PIs to assess the impact of water and energy inefficiencies in economic, infrastructural, operational, resources efficiency and quality of service dimensions and reference values that consider different types of CISs (gravity, pressurised, combined).

The main contributions of this paper correspond to the proposal and application of a comprehensive framework for assessing the water and energy efficiency use and its practical application in a CIS to support diagnosis and decision about measures to improve water and energy efficiency and for comparative analysis between CISs. This work was motivated by the lack of a framework for systematic assessment of water and energy inefficiencies and their relations with economic, infrastructural and service dimensions and support the management of CISs infrastructures associated with abstraction, intermediate storage, transport and distribution of water to end-users. This PAS brings a new mindset to the irrigation market at the national and international levels to support benchmarking between WUAs and planning of water and energy efficiency measures, considering the impact on the multiple dimensions of the service provided.

Besides the current section, this paper presents the PAS developed for CISs and the approach for diagnosis and decision support in the material and methods section. In the results section, two different applications of the assessment system are discussed. The first application involves applying the PAS for diagnosis and decision support about measures to improve efficiency in a gravity CIS. The second application presents a comparative analysis between CISs considering the corporate objectives to highlight the significant water losses and energy inefficiency problems. Two CISs were selected for demonstration in this latter application: a traditional gravity system and a pressurised gravity system. Finally, the conclusions are presented.

## 2. Materials and methods

### 2.1. Performance assessment system (PAS)

The PAS proposed in this study is driven by the organisational objectives of WUAs and based on clearly defined data (internal or external to the water utility), including assessment criteria, PIs and reference values, focused on the efficiency and effectiveness assessment. According to each criterion, only essential and complementary PIs were selected for the evaluation, avoiding redundant information. Consequently, diagnosis and decision-making should be based on the joint analysis of PIs that integrate the PAS, considering context information provided in water utility and CIS profiles (Fig. 1). Besides the water and energy efficiency dimensions, the PAS proposes a comprehensive set of PIs that influence water losses and energy inefficiencies (*e.g.*, infrastructural dimension) or are influenced by these inefficiency problems (*e.g.*, economic, quality of service dimensions). A comprehensive assessment system ensures that efficiency issues are not seen in isolation and that improvement solutions do not conflict with WUAs' objectives. PIs were proposed based on the preliminary diagnosis of three different CIS (gravity, pressurised, combined) in the scope of a national research project about "Assessment of water and energy efficiency in collective irrigation systems (AGIR)". Afterwards, PIs formulation and results were discussed with a panel of specialists in CISs from the national authority for irrigation, WUAs, irrigators, national associations in the sector, and academic institutions within the scope of the research project to have a first perception of the application in different CISs and contexts. The PAS comprises 14 variables describing the water utility profile, 19 variables in the CIS profile, and 20 PIs. A schematic representation of the PAS components and data flow is presented in Fig. 1.

The water utility profile (Table 1) includes essential information about the water utility responsible for the service, the contract period and end-users types. Since the focus is on the water utility, the number of irrigators (dEG07), the billed authorised consumption (dBH02, PAH01, PAH02), and the average irrigated area (PAH03) also cover information about irrigated areas that collect water from the system but do not benefit from the irrigation infrastructure. Moreover, since the objective is to assess energy costs and consumption for CIS operation relatively to annual operational costs and energy produced by the water utility, these last variables (PAH04, PA05) are calculated for the analysis year and not only for the irrigation period.

Besides the regional aspects, the collective irrigation system profile (Table 2) includes information about the licence for the use of water resources, the operation start date, characteristics of the water supply infrastructure for irrigation, including abstraction, conveyance and distribution, area equipped with a collective irrigation system, irrigation period and volume licensed for water abstraction. It also includes some variables that characterise the coverage of end-use points with water metres, annual irrigation shortage and the potential to use water for reuse.

The PIs are the key elements of the PAS, and they were established

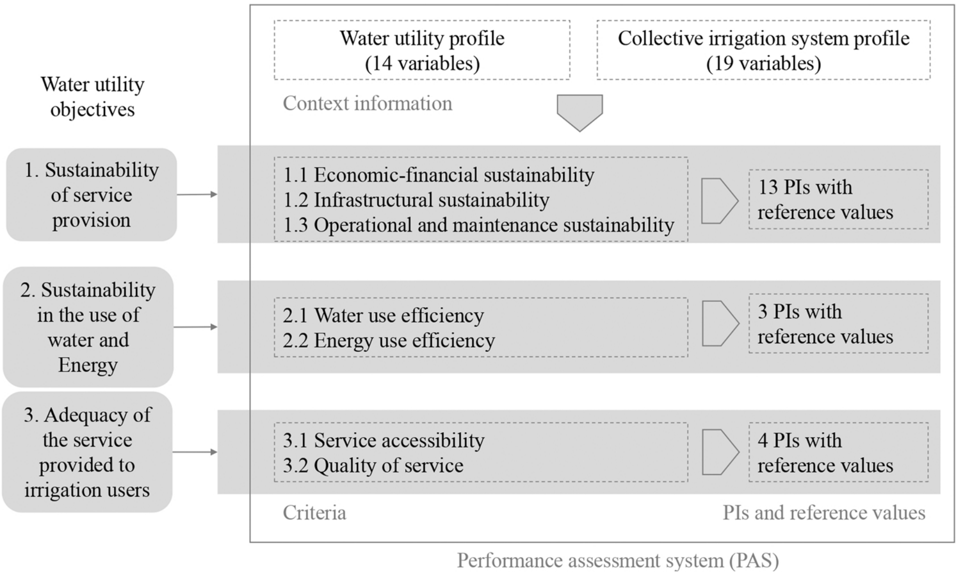

**Fig. 1.** Components of the PAS.

**Table 1**
Water utility profile.

| Code | Variable name (units) and description |
|---|---|
| dEG01 | **Water utility identification** (-):<br>Water utility official designation and address |
| dEG02 | **Water utility type** (-):<br>The type of water utility following the legal regime for CISs (*e.g.*, water users association, public water company). |
| dEG03 | **Concession contract period** (-):<br>The initial and final years covered by the concession contract. |
| dEG04 | **Agricultural beneficiaries** (no.):<br>The number of agricultural owners and tenants in the intervention area where the utility operates to ensure the water supply service to end-users. |
| dEG05 | **Non-agricultural beneficiaries** (no.):<br>The number of non-agricultural owners in the intervention area where the utility operates to ensure the water supply service to end-users. |
| dEG06 | **Associated irrigators** (no.):<br>The total number of irrigators in a water users association. |
| dEG07 | **Number of irrigators** (no.):<br>The total number of users registered for irrigation during the analysis period. This number includes beneficiaries (associated and non-associated irrigators) and non-beneficiaries. |
| dEG08 | **Human resources** (no.):<br>The total number of human resources allocated to a water utility. |
| dBH02 | **Billed authorised consumption** ($m^3$/year):<br>The total billed authorised volume by a water utility (includes billed authorised volume to agricultural and non-agricultural beneficiaries, non-beneficiaries that collect water from reservoirs or watercourses, under the water utility's responsibility or from the conveyance and distribution network of the CIS). |
| PAH01 | **Average billed authorised consumption for irrigation** ($m^3$/(irrigation user.year)):<br>The total billed authorised volume for irrigation divided by the total number of irrigators during the irrigation period. |
| PAH02 | **Billed authorised consumption to non-beneficiaries** (%):<br>The percentage of billed authorised volume to non-beneficiaries that collect water from reservoirs, watercourses, or the conveyance and distribution network relative to the total billed authorised volume. |
| PAH03 | **Average irrigated area** (ha/(irrigation user.year)):<br>The ratio between the total irrigated area, including irrigated areas that do not currently benefit from irrigation infrastructure, and the total number of irrigation users. |
| PAH04 | **Energy costs** (%):<br>The ratio between energy costs concerning the operation of the CIS (*e.g.*, Energy for pump operation, Energy for network operation, maintenance) and operating costs (*i.e.*, total cost without amortisations). |
| PAH05 | **Own energy production** (%):<br>The ratio between energy consumption for CIS operation (*e.g.*, Energy for pump operation, Energy for network operation, maintenance) during the irrigation period and the energy produced by the water utility in the analysis year, including the energy from hydropower, solar panels, or other processes. |

**Table 2**
Collective irrigation system profile.

| Code | Variable name (units) and description |
|---|---|
| dReg01 | **Geographic region** (-):<br>The territorial unit or units in which the CIS is located. |
| dReg02 | **Hydrographic region** (-):<br>The hydrographic region where the CIS is located (*e.g.*, according to the actual hydrographic region management plan). |
| dReg03 | **Climatic region** (-):<br>The climatic region where the CIS is located. |
| dInfra01 | **Water resources license** (-):<br>The collective irrigation system's license period to extract water from rivers or aquifers (initial and final dates). |
| dInfra02 | **Operation start date** (-):<br>The initial year of water distribution to irrigators |
| dInfra03 | **Surface water intakes from reservoirs** (no.):<br>The number of surface water intakes from reservoirs in the CIS. |
| dInfra04 | **Surface water intakes from watercourses** (no.):<br>The number of surface water intakes from watercourses in the CIS. |
| dInfra05 | **Groundwater intakes** (no.):<br>The number of underground water intakes in the CIS. |
| dInfra06 | **Pumping stations** (no.):<br>The number of pumping stations in the CIS. |
| dInfra07 | **Intermediate reservoirs** (no.):<br>The number of compensation and control reservoirs in the CIS. |
| dInfra08 | **Conveyance and distribution canal network for collective irrigation** (km):<br>The total canal extension for conveyance and water distribution to end-users. |
| dInfra09 | **Conveyance and distribution pipe network for collective irrigation** (km):<br>The total pipeline extension for conveyance and water distribution to end-users. |
| dInfra12 | **Area equipped with collective irrigation system (ha):**<br>The total area equipped with infrastructure for abstraction, conveyance and collective water distribution to end-users. |
| dInfra13 | **Irrigation period** (-):<br>The period of service for irrigation in the CIS (initial and final dates). |
| dInfra14 | **Irrigation duration** (days):<br>The duration of the irrigation period. |
| dBH01 | **Volume licensed for water abstraction** ($m^3$/year)<br>The volume of water licensed from rivers or aquifers by the collective irrigation system. |
| PAH06 | **End-use points equipped with water metres** (%):<br>The number of end-use points under the responsibility of the water utility with equipment installed for measuring the water volume delivered (*e.g.*, flow metres, Neyrpic modules). |
| PAH07 | **Annual irrigation shortage** (%):<br>For the analysis year, the difference between the average potential evapotranspiration and the average precipitation relative to the average potential evapotranspiration in the geographical area where the CIS is located. |
| PAH08 | **Potential to use water for reuse** ($m^3$/ha/year):<br>Available volume of water for reuse produced in a wastewater treatment plant near the CIS per respective area equipped in the year under analysis. |

according to WUAs service objectives: i) sustainability of service provision (Obj. 1); ii) sustainability in the use of water and energy (Obj. 2); iii) adequacy of the service provided to irrigation users (Obj. 3). The objectives were defined under a co-production environment of researchers, WUAs, and irrigators during the AGIR project. The objectives reflect the vision and mission of water utilities, not only water and energy efficiency goals. A set of relevant dimensions - assessment criteria, to assess objectives and respective performance indicators (PIs) are proposed to measure the water and energy efficiency and effectiveness in the service provided (Table 3). For the criteria identification, the first digit corresponds to the respective objective.

PIs should be assessed for the year relative to the irrigation period under analysis. The Total costs coverage (AH01), Infrastructure value index (AH05), Pumping groups value index (AH06), and Network rehabilitation (AH08), based on ERSAR and LNEC (2021), should be calculated with yearly data. Rehabilitation interventions may occur outside the irrigation period and should be considered in the analysis year to ensure the service during the irrigation period. Additionally, since the irrigation period varies between years for the same CIS and between CISs, Network failures (AH07), Failures in pumping groups (AH13) and Service interruptions (AH19), adapted from Alegre et al. (2017), were normalised for a one-year time interval. The PAS encompass novel PIs to highlight the main components of water losses in CISs – due to canal or pipe leakage (AH09, AH10), associated with Infrastructural sustainability, and water discharges in canals and reservoirs (AH11), related to Operational and maintenance sustainability criterium. Also, Non-revenue water (AH04) (*i.e.*, the volume due to authorised unbilled consumption, evaporation, apparent and real losses) is used to assess the Economic-financial sustainability, traducing an essential relationship between water and energy efficiency and the sustainability of service provision.

In addition, water loss components responsible for the efficiency in the use of water resources – real and evaporation losses (AH14) is also considered to assess the fulfilment in terms of sustainability in the use of water and energy. Cunha et al. (2019a) presented a comprehensive approach for water balance calculation and estimating water loss variables used in the PIs listed in Table 3. The Infrastructure value index

**Table 3**
Criteria, PIs identification and formulation.

| Criteria | PI | Formulation |
|---|---|---|
| 1.1 Economic-financial sustainability | **AH01** – Total costs coverage (%) | Total revenues regarding the water supply service / Total costs regarding the water supply service x 100 |
| | **AH02** – Adhesion to service in the area equipped with collective irrigation (%) | Irrigated zone inside the area equipped with collective irrigation during the irrigation period / Area equipped with collective irrigation x 100 |
| | **AH03** – Total adhesion (%) | (Irrigated zone inside the area equipped with collective irrigation + Irrigated zone outside the equipped area) / Area equipped with collective irrigation x 100 |
| | **AH04** – Non-revenue water (%) | Non-revenue water / System input volume x 100 |
| 1.2 Infrastructural sustainability | **AH05** – Infrastructure value index (-) | Current network value (canals and pipes) / Network replacement costs (canals and pipes) |
| | **AH06** – Pumping groups value index (-) | Current pumping group value / Pumping groups replacement costs |
| | **AH07** – Network failures [no./(100 km.year)] | (Failures in canals and pipes x 365 / Irrigation duration) / Canals and pipes network length x 100 |
| | **AH08** – Network rehabilitation (%) | Canals and pipes network rehabilitated in the last five years / Average canal and pipe network length in service in the last five years x 100 |
| | **AH09** – Water losses due to canal leakage [l/(m$^2$.day)] | Volume of water losses due to canal leakage / (Canal wet area x Irrigation duration) |
| | **AH10** – Water losses due to pipe leakage [m$^3$/(km.day)] | Volume of water losses due to pipe leakage / (Pipe network length x Irrigation duration) |
| 1.3 Operational and maintenance sustainability | **AH11** - Water losses due to discharges (%) | Volume of water losses due to discharges in canals and reservoirs / System input volume x 100 |
| | **AH12** – Failures in measurement, control and cleaning equipment [no./(100 km.year)] | (Failures in measurement, control and cleaning equipment x 365 / Irrigation duration) / Canals and pipes network length x 100 |
| | **AH13** – Failures in pumping groups [no./(pumping group.year)] | (Failures in pumping groups x 365 / Irrigation duration) / Number of pumping groups |
| 2.1 Water use efficiency | **AH14** – Efficiency in water resources (%) | [1 – (Real losses + Evaporation losses) / System input volume] x 100 |
| 2.2 Energy use efficiency | **AH15** – Energy efficiency of pumping stations (%) | Useful pump energy / Pump energy consumption x 100 |
| | **AH16** – Energy in excess per authorised consumption (kWh/m$^3$) | (System input energy – Minimum required energy to supply irrigators – Recovered energy) / Volume associated with authorised water consumption |
| 3.1 Service accessibility | **AH17** – Own water supply capacity (-) | (System input volume + Water volume stored and available for use at the end of the irrigation period – Imported water during the irrigation period) / Average volume associated with authorised consumption in the last three years |
| | **AH18** – Water charges (%) | (Irrigators water charges + Irrigators pumping charges)/(Crop revenue – Crop costs + Irrigators pumping charges) x 100 |
| 3.2 Quality of service | **AH19** – Service interruptions [no./(1000 water intake to users. year)] | (Number of service interruptions with a duration higher than one day x 365/Irrigation duration) / Number of water intake to users x 1000 |
| | **AH20** – Irrigated area with on-demand service (%) | Area equipped with collective irrigation system with on-demand service / Area equipped with collective irrigation system x 100 |

(AH05) represents the average age of the pipe and canal network through the devaluation degree (Alegre et al., 2014). Values close to 1 mean that the network is new and low values (*i.e.*, below 0.2) indicate that the average age of the network is high and significant investment in rehabilitation may be necessary. Ideally, the value should be close to 0.5. The same rationale was adopted for pumping groups' value index.

Failures in canals, pipes, valves and fittings that require interruption of transport and distribution service should be considered for the calculation of AH07, independently of duration. In contrast, service interruption with a duration higher than one day and independent of the cause (internal or external to the CIS) should be considered to calculate service interruptions (AH19). Besides assessing pump equipment efficiency (AH15), the energy supplied in excess (AH16) requires energy balance calculation (Cunha et al., 2019b). It includes the energy associated with water losses, inefficiencies in pumping stations and hydraulic turbines, continuous and singular head losses, and the surplus energy delivered (relevant in the case of pressurised irrigation systems).

Table 4 proposes reference values for each PI. Reference values can be expressed into performance intervals and have the same units of the respective PI. These reference values allow converting PIs into a three-level grade (good: "green circle", fair: "yellow circle", poor: "red circle"), by comparing each PI value with the reference values. Some PIs have different reference values regarding the CIS type: gravity, pressurised or combined. Even though the conveyance and distribution networks are generally in canal, low-pressure pipe networks (*e.g.*, 1 m) may also exist in the gravity system. The pipe network can also have punctual pumping. Pressurised systems have high-pressure conveyance and distribution pipe networks (e.g, above 30 m). In combined systems, gravity and pressurised systems can coexist. For AH04, AH10, AH11, AH14 and AH16 PIs, reference intervals for combined systems depend on the reference values for gravity and pressurised systems, weighted by the respective network length, according to:

$$\text{Combined systems}=\begin{cases}\text{PI with good performance (🟢), if} \in \left[\alpha\cdot LL_g^{good}+(1\text{-}\alpha)\cdot LL_p^{good};\ \alpha\cdot UL_g^{good}+(1\text{-}\alpha)\cdot UL_p^{good}\right]\\ \text{PI with fair performance (🟡), if} \in \left]\ \alpha\cdot LL_g^{fair}+(1\text{-}\alpha)\cdot LL_p^{fair};\ \alpha\cdot UL_g^{fair}+(1\text{-}\alpha)\cdot UL_p^{fair}\right]\\ \text{PI with poor performance (🔴), if} \in \left]\ \alpha\cdot LL_g^{poor}+(1\text{-}\alpha)\cdot LL_p^{poor};\alpha\cdot UL_g^{poor}+(1\text{-}\alpha)\cdot UL_p^{poor}\right]\end{cases}$$

**(1).**

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Where $\alpha$ (-) is the proportion of network length in gravity, given by $(L_g/(L_g+L_p))$; $L_g$ and $L_p$ (km) the network length in gravity and pressurised, respectively. The $LL_g^{good}$ and $LL_p^{good}$ are the lower and $UL_g^{good}$ and $UL_p^{good}$ the upper limits of the performance intervals graded with good performance, in gravity and pressurised, respectively. The $LL_g^{fair}$ and $LL_p^{fair}$ are the lower and $UL_g^{fair}$ and $UL_p^{fair}$ the upper limits of the performance intervals graded with fair performance, in gravity and pressurised, respectively. The $LL_g^{poor}$ and $LL_p^{poor}$ are the lower and $UL_g^{poor}$ and $UL_p^{poor}$ the upper limits of the performance intervals graded with poor performance, in gravity and pressurised, respectively. For example,

**Table 4**
Reference values for each PI.

| PI | Application domain in CIS | Reference intervals | | | |
|---|---|---|---|---|---|
| | | Good (🟢) | Fair (🟡) | Poor (🔴) | Source |
| **AH01** – Total costs coverage (%) | All types | [100; 110] | [90; 100[ or] 110; 120] | [0.0; 90[ or] 120; + ∞[ | (i) |
| **AH02** – Adhesion to service in the area equipped with collective irrigation (%) | All types | [70; 100] | [50; 70 [ | [0.0; 50[ | (ii) |
| **AH03** – Total adhesion (%) | All types | [80; 100] | [60; 80 [ or] 100; 120] | [0.0; 60[ or] 120; + ∞[ | (ii) |
| **AH04** – Non-revenue water (%) | Gravity | [0.0; 20] | ]20; 35] | ]35; 100] | (iii) |
| | Pressurised | [0.0; 10] | ]10; 15] | ]15; 100] | |
| | Combined | See Equation (1) | | | |
| **AH05** – Infrastructure value index (-) | All types | [0.4; 0.6] | [0.2; 0.4[ or]0.6, 1.0] | [0.0; 0.2[ | (iv) |
| **AH06** – Pumping groups value index (-) | All types | [0.4; 0.6] | [0.2; 0.4[ or]0.6, 1.0] | [0.0; 0.2[ | (iv) |
| **AH07** – Network failures [no./(100 km.year)] | All types | [0.0; 15] | ]15; 30] | ]30; + ∞[ | (i) |
| **AH08** – Network rehabilitation (%/year) | All tyes | [1.0; 4.0] | [0.8; 1.0[ or]4.0; 100] | [0.0; 0.8[ | (i) |
| **AH09** – Water losses due to canal leakage [l/(m$^2$.day)] | Gravity | [0.0; 20] | ]20; 50] | ]50; + ∞[ | (iii) |
| **AH10** – Water losses due to pipe leakage [m$^3$/(km.day)] | Gravity | [0.0; 4.0] | ]4.0; 8.0] | ]8.0; + ∞[ | (iii) |
| | Pressurised | [0.0; 10] | ]10; 15] | ]15; + ∞[ | |
| | Combined | See Equation (1) | | | |
| **AH11** - Water losses due to discharges (%) | Gravity | [0.0; 10] | ]10; 30] | ]30; 100] | (iii) |
| | Pressurised | [0.0; 5.0] | ]5.0; 15] | ]15; 100] | |
| | Combined | See Equation (1) | | | |
| **AH12** – Failures in measurement, control and cleaning devices [no./(100 km.year)] | All types | n.a. | | | (v) |
| **AH13** – Failures in pumping groups [no./(pumping group.year)] | All tyes | n.a. | | | (v) |
| **AH14** – Efficiency in water resources (%) | Gravity | [80; 100] | [65; 80 [ | [0.0; 65[ | (iii) |
| | Pressurised | [90; 100] | [75; 90 [ | [0.0; 75[ | |
| | Combined | See Equation (1) | | | |
| **AH15** – Energy efficiency of pumping stations (%) | All types | [68; 100] | [50; 68 [ | [0.0; 50[ | (i) |
| **AH16** – Energy in excess per authorised consumption (kWh/m$^3$) | Gravity | [0; 0,2] | ]0,2; 0,4] | ]0,4; + ∞[ | (iii) |
| | Pressurised | [0; 0,1] | ]0; 0,2] | ]0,2; + ∞[ | |
| | Combined | SeeE (1) | | | |
| | All types | | | [0; 1.0[ | (iii) |
| **AH17** – Own water supply capacity (-) | | [1.5; + ∞[ | [1.0; 1.5[ | | |
| **AH18** – Water charges (%) | All types | n.a. | | | (v) |
| **AH19** – Service interruptions [no./(1000 water intake to users. year)] | All types | [0.0; 5.0] | ]5.0; 10] | ]10; + ∞[ | (iii) |
| **AH20** – Irrigated area with on-demand service (%) | All types | n.a. | | | (v) |

Note: (i) ERSAR and LNEC (2021); (ii) data from 30 Portuguese CIS (DGADR, 2017); (iii) data from the case studies in AGIR Project; (iv) Alegre and Coelho (2012); (v) references values were not proposed (n.a.) due to the lack of data in the bibliography or this study.

using Equation (1), the reference values associated with non-revenue water (AH04) in a combined system with a network with 100 km in gravity and 300 km in pressure are the following:

$$\text{AH04} = \begin{cases} \text{Good performance (🟢), if } \epsilon \text{ } [0;\ 12.5] \\ \text{Fair performance (🟡), if } \epsilon \text{ } ]12.5;\ 20.0] \\ \text{Poor performance (🔴), if } \epsilon \text{ } ]20.0;\cdot 100] \end{cases}$$

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References values were estimated based on the references mentioned in Table 4. For some PIs (AH12, AH13, AH18 and AH20), reference values were not proposed due to a lack of data in the bibliography or relative to the case studies.

### 2.2. *Approach for diagnosis and decision support in a planning process*

A PAS constitutes a core instrument for diagnosis, planning, monitoring, and revising the impact of actions to improve water and energy efficiency in CISs in the medium-term (3–5 years' time horizon). The water utility and the CIS profiles are oriented to collect relevant information for the PAS application. Based on Alegre and Coelho (2012) and Alegre et al. (2013), the proposed approach focuses on diagnosing and planning measures to improve water and energy efficiency in a three-year to five-year planning horizon.

Before diagnosis, data collection is carried out according to the variables required in the water utility profile (Table 1), the CIS profile (Table 2) and the PIs that integrate the PAS (Table 3) for global system analysis. Since the focus is on improving water and energy efficiency, the calculation of several PIs (AH04, AH09, AH10, AH11, AH14, AH15 and AH16) requires a prior calculation of the annual water and energy balances (Cunha et al., 2019a, 2019b).

Diagnosis encompasses a first step dedicated to a global analysis to identify the main problems and possible cross-cutting system measures (*e.g.*, inventory data improvement, monitoring of system input volume and water discharges, flow metering calibration), using the performance assessment panel (Tables 3 and 4) and analysis of context information from the water utility and CIS profiles (Tables 1 and 2).

The second step of diagnosis consists in identifying priority network areas for a more detailed diagnosis and planning interventions. Through PAS application to each network area for prioritisation, the analysis involves a possible selection of PIs from Table 3 to highlight the differences between network areas. Before the analysis, each network area water and energy balance calculation is carried out. For network area prioritisation using multiple PIs, a ranking is established based on the overall assessment. The ranking is based on the methodology proposed by Alegre and Coelho (2012). Therefore the PIs, expressed in different units and judged by reference values, are converted into performance indices (dimensionless) through the application of performance levels ([0; 1], poor performance; [1; 2], fair performance, [2; 3], good performance). The global assessment corresponds to the average of normalised PIs or a weighting average if the relative importance of each PI is different.

Diagnosis takes into consideration the performance in the current situation (reference year(s)) and the expected performance in the future (20 years' time horizon) for a more informative diagnosis about current problems and their evolution. Probable scenarios (*e.g.*, demographic trends and regulatory changes), corresponding to conditions not controlled by the WUAs and impacting performance evolution should be considered (Alegre et al., 2012). Moreover, internal factors in the WUAs (*e.g.*, already planned interventions) might also influence performance in each scenario. Thereby, performance assessment in future is carried out for each probable scenario and considering the impact of internal factors. Both depend on the specific context and should be identified in articulation with the utility. A set of assumptions were established to assess future CIS performance, which depends on the WUA and CIS contexts and should be tailored (*e.g.*, water and energy prices, water demand, the evolution of apparent and real water loss components, pump efficiency degradation, and maintenance costs).

For planning improvement measures, the PAS (Table 3) is applied to the network area with a high priority of intervention for a detailed diagnosis. Afterwards, the analysis of improvement measures includes i) identification of alternatives, which may correspond to a combination of measures, ii) comparative analysis of alternatives in terms of performance assessment, iii) comparative economic analysis of alternatives, and iv) prioritisation of alternatives. For global assessment of each alternative, using multiple PIs, it is necessary to convert them into performance levels, as described previously. In addition, the global assessment takes into consideration the performance in the current situation (reference year(s)) and the expected performance in the future (20 years time horizon), similarly to diagnosis. In terms of economic analysis, besides estimating intervention costs based on the information and rehabilitation budgets provided by the water utility, some economic indicators were adopted, namely the net present value, the internal rate of return and the payback period.

Furthermore, the proposed water utility and collective irrigation profiles (Tables 1 and 2) and the performance assessment panel (Tables 3 and 4) have an additional application. They can be transferable for global analysis of different CIS (*i.e.*, gravity, pressurised or combined systems) to highlight the main problems in these systems and support public policies.

## 3. Results

### 3.1. System diagnosis

#### 3.1.1. Water utility and CIS profiles

The proposed approach for water and efficiency diagnosis and decision support was applied in a gravity system in Portugal. The analysed system includes the conveyance and distribution infrastructures from the water intakes in reservoirs to the water delivery point to beneficiaries and non-beneficiaries. The irrigation period for analysis was established based on the availability of the service to the users.

The gravity-flow system began operating in 1959, presents a total irrigated area of 16 351 ha and had 947 irrigation users in 2018. The conveyance system is an open-canal, and the distribution system integrates canals and low-pressure pipes. Three reservoirs supply this system with associated hydropower stations and 13 pumping stations. The gravity-flow system comprises five network areas (S1, S2, S3, S4, and S5). Network areas S1, S2, S3, and S4 are interconnected, and network area S5 is independent. Due to infrastructure ageing, some rehabilitation interventions were already implemented, corresponding mainly to the complete rehabilitation of the canal network in S5 area in 2001. Tables 5 and 6 list the water utility and conveyance and distribution system profiles for the gravity-flow system for the reference year (2018).

With a contract period of 20 years, the water utility provides water to 947 irrigators. Still, it only ensures the service to 906 beneficiaries (895 agricultural and 11 non-agricultural) covered by the area equipped with the collective irrigation system (16 351 ha). The energy costs and the own energy production variables calculated annually indicate that the proportion of energy costs concerning the operation of the CIS is reduced (6.9%), with 13 pumping stations in operation. The energy production represented 8.5 times the energy consumption for pumping, which is relevant for the utility's economic and natural resources' sustainability.

In operation since 1959, it includes three water intakes in reservoirs, six in watercourses, and a total network length of 402.4 km. In 2018, the irrigation period corresponded to 174 days and the Annual irrigation shortage represented only 16.6% relative to the average potential evapotranspiration. For the estimation of evapotranspiration, the well-established Penman-Monteith method was adopted (Allen et al., 1998).

#### 3.1.2. Global analysis

The PAS application is presented to identify the main water and energy efficiency problems and possible cross-cutting measures for the gravity CIS. The global analysis includes assessing the service provided for the reference situation (2018) and analysis horizon (2038) based on scenarios and the expected changes in the internal context of the water utility (Table 7).

Enhancing the infrastructural, operational, and maintenance sustainability and water and energy efficiency represent the main improvement opportunities. Relative to economic-financial sustainability, the Non-revenue water (AH04 =39.8%), with poor performance (*i.e.*, above 35% of the system input volume, Table 4), indicates a potential to reduce unbilled authorised consumption and water losses.

Significant water losses due to canal and pipe leakage (AH09 and AH10 with fair performance) and the ageing canal and pipe network (AH05 with fair performance) indicate that infrastructural problems are already noticeable. The rehabilitation rate in the last five years (AH08 with good performance) suggests that infrastructural intervention is already a concern for the WUA and should be continued for infrastructure sustainability. Water losses due to the canal and intermediate reservoirs discharges, estimated according to Cunha et al. (2019a), are also significant (AH11 above 30% of the water input volume, with poor performance), indicating problems with operation and maintenance. However, further work is recommended to identify the most relevant discharges, with the support of operators, for temporary or permanent flow monitoring to validate this water loss component. As such, identifying solutions to improve canal operational control is required to reduce this volume of water losses. Moreover, Fernández-Pacheco et al. (2015) demonstrated that automation systems for remote monitoring

**Table 5**
Water utility profile in 2018.

| Variable/Context PIs | Water utility |
|---|---|
| Water utility identification, dEG01 (-) | WUA #1 |
| Water utility type, dEG02 (-) | Water user association |
| Concession contract period, dEG03 (-) | 2011–2031 |
| Agricultural beneficiaries, dEG04 (no.) | 895.0 |
| Non-agricultural beneficiaries, dEG05 (no.) | 11.0 |
| Associated irrigators, dEG06 (no.) | 138.0 |
| Number of irrigators, dEG07 (no.) | 947.0 |
| Human resources, dEG08 (no.) | 62.0 |
| Volume associated with billed authorised consumption, dBH02 ($m^3$/year) | 109 122 970.3 |
| Average irrigated area, PAH03 (ha/irrigation user/year) | 18.7 |
| Energy costs, PAH02 (%) | 6.9 |
| Own energy production, PAH05 (-) | 8.5 |

**Table 6**
Gravity system profile in 2018.

| Variable/Context PI | System |
|---|---|
| Geographic region, dReg01 (-) | Lezíria do Tejo/Alto Alentejo |
| Hydrographic region, dReg02 (-) | RH5 - Tagus |
| Climatic region, dReg03 (-) | South |
| Water resources license, dInfra01 (-) | 2010–2030 |
| Operation start date, dInfra02 (-) | 1959 |
| Surface water intakes in reservoirs, dInfra03 (no.) | 3 |
| Surface water intakes in watercourses, dInfra04 (no.) | 6 |
| Groundwater intakes, dInfra05 (no.) | n.a. |
| Pumping stations, dInfra06 (no.) | 13 |
| Intermediate reservoirs, dInfra07 (no.) | 1 |
| Conveyance and distribution canal network for collective irrigation, dInfra08 (km) | 208.5 |
| Conveyance and distribution pipe network for collective irrigation, dInfra09 (km) | 193.9 |
| Area equipped with collective irrigation system, dInfra12 (ha) | 16 351 |
| Irrigation period, dInfra13 (-) | 03/05/2018–30/10/2018 |
| Irrigation duration, dInfra14 (days) | 174 |
| Volume licensed for water abstraction, dBH01 ($m^3$/year) | 180 000 000 |
| End-use points equipped with water metres, PAH06 (%) | 100 |
| Annual irrigation shortage, PAH07 (%) | 16.6 |
| Potential to use water for reuse, PAH08 ($m^3$/ha/year) | 1 731 |

n.a. – not applicable, n.d. – information not available

and control in WUAs may correspond to low-cost investments with large water and energy savings benefits. For more information about water loss estimates in this case study, see Cunha et al. (2019a). This study lacked historical databases about failures in measurement, control and cleaning equipment, and pumping groups (AH12, AH13).

Regarding water use efficiency, the fair performance in Efficiency in water resources (AH14), together with the fair performance in Water losses due to canal and pipe leakage (AH09, AH10) and the poor performance in Water losses due to discharges (AH11) indicate a significant potential to improve real losses. Significant water losses contribute to high energy in excess (AH16 with fair performance). In addition, the low efficiency of pumping stations (AH15 with poor performance) also indicates a potential to reduce energy supplied in excess by improving pump efficiency and water loss control. The Pumping groups' value index (AH06) 's good performance indicates that pumping groups are globally new. Therefore, the low pumping stations' efficiency (AH15 with poor performance) suggests the opportunity to improve the operation and maintenance of pumping groups for higher efficiency. Finally, with the expected evolution in performance for AH06 and AH15, the oldest equipment, with low efficiency, should be replaced by new equipment with adequate design.

Relative to the adequacy of the service provided to irrigation users, the results highlight that Own water capacity was adequate (AH17 with good performance), indicating the availability of water resources to ensure demand in 2018. However, the number of service interruptions was significant (AH19 with poor performance), which might compromise the quality of service. Additionally, most interruptions were due to infrastructure problems (*e.g.*, pipe or canal bursts), impacting water losses and the service provided to users.

Concerning the expected evolution, three probable scenarios were established together with the WUA: i) maintain current water availability and demand for irrigation, ii) increase demand for irrigation due to installation of more water intensive crops, iii) decrease water

**Table 7**
PAS for the gravity system in 2018 and expected evolution in terms of performance (→, maintains; ↗, improves; ↘, decreases) in the analysis horizon (2038), considering internal factors and the scenario where water availability and demand for irrigation keep actual conditions.

| Criteria | PIs | 2018 | 2038 |
|---|---|---|---|
| 1.1 Economic-financial sustainability | AH01 – Total costs coverage (%) | 🟡 111.9 | → |
| | AH02 – Adhesion to service (%) | 🟢 70.1 | → |
| | AH03 – Total adhesion (%) | 🟡 108.3 | → |
| | AH04 – Non-revenue water (%) | 🔴 39.8 | ↗ |
| 1.2 Infrastructural sustainability | AH05 – Infrastructure value index (-) | 🟡 0.28 | ↗ |
| | AH06 – Pumping groups value index (-) | 🟢 0.50 | ↘ |
| | AH07 – Network failures [no./(100km.year)] | 🟢 10.9 | → |
| | AH08 – Network rehabilitation (%/year) | 🟢 2.24 | ↘ |
| | AH09 – Water losses due to canal leakage [l/($m^2$.day)] | 🟡 22.2 | ↗ |
| | AH10 – Water losses due to pipe leakage [$m^3$/(km.day)] | 🟡 4.97 | ↘ |
| 1.3 Operational and maintenance sustainability | AH11 – Water losses due to discharges (%) | 🔴 30.5 | ↗ |
| | AH12 – Failures in devices [no./(100km.year)] | ● n.d. | n.d. |
| | AH13 – Failures in pumping groups [no./(pumping group. year)] | ● n.d. | n.d. |
| 2.1 Water use efficiency | AH14 – Efficiency in water resources (%) | 🟡 66.9 | ↗ |
| 2.2 Energy use efficiency | AH15 – Energy efficiency of pumping stations (%) | 🔴 46.8 | → |
| | AH16 – Energy in excess per authorised consumption (kWh/$m^3$) | 🟡 0.29 | ↗ |
| 3.1 Service accessibility | AH17 – Own water capacity (%) | 🟢 2.50 | → |
| | AH18 – Water charges (%) | ● 18.9 | n.d. |
| 3.2 Quality of service | AH19 – Service interruptions [no./(1000 water intake to users. year)] | 🔴 34.5 | ↗ |
| | AH20 – Irrigated area with on-demand service (%) | ● 0.0 | n.d |

Notes: n.a. – not applicable, n.d. – not available.

abstraction from reservoirs due to a new dam in the region, located upstream of the CIS. The expected qualitative performance evolution for the first scenario and the internal factors is shown in Table 7. The WUA is planning changes in the internal context, namely the rehabilitation of approximately 37% of the canal network and only about 11% of the pipe network in the next ten years. These interventions also involve installing devices for automatic monitoring and control of discharges and replacing irrigators' water metres to improve metering accuracy and billed consumption.

Thus, a performance improvement is expected, namely, in Non-revenue water (AH04), Infrastructure value index (AH05), Water losses due to canal leakage (AH09) and due to discharges (AH11), Efficiency in water resources (AH14), Energy in excess (AH16) and Service interruptions (AH19). Moreover, with a partial network modernisation to a pressurised system, it is expected to increase the area irrigated with on-demand service (AH20). However, lower performance in the Pumping groups' value index (AH06) and Water losses due to pipe leakage (AH10) is expected, indicating the importance of identifying those with high priority for intervention planning. In terms of energy consumption and costs (only 6.9% in 2018, Table 5), an increase is expected due to pump efficiency degradation of existing groups and the installation of new pumping stations associated with network modernisation. Network rehabilitation performance is likely to decrease in the long term. After the first ten years, future interventions should be planned gradually to ensure an adequate quality of service.

Based on the global analysis of the gravity system, considering the initial reference situation and its expected evolution, several cross-cutting measures to increase water and energy efficiency were identified (Table 8).

### *3.1.3. Network area prioritisation*

The PAS application at the network area level allows for identifying the areas with high priority for intervention. For prioritising, a set of PIs was selected from criteria relative to the sustainability of service provision (Obj. 1) and sustainability in water and Energy (Obj. 2). PIs relative to the adequacy of the service provided to irrigation users' objective (Obj. 3) were not differentiating among the areas and were not considered for prioritisation.

Table 9 presents the results of network area analysis for the reference year (2018), classifying the areas in terms of priority for intervention (*i.e.*, the area with lower global performance assessment is of high priority). Since PIs are expressed in different units, the global assessment was determined by converting PIs into performance indices, as described in section 2.2.

From the global performance assessment, network areas S1 to S4 show a fair performance, particularly S1 and S2, with a lower global performance level indicating a high priority for a more detailed diagnosis and planning interventions. Network area S5 (entirely rehabilitated in the last 20 years) shows a good performance level (above 2.0). The main problems identified in S1 to S4 correspond to the high non-revenue water (AH04), water losses due to discharges (AH11) and Energy in excess (AH16), and the low energy efficiency of the pumping stations (AH15).

Network area S2 (1st priority) presents the highest values in Non-revenue water (AH04) and Water losses due to discharges in intermediate reservoirs and canals (AH11). Furthermore, the fair performance in the Infrastructure value index (AH05), Water losses due to canal (AH09) and pipe leakage (AH10) and Efficiency in water resources (AH14), with poor performance, indicate an ageing network, with possible problems in infrastructure condition and network operation and control. This area also presents poor performance relative to the Energy efficiency of pumping stations (AH15) and Energy in excess (AH16). The significant water losses and the low efficiency in pumping stations contribute noticeably to the energy supplied in excess.

Network area S1 (2nd priority), although with similar problems to S2, the poor performance in the Infrastructure value index (AH05) and the canal (AH09) and pipe leakage (AH10) with fair performance indicate that network rehabilitation is crucial in this network area. Though with fair performance in water losses due to discharges in intermediate reservoirs and canals (AH11), the value is lower relative to S2, indicating the operational issues are less relevant in S1. This network area also presents potential to improve pump efficiency, similarly to S2.

Network area S4 (3rd priority) presents the second-highest value of Non-revenue water (AH04) and stands out for its high water losses due to discharges (AH11). With good performance in the Infrastructure value index, AH05 (*i.e.*, more recent network than S1 and S2), it is

**Table 8**
Synthesis of measures to increase water and energy efficiency.

| Water and energy efficiency measures/ Criteria | 1.1 Economic-financial sustainability | 1.2 Infrastructural sustainability | 1.3 Operational and maintenance sustainability | 2.1 Water use efficiency | 2.2 Energy use efficiency | 3.1 Service accessibility | 3.2 Quality of services |
|---|---|---|---|---|---|---|---|
| • Verification and calibration of network flowmeters and irrigators' water metres. | x | | x | | | | x |
| • Water metres, billing and customer data management. | x | | | | | | x |
| • Hydraulic turbine inspection and auditing. | x | | | | x | | |
| • Installation of water metres for all irrigation users. | x | | | | | | x |
| • Inventory data about the network, failures (network, pumping groups control and cleaning devices), rehabilitation interventions and service interruptions. | | x | | x | | | x |
| • Canal condition assessment to identify components with high priority for replacement. | | x | | x | | | x |
| • Identification of canal and intermediate reservoir main discharges and installation of flow metres for volume discharge control. | x | | x | x | | | |
| • Pump inspection, auditing, and installation of flow and pressure measurement equipment in all pumping groups. | x | | | | x | | |
| • Systematic recording of water volumes associated with network cleaning and maintenance. | | | x | | | | |

**Table 9**
Network area analysis for the reference year (2018).

| Network area | AH04 – Non-revenue water (%) | AH05 – Infrastructure value index (-)(1) | AH06 – Pumping groups value index (-) | AH09 – Canal leakage [l/(m$^2$ .day)] | AH10 – Pipe leakage [m$^3$/(km.day)] | AH11 – Water loss due to discharges (%) | AH14 – Efficiency in water resources (%) | AH15 – Energy Efficiency of pumping stations (%) | AH16 – Energy in excess (kWh/m$^3$) | Global assessment (-) | Prioritisation (-) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 🔴 36.1 | 🔴 0.13 | 🟡 0.32 | 🟡 20.4 | 🟡 7.02 | 🟡 13.2 | 🟡 71.5 | 🔴 47.9 | 🟡 0.32 | 🟡 1.34 | 2 |
| S2 | 🔴 46.6 | 🟡 0.27 | 🟡 0.38 | 🟡 22.4 | 🟡 4.93 | 🔴 36.3 | 🔴 60.2 | 🔴 46.6 | 🔴 0.41 | 🟡 1.28 | 1 |
| S3 | 🟡 25.2 | 🟡 0.38 | 🟢 0.50 | 🟢 19.6 | 🟢 3.64 | 🟡 15.1 | 🟢 83.4 | 🔴 16.8 | 🔴 0.44 | 🟡 1.67 | 4 |
| S4 | 🔴 40.2 | 🟢 0.45 | 🟢 0.73 | 🟡 24.1 | 🟢 3.58 | 🔴 32.6 | 🟡 65.8 | 🟢 68.9 | 🔴 0.55 | 🟡 1.58 | 3 |
| S5 | 🟢 9.29 | 🟢 0.46 | 🟢 0.52 | 🟢 13.7 | 🟡 7.06 | 🟢 6.80 | 🟢 92.2 | 🔴 29.8 | 🟢 0.03 | 🟢 2.07 | 5 |

(1) Network area prioritisation was developed to identify the most aged areas with the greatest efficiency problems. For this reason, only the increasing branch of the reference values of the Infrastructure value index (AH05) and Pumping groups value index (AH06) was adopted (poor, [0.0; 0.2[; fair, [0.2; 0.4[; good, [0.4;1.0]).

crucial to analyse measures to improve canals' operational control to improve performance in water losses due to discharges. It stands out that the energy efficiency of pumping stations is good (AH15) in this network area. Thereby, the major contribution to the energy supplied in excess may be due to water losses.

Regarding network area S3 (4th priority), even though its Non-revenue water (AH04) is lower than in S1, S2 and S4, it presents a fair performance in Water losses due to discharges (AH11) and poor performance in Energy efficiency of pumping stations (AH15) and energy in excess (AH16). Besides the need to improve network operation, the lowest efficiency of the pumping stations (AH15), in the middle of their useful life (AH06), highlights the high need to verify the operation practices (*e.g.*, installation of variable speed devices).

Finally, network area S5, with a good performance level, stands out for the low efficiency of the pumping stations (AH15), which are in the middle of their useful life (AH06), besides a fair performance in water losses due to pipe leakage (AH10). Therefore, improving the operating control and practices is important, as analysing the need to install variable speed devices.

### 3.2. *Network area diagnosis and prioritisation of improvement measures*

After identifying S2 as the priority network area, the most extensive network (with 115 km of canals and 91 km of pipes), the diagnosis at network area level is developed to identify the main problems and measures to improve water and energy efficiency.

Network area S2 was responsible for 63% of the volume of water losses due to canal discharges in 2018, which corresponded to approximately 30 hm$^3$. Furthermore, the fair performance in the Infrastructure value index (AH05) in Table 9 indicates that some water losses may relate to the ageing and degraded infrastructure. On the other hand, energy consumption in pumping stations represented 31% of the energy consumption in the water utility in 2018. This high consumption and the poor performance in pumping stations' efficiency (AH15) in Table 9 highlight the need to adopt specific measures to improve the efficiency of this equipment. Secondly, the efficiency of the Francis turbine installed upstream of network area S2 was low in 2018 (63%), according to Liu et al. (2015), which indicates the potential to improve energy production from the natural energy supplied to the system.

For the analysis horizon, changes in the WUA internal context will involve the phased rehabilitation of 43.8% of the total canal extension of S2 in 10 years, contributing to a better performance in the Infrastructure value index. For the future long-term behaviour, performance improvement is expected mainly in water losses due to canal leakage and discharges, improving efficiency in water resources and non-revenue water. Nevertheless, performance in terms of pumping groups' value index (AH06), water losses due to pipe leakage (AH10) and energy efficiency in pumping stations (AH15) will decrease or maintain due to the lack of rehabilitation in the components. Moreover, it also identified the need to improve the efficiency of the hydraulic turbine to improve energy production and related revenues. Five exploratory alternatives were identified in collaboration with the WUA, where A4 and A5 correspond to a combination of interventions in network area S2:

- Alternative A0: *Status quo*, not considering interventions and maintaining the current operation and maintenance practices.
- Alternative A1: Rehabilitation of 50.3 km of the main canal in 5 years (2019–2023).
- Alternative A2: Replace 149 old paddle wheel water metres with a nominal diameter DN150 and DN200.
- Alternative A3: Optimisation of the operation of the hydraulic turbine Francis.
- Alternative A4: Combination of alternatives A1 and A2 (A1 +A2).
- Alternative A5: Combination of alternatives A1, A2, and A3 (A1 +A2 +A3).

The prioritisation was developed based on the comparative analysis in terms of performance and economic viability of the proposed alternatives in a 20 years' analysis horizon. The same PIs selected for prioritising network areas (Table 9) were adopted for comparative performance analysis between alternatives. Table 10 illustrates the global performance level for each solution analysed in 2023 (*i.e.*, after the implementation period of alternatives).

Despite a fair performance, the global assessment (1.43) indicates that canal rehabilitation (Alternative A1) has a relevant positive impact relative to A0, with expected global performance in 2023 of only 1.12. Relative to alternatives A2 and A3, the contribution to global improvement is minimal, indicating that these types of interventions are punctual and are insufficient to improve performance. Optimisation of the hydraulic turbine (A3) operation only impacts excess energy (AH16). In contrast, the replacement of water metres (A2), besides a slight impact on non-revenue water (AH04), also impacts the energy in excess (AH16) to some extent. With water metre replacement, the

**Table 10**
Performance assessment of alternatives to improve water and energy efficiency in network area S2 (2023).

| | AH04 – Non-revenue water (%) | AH05 – Infrastructure value index (-)(1) | AH06 – Pumping groups value index (-)(1) | AH09 – Canal leakage [l/(m$^2$.day)] | AH10 – Pipe leakage [m$^3$/(km.day)] | AH11 – Water losses due to discharges (%) | AH14 – Efficiency in water resources (%) | AH15 – Energy efficiency of pumping stations (%) | AH16 – Energy in excess (kWh/m$^3$) | Global assessment (-) |
|---|---|---|---|---|---|---|---|---|---|---|
| **A0** | 🔴 47.8 | 🟡 0.21 | 🟡 0.18 | 🟡 23.7 | 🟡 5.15 | 🔴 37.3 | 🔴 59.1 | 🔴 44.0 | 🔴 0.42 | 🟡 1.12 |
| **A1** | 🔴 37.7 | 🟢 0.58 | 🟡 0.18 | 🟢 16.1 | 🟡 5.15 | 🟡 25.6 | 🟡 71.1 | 🔴 44.0 | 🟡 0.35 | 🟡 1.43 |
| **A2** | 🔴 46.9 | 🟡 0.21 | 🟡 0.18 | 🟡 23.7 | 🟡 5.15 | 🔴 38.0 | 🔴 59.1 | 🔴 44.0 | 🟡 0.41 | 🟡 1.12 |
| **A3** | 🔴 47.8 | 🟡 0.21 | 🟡 0.18 | 🟡 23.7 | 🟡 5.15 | 🔴 38.0 | 🔴 59.1 | 🔴 44.0 | 🟡 0.39 | 🟡 1.13 |
| **A4** | 🔴 36.0 | 🟢 0.58 | 🟡 0.18 | 🟢 16.1 | 🟡 5.15 | 🟡 25.6 | 🟡 71.3 | 🔴 44.0 | 🟡 0.34 | 🟡 1.45 |
| **A5** | 🔴 36.0 | 🟢 0.58 | 🟡 0.18 | 🟢 16.1 | 🟡 5.15 | 🟡 25.6 | 🟡 71.3 | 🔴 44.0 | 🟡 0.32 | 🟡 1.46 |

(1) Only the increasing branch of the reference values was adopted for alternatives prioritisation (poor, [0.0; 0.2[; fair, [0.2; 0.4[; good, [0.4;1.0]).

energy in excess reduces since authorised consumption increases due to a decrease in water metering errors. While most of the authorised billed consumption (about 70% of consumption) is measured using old Neyrpic modules in network area S2 and the alternative A2 focus only on replacing paddle wheel water metres. Thus, future comparative analysis should study the replacement of Neyrpic modules.

Alternatives A1, A4 and A5 show a better global assessment in 2023, especially in the Infrastructure value index (AH05), the Water losses due to canal leakage (AH09), both with good performance, and the efficiency of water resources (AH14), with fair performance, compared to the alternative A0 (*status quo*). The rehabilitation of the main canal (A1) involves an initial reduction of approximately 40% of water losses due to canal discharges (A11 with fair performance) relatively to alternative A0. However, non-revenue water (AH04) and the energy efficiency of pumping stations (AH15) continue with poor performance in 2023. These results indicate that additional measures to alternatives A1, A4 or A5 would be necessary to improve water and energy efficiency (*e.g.*, enhance monitoring and control of discharges and rehabilitation of pumping stations).

Fig. 2a presents the progress of the non-revenue water (AH04), Fig. 2b the energy supplied in excess (AH16), during the analysis period, and Fig. 2c the cost of the alternatives *versus* the average global assessment. In the evolution of both PIs (Fig. 2a,b), a significant decrease is observed until the end of the implementation of canal rehabilitation (2023) in alternatives involving canal rehabilitation (A1, A4 and A5). The behaviour until 2023 is due to a reduction in water losses due to canal leakage (AH09) and water discharges (AH11), since intervention involved canal waterproofing and better control of water discharges. Since water losses also contribute to reducing energy in excess (AH16), these alternatives also positively influence energy efficiency. After the rehabilitation period, it was considered that water losses increased at a similar rate as in A0 in the network area S2, indicating that it is necessary to maintain a continuous practice of rehabilitation. The assumption relative to the evolution of water losses can be improved by considering different rates for rehabilitated and non-rehabilitated components. The interventions' cost was estimated based on the information and rehabilitation budgets provided by the water utility.

For the non-revenue water, despite maintaining an unsatisfactory performance, the alternatives A1 and A5 present the best performance in the analysis horizon period with its minimum value in 2023 (Fig. 2a), after implementation. Regarding the energy in excess, as for the non-revenue water, the alternatives A1, A4 and A5 will involve higher performance enhancement, even though presenting a fair performance during the analysis period (Fig. 2b). However, the gradual performance decrease in both PIs between 2023 and 2039 highlights the importance of the water utility continuing to rehabilitate network area S2 gradually.

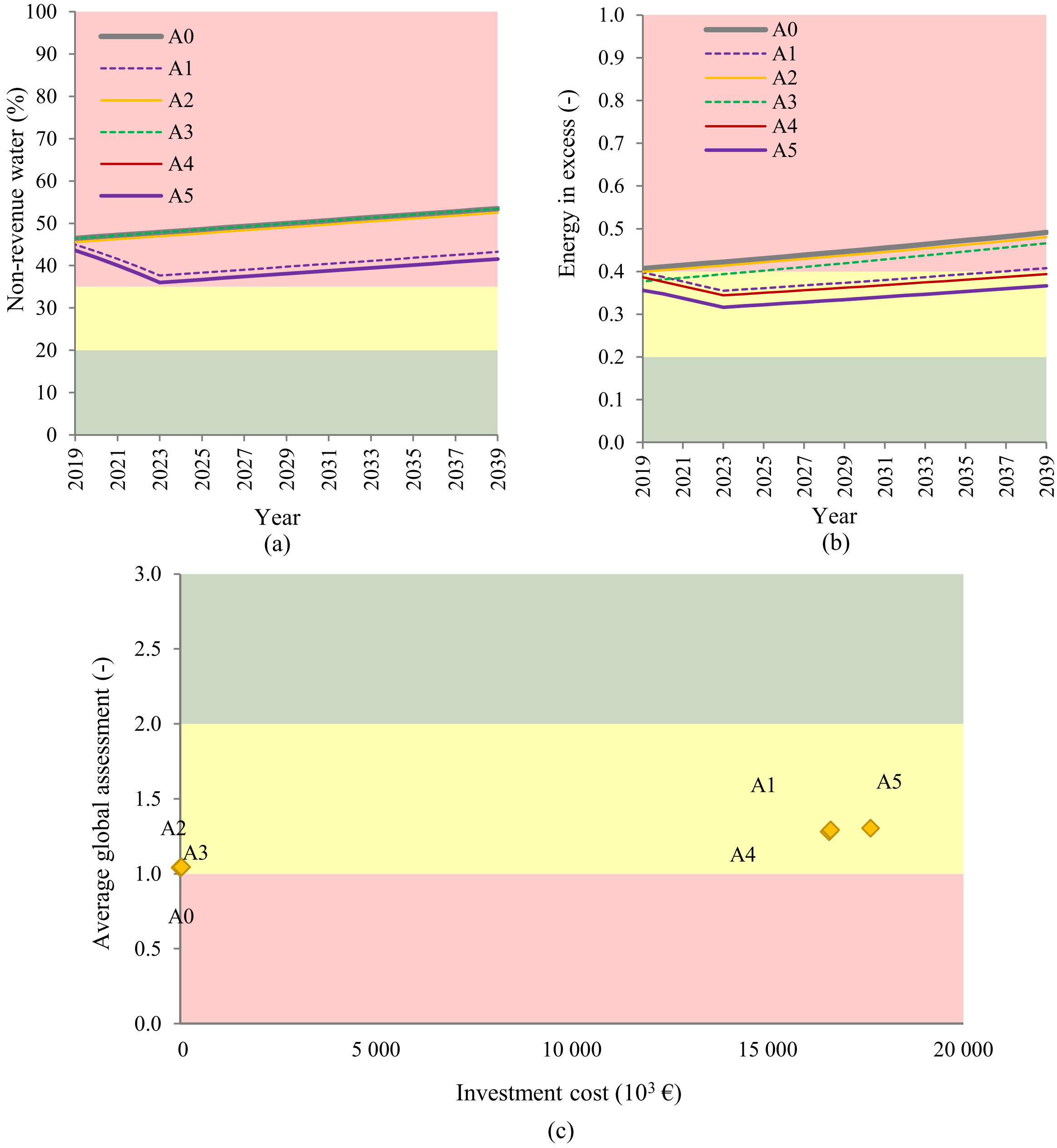
The comparative performance analysis (Fig. 2c) allows identifying the alternatives A1, A4 (A1 +A2) and A5 (A1 +A2 +A3), with a similar value for global assessment (approximately 1.30), as the best solutions for network area S2 (Fig. 2c). For the global evaluation, PIs expressed in different units and judged by reference values were converted into performance indices through the application of performance levels ([0; 1[, poor performance; [1; 2[, fair performance, [2; 3], good performance). Thereby, in Fig. 2c the "red area" corresponds to poor, the "yellow area" to the fair and the "green area" to good performance in terms of the global assessment. These solutions will significantly reduce losses and energy in excess and increase authorised consumption and efficiency in water resources. Although, the cost investment of A1 and A4 is similar (16.6 M€) and the cost of A5 is higher (17.7 M€) for a similar global performance. Specific interventions in equipment (A2 and A3) have a punctual impact on some performance indicators in this study.

Relative to the economic feasibility of the proposed alternatives, three economic indicators were adopted, namely the net present value, the internal rate of return and the payback period. Based on these indicators, alternatives A2 (payback period = 4 years) and A3 (payback period = 9 years) would be viable solutions for the 20-year analysis horizon. The remaining alternatives require a more extended period to recover the initial investment. Nevertheless, the payback period is smaller (34 years) when considering the three options combined (A5) due to increased efficiency in real and apparent losses and recovered energy relative to alternative A1 (41 years). Therefore, using the proposed PAS it was possible the analysis interventions in terms of performance and cost that will support WUAs in prioritisation. Moreover, it was demonstrated the importance of rehabilitation measures to improve water and energy efficiency in CIS.

### *3.3. Comparative analysis between CISs*

#### *3.3.1. Water utility and CISs profiles*

The comparative analysis between CISs was performed considering the gravity CIS, previously described in 3.1, and a pressurised CIS. This comparative analysis exemplifies the differences between a traditional and a more recent CIS and tests the proposed PAS. The irrigation period



(a)

(b)

(c)

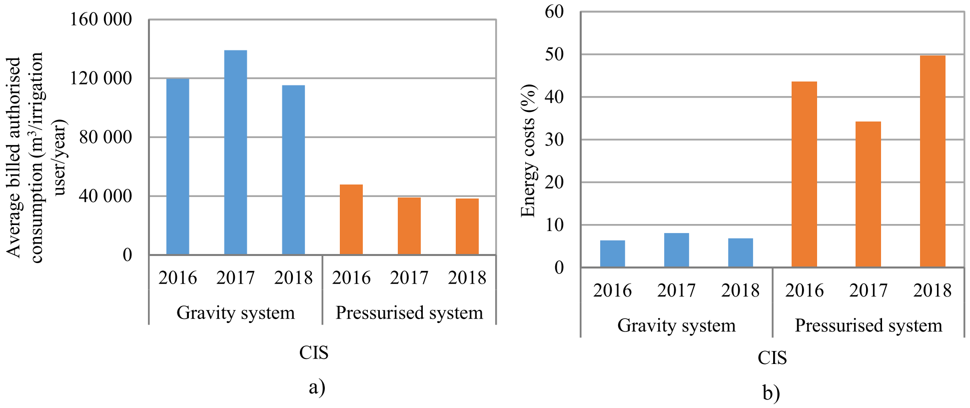
**Fig. 2.** Analysis of alternatives A0: *Status quo*, A1: Rehabilitation of the main canal A2: Replacement of old water metres, A3: Optimisation of operation of hydraulic turbine, A4: Combination of alternatives A1 and A2, A5: Combination of alternatives A1, A2, and A3 in the analysis period (2019–2039), considering internal factors and the scenario where water availability and demand for irrigation keep actual conditions: (a) evolution of the non-revenue water (AH04), (b) the evolution of energy in excess (AH16) and (c) investment cost and average global assessment.

in 2018 for the gravity and the pressurised CISs was 174 and 365 days, respectively.

The pressurised CIS began its exploration in 1981 and presents a more reduced dimension with 1500 ha of irrigation area and 108 irrigation users relative to the gravity system (see 3.1.1). In the pressurised CIS, the pipe conveyance and distribution system collects water from a reservoir, receives additional energy from a pumping station installed downstream, and is set up by two network areas (C1 and C2). During 2014 and 2015, 57.4% of the pipe network was rehabilitated, corresponding to the entire network area C2 and part of C1.

Overall, the gravity CIS has a higher dimension, especially regarding agricultural beneficiaries, irrigation users, human resources, and the total and average authorised consumption volume (Tables 5 and 6). Furthermore, the average billed authorised consumption in the gravity CIS, where the irrigated area for rice crops predominates, was almost three times the billed consumption of the pressurised CIS, where the irrigated area for olive crops dominates, between 2016 and 2018 (Fig. 3a). In the gravity system, the average billed authorised consumption was similar in 2016 and 2018 (average precipitation 628 mm) and increased in 2017 (average precipitation, 331 mm). This latter was the driest year in the period of analysis in this CIS, which entailed a greater crop water demand.

In terms of energy costs (Fig. 3b), the pressurised CIS shows much higher energy costs (up to 50% of operational costs) than the gravity system (energy costs less than 10% of operational costs). The pressurised CIS presents a higher dependency on electrical energy, varying the energy cost between 34.2% and 49.8% of operational cost during the analysed period. In this system, the low precipitation in 2018 (average precipitation, 359 mm), lead to higher crop water demand. Thus, more intensive use of pumping groups led to increased energy costs this year.



a)

b)

**Fig. 3.** CIS profile for gravity and pressurised systems between 2016 and 2018: a) average billed authorised consumption, b) energy costs.

### 3.3.2. *Comparative analysis*

Based on the PAS application, a benchmarking analysis at the global level regarding the main water losses and energy inefficiency problems is presented. Table 11 presents the comparative analysis between the gravity and the pressurised CISs for the reference year (2018).

In the economic-financial sustainability, the performance is fair or poor in terms of Total adhesion (AH03) and Non-revenue water (AH04) in both systems. The extensive irrigated area outside the equipped area highlights the need to incorporate areas with non-beneficiaries in these CISs. Moreover, as suggested in previous studies (Zema et al., 2018), the increase in service coverage is very important for the cost recovery of WUAs. Concerning non-revenue water, both systems show poor performance, even though the causes for this problem may be different.

In the gravity system, the high water losses due to discharges (*i.e.*, AH11 with poor performance), due to canal and pipe leakage (AH09 and AH10 with fair performance), associated with the low value of the Infrastructure value index (AH05 with fair performance) suggest insufficient network monitoring and control of discharges and an ageing network with poor infrastructural conditions. In the pressurised system, the low water losses due to pipe leakage (AH10 with good performance), the good efficiency of water resources use (AH14 with good performance) and the high value of the Infrastructure value index (AH05 with fair performance) indicate other problems of non-revenue water. Since the existing water metres are recent and respective errors reduced, the utility stated that the main issue might be pipe discharges for cleaning and unblocking the network (unbilled unmeasured authorised consumption).

Concerning infrastructural sustainability, network failures (AH07) represent the main problem of the pressurised CIS, with poor performance in 2018. Despite a recent network (AH05 =0.74), due to significant pipe rehabilitation carried out between 2014 and 2015, problems persist due to the poor infrastructural condition of the remaining network without rehabilitation, with high pipe failures. Relatively to the Infrastructure value index (AH05), although indicating a recent

**Table 11**
Comparative analysis between the gravity and the pressurised CISs for the reference year (2018).

| Criteria | PIs | Gravity | Pressurised |
|---|---|---|---|
| 1.1 Economic-financial sustainability | AH01 – Total costs coverage (%) | 🟡 111.9 | 🟢 103.2 |
| | AH02 – Services adhesion (%) | 🟢 70.1 | 🟢 78.5 |
| | AH03 – Total adhesion (%) | 🟡 108.3 | 🔴 147.1 |
| | AH04 – Non-revenue water (%) | 🔴 39.8 | 🔴 15.5 |
| 1.2 Infrastructural sustainability | AH05 – Infrastructure value index (-) | 🟡 0.28 | 🟡 0.74 |
| | AH06 – Pumping groups value index (-) | 🟢 0.50 | 🟢 0.59 |
| | AH07 – Network failures [no./(100km.year)] | 🟢 10.9 | 🔴 48.6 |
| | AH08 – Network rehabilitation (%/year) | 🟢 2.2 | 🟡 11.5 |
| | AH09 – Water losses due to canal leakage [l/(m$^2$.day)] | 🟡 22.2 | n.a. |
| | AH10 – Water losses due to pipe leakage [m$^3$/(km.day)] | 🟡 5.0 | 🟢 9.3 |
| 1.3 Operational and maintenance sustainability | AH11 – Water losses due to discharges (%) | 🔴 30.5 | n.a. |
| | AH12 – Failures in devices [no./(100km.year)] | n.d. | ⚫ n.d. |
| | AH13 – Failures in pumping groups [no./(pumping group.year)] | n.d. | ⚫ n.d. |
| 2.1 Water use efficiency | AH14 – Efficiency in water resources (%) | 🟡 66.9 | 🟢 96.8 |
| 2.2 Energy use efficiency | AH15 – Energy efficiency of pumping stations (%) | 🔴 46.8 | 🟡 66.9 |
| | AH16 – Energy in excess per authorised consumption (kWh/m$^3$) | 🟡 0.29 | 🟡 0.17 |
| 3.1 Service accessibility | AH17 – Own water capacity (%) | 🟢 2.5 | 🟢 1.5 |
| | AH18 – Water charges (%) | ⚫ 18.9 | ⚫ 20.0 |
| 3.2 Quality of service | AH19 – Service interruptions [no./(1000 irrigation intake to user.year)] | 🔴 34.5 | 🟢 0.0 |
| | AH20 – Irrigated area with on-demand service (%) | ⚫ 0.0 | ⚫ 100.0 |

Notes: n.a. – not applicable, n.d. – not available.

network, the fair performance highlights the importance of phased planning, avoiding future concentrated rehabilitation. The gravity system has an ageing network (AH05 =0.28, with fair performance) with the potential to improve water losses due to canal and pipe leakage (AH09, AH10 with fair performance), indicating possible infrastructural problems and the relevance of planning rehabilitation interventions in this system.

In terms of operational and maintenance sustainability, the water losses due to discharges in the gravity system are significant (AH11 with poor performance). There is a lack of data about failures in measurement, control and cleaning equipment, and pumping groups for both systems. The gravity system shows a fair performance relative to water use efficiency, whereas the pressurised system's performance is good. There is potential to improve energy efficiency in both systems (AH15, AH16 with fair or poor performance). In the pressurised system, with energy costs representing up to 50% of operational costs, measures to improve energy efficiency (*e.g.*, installation of variable speed devices, replacement of old pumping groups, pressure management, network sectorization), suggested in previous studies (Rodríguez Díaz et al., 2011) are particularly relevant. However, further analysis would be necessary to evaluate the adequacy of these measures and their impact on water and energy efficiency. In the gravity system, energy costs represented less than 10%. Regarding service accessibility, the performance was good in Own water capacity (AH17) and similar in Water charges (AH18) in both systems. Service interruptions (AH19) have poor performance in terms of the quality of service, and on-demand service is absent (AH20) in the gravity system, in opposition to the pressurised system.

Therefore, the comparative analysis carried out in this paper suggests that the proposed PAS applies to different CISs, with different contexts. These promising results constitute a first step for establishing a general PAS for CISs, similar to the urban water sector experience where a framework of PIs was established for application worldwide (Alegre et al., 2017) and adopted as a reference for regulation of the quality of service in different countries, namely in Portugal.

## 4. Conclusions

A novel PAS to improve water and energy efficiency in collective irrigation systems was proposed in this study. Aligned with the Water Users Association objectives, it integrates the water utility profile, the collective irrigation system profile, a set of criteria and respective performance indicators (PIs), with reference values applicable to gravity, pressurised or combined CISs. Based on previous studies, an approach for diagnosis and planning measures to improve water and energy efficiency using the PAS is also proposed.

The PAS application for diagnosis and decision support about measures to improve water and energy efficiency was firstly tested under a traditional gravity CIS. Secondly, the PAS was used to compare gravity and pressurised CISs.

The PAS application for global analysis indicated significant canal and pipe leakage possible due to an ageing network with poor infrastructural conditions for the gravity system. In the second place, considerable water losses due to canal and intermediate reservoir discharges indicate the potential to improve network monitoring and control. Thereby, with relevant real losses due to canal and pipe leakage and discharges, the efficiency of water resources has a significant potential to improve. Besides the economic impact of water losses, it was possible to assess the effect on energy efficiency. Poor efficiency in pumping stations and performance in real losses lead to high energy in excess supply to the system. Possible cross-cutting measures to increase water and energy efficiency were proposed from the global analysis: improving water metres, billing and customer data management, installing water in all irrigation users, inventory data about the network, failure events and rehabilitation interventions, and monitoring the main canal discharges. At the network area level, network area S2, with the potential to improve canal and pipe leakage and pump efficiency and responsible for 63% of water losses due to canal discharges in 2018, was identified with the highest priority for intervention. Based on the performance and economic analysis, the alternative combining rehabilitation of the main canal, replacing water metres, and optimising the hydraulic turbine will further improve the performance of network area S2.

Based on the PAS application, and the comparative analysis between the gravity and the pressurised CISs, both systems present poor performance in non-revenue water, impairing economic sustainability. In the gravity system, the most relevant component of non-revenue water corresponds to real losses, possible due to an ageing network with poor infrastructural conditions and insufficient monitoring and control of discharges. In the pressurised system, with a recent pipe network, the high number of network failures in the pressurised system indicates that some infrastructure problems persist despite the intense rehabilitation carried out by the WUA. With good pipe leakage performance and water resources efficiency, the most relevant component of non-revenue water is due to authorised unbilled consumption for network maintenance and cleaning due to water quality problems. Concerning energy efficiency, both systems show potential to improve energy efficiency in pumping stations and reduce energy in excess. In the pressurised system, measures to improve energy efficiency (*e.g.*, installation of variable speed devices, replacement of old pumping groups, pressure management) are particularly relevant since energy costs represent up to 50% of operational costs. In contrast, the gravity system represents less than 10%.

This paper demonstrated the adequacy of the proposed PAS for diagnosing CISs at the global and network area levels, decision-making to improve water and energy efficiency, and comparing different CIS, considering the different contexts. Nevertheless, future work should include the application of the PAS for diagnosis and decision support in an extensive set of CISs from other contexts (*e.g.*, region, climate), which will also allow testing proposed PIs and reference values.

## Declaration of Competing Interest

The authors declare no conflict of interest.

## Data availability

The data that has been used is confidential.

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