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RESEARCH ARTICLE

# Are digital twins improving urban-water systems efficiency and sustainable development goals?

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**ABSTRACT**
The use of these new interaction tool implies the improvement of the awareness of the whole system and it lies in improving the sustainability and efficiency of the water systems with the integration of measurements. The research proposed a methodology, which enables improvement in the accuracy and reliability of data and it increases the performance of water systems. This study proposes a pressure-reduction strategy and the implementation of pumps as turbines (PATs), applicable in Sta Cruz, Madeira water system. The use of the developed digital twin model assures a decrease of 3.3 $hm^3$ in water-demand volume, increasing renewable generation by micro-hydropower up to 1.2 GWh. These actions would result in savings above 1.5 M€, decreasing around 530 tons of $CO_2$ emissions each year. The consideration of these values implies the improvement of different indicators, which allows the evaluation of different targets linked to sustainable development goals (SDGs).

A digital twin is a tool, which enables a real-time simulation of the water systems and therefore, the water managers can make a decision in the management of the water system over time. The use of these new interaction tool implies the improvement of the awareness of the whole system and it lies in improving the sustainability and efficiency of the water systems with the integration of measurements. The research proposed a methodology to integrate GIS and water models, being the main goal the integration of social, economic, environmental and technical issues. This integration enables improvement in the accuracy and reliability of data and it increases the performance of water systems. This study proposes a pressure-reduction strategy and the implementation of pumps as turbines (PATs), applicable in Sta Cruz, Madeira water system. The use of the developed digital twin model assures a decrease of 3.3 $hm^3$ in water-demand volume, increasing renewable generation by micro-hydropower up to 1.2 GWh. These actions would result in savings above 1.5 M€, decreasing around 530 tons of $CO_2$ emissions each year. The consideration of these values implies the improvement of different indicators, which allows the evaluation of different targets linked to sustainable development goals (SDGs).

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Digital twin; leakage control; micro-hydro production; pump as turbines (PATs); urban-water systems; sustainable development goals (SDGs); water systems efficiency

## 1 Introduction

Water losses in water supply and distribution systems, induced mainly by the excess of pressure and a poorly integrated network management, place an immense economic burden on infrastructure grants, as well as the sustainability of water resources, particularly in the context of climate change (Pahl-Wostl 2007; Covelli et al. 2016). Increasing the efficiency of water provision by optimizing and rehabilitating existing infrastructures, alternating flow patterns in water networks and control devices, and creating control tools to improve the system behavior and to avoid water and energy wastage, it is an essential measure to be implemented. Therefore, water losses and the associated water–energy nexus should be mitigated to achieve social, economic, and environmental sustainability (Ringler, Bhaduri, and Lawford 2013; Bhaduri et al. 2015). If effective measures are not implemented, the water supply will be insufficient for essential needs, and energy costs will become prohibitive.

A digital-twin hydraulic model can be created, as a crucial and useful management tool that enables the understanding the correlation between different system variables, such as the evolution of pressure patterns, the performance of operating devices, the change of flow velocities and direction, and headlosses occurring in real-time, depending on the operating conditions that change over extended periods. The more information fed into the model, which requires ‘big data’ management, the more results, predictions, and analyses of performance can be implemented.

A sustainable development requires new actions to be considered in different social frameworks (Ruggerio 2021) that are important to the water cycle (Yang, Yang, and Xia 2021). The scarcity of water resources and the increasing of economic and environmental costs of non-renewable energies have initiated a search for novel alternatives (Askari Fard, Hashemy Shahdany, and Javadi 2021). Some of these alternatives focus on using

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renewable systems such as photovoltaic panels or wind turbines to meet the energy demand.

The use of these new tools should be considered since the energy demand will nearly double globally, with water and food demand predicted for 2050 (Karan et al. 2018). The analysis of sustainability could be considered using sustainability indexes, which consider different iteration and relation between water, energy and food nexus (Karan and Asadi 2018). In this line, the improvement in the data-driven methodologies is able to generate inputs relatively cheaply and easily. The advances in analytics, sensing, transmission, computing and data management are crucial in the upgrading of the urban water systems (Eggimann et al. 2017). Ramos et al. (2020) developed a deep description of different equipments, advices and tools used by water managers in the development of smart water systems, which could help to improve the global efficiency of the water sector. Several authors introduced different techniques to improve the data driven management of water systems, considering different point of views (resources availability, service fails, bad water quality, pressure drops, among others). Xiang et al. (2021) proposed a new adaptive intelligent dynamic water resources planning to improve water efficiency by transforming information into a learner process, improving decision-making based on data-driven by combining numeric AI tools and human intellectual skills. Wu and Liu (2017) developed a deep review of data-driven approaches to improve the knowledge of fails in urban water systems. Wu, Wang, and Seidu (2020) presented an adaptive learning rate BP neural network to determine the quality in urban water system, improving the data driven and management. Manny (2022) proposed an analysis data-driven and integrated urban water management to reduce surface water pollution in light of climate change and urbanization impacts in water systems. A spatio-temporal multi-task and multi-view learning was proposed by Liu et al. (2022). All these improvements are linked to applying new technological techniques (Ramos et al. 2020). Then digital decision-making in a water system is based on a digital water twin. It combines knowledge of water infrastructure using information, communication, big data, and social and economic aspects (Pesantez et al. 2022).

Using a digital twin as a digital mirror of a real infrastructure allows to improve decision-making. These decisions can be based on two issues: firstly, the analysis of leakages implies to know the all system characteristics and the water system leakages history (Lu et al. 2020). The analysis of leakages has implications for the water-energy nexus, and the control of leakage, which directly reduces the energy consumption in the network, enabling the consciousness of sustainable development goal targets (SDGs) (Ávila et al. 2021); secondly, using digital twins provides a better understanding of the influence of new facility development and enables the recovery of energy or the improvement of the water system management (Bonilla et al. 2022).

Water losses in water-distribution systems are directly reflected in economic losses because all associated treatment and transport processes must be conducted. There is a waste of natural resources. Thus, by decreasing the volume of water loss, the pumping energy and the treatment and transport will decrease significantly, improving the whole system efficiency. The analysis of different variables associated with the water and energy consumption, is crucial to define strategies and algorithms to reduce the water and energy use, as well as the integration of renewable systems (Asadi et al. 2020). This complex relationship between them, as well as the social pressure increase, cause the establishment of new approaches to improve the sustainability in water systems (Zare et al. 2020).

Energy recovery using micro-hydro solutions can be a valuable strategy for meeting low-cost and long-term–renewable-energy production needs; these solutions include using environmentally sensitive natural or artificial waterfalls integrated into water systems. In developing countries, unconventional solutions are at the forefront of achieving energy self-sufficiency (Ramos and Borga 1999). Reducing water leakage should be considered a new challenge when using water–energy nexus recovery systems (Giustolisi, Savic, and Kapelan 2008). Water-distribution networks are low-energy efficiency systems because they require high energy levels to satisfy consumption in terms of available pressure, increasing the water leakage volume, the energy consumed by the system, and decreasing the sustainability indices (Morani et al. 2020).

Many studies have analyzed the use of micro-hydropower systems in water systems using a pump as a turbine (PAT) (Zhou et al. 2022). The estimation of their main operational curves (Kandi et al. 2021), different regulation strategies (Pugliese and Giugni 2022), and efficiency improvements have been demonstrated in various studies as both advantages and disadvantages (Satish et al. 2021). However, integrating these recovery systems in the digital water twin is not common in published research (Liu et al. 2021); this study proposes the development of a procedure in which the digital water model incorporates PAT systems to improve water system management indicators.

The excess pressure in water-supply systems (WSS) can be reduced and controlled through specific devices, such as the installation of pressure-reducing valves (PRVs) and flow control valves (FCVs) in strategic locations, and by replacing critical pipe sections to promote good hydraulic system behavior and management (Morani et al. 2020; Ramos et al. 2020). PRVs are typically installed in these systems to control the pressure or the hydraulic head owing to the energy dissipation. These devices can operate in three ways: by closing when the downstream pressure is higher than the value configured in the valve, increasing the headloss until it reaches the established value – if the downstream pressure is lower than the reference value, the valve opens, reducing the headloss – and by closing when the downstream pressure is higher than the upstream pressure, which operates as a check valve by imposing the directional flow change in the water network. Due to the reduced investment made over the years by the concerned water-management entities, water networks operate beyond their useful life and cannot supply the consumption demand resulting from the population growth. This results in supply failures and excessive water losses in systems, which are demonstrated by leakage levels, pipeline ruptures, and reservoir overflows.

Water system efficiencies have become a huge concern for management entities, and it should be seen as an opportunity to improve the management of the entire systems (Gleick 2000; Ramos et al. 2021). As a novelty, this study presents a new methodology with practical implementation considerations in line with technical, economic, social, and environmental concerns. The proposed methodology includes the environmental analysis in terms of SDGs targets, as well as the symbiosis between the energy flow available in the water system and micro-hydropower implementation in the improvement of the water-energy nexus, including a feasibility balance with real data applied to a case study. The remaining parts of the paper is organized as follows: Section 2 presents the Methodology, Section 3 states the main results and discusses their relevance in light of similar literature and the economic and environmental benefits of the tested methodology applied in this study. Finally, the main conclusions drawn from this study are summarized in Section 4.

## 2 Methodology

A digital twin uses different technologies to create an interface between a virtual model and a real physical object to send and receive information in real-time (Jiang, Guo, and Wang 2021). The following key technologies must be considered to understand better a digital twin's architecture and infrastructure for a water system:

- Modelling: Physical and virtual models describe the key features of a water network.

- Connection: Physical and virtual systems must be constantly connected; moreover, data transmission, conversion, storage, and protection must be performed.

- Data mining: Data received must be processed, cleaned, and filtered using data analysis techniques and artificial intelligence (AI) to avoid uncertainties or outside correlation values.

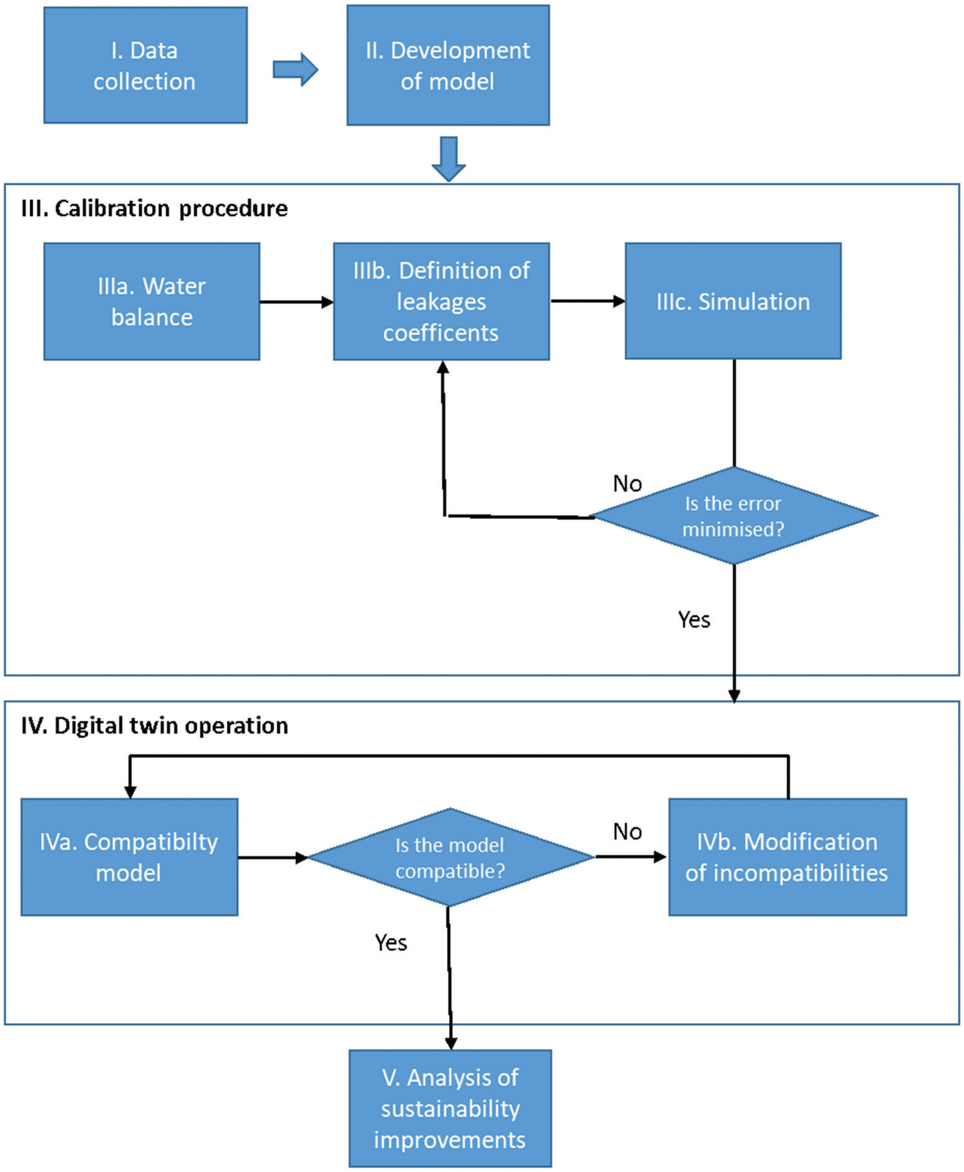

**Figure 1.** Proposed Methodology.

- Interaction and service: Once a simulation is validated, the digital twin must be able to suggest, optimize, and adapt the system processes to induce external changes.

Hence, a digital twin is a platform with a set of models that contains different elements depending on the sector or industry. In the water sector, the digital twin should include a water-process model forced to work with suitable boundary conditions, an asset model related to GIS describing physical assets and infrastructure characteristics, topographic representation used to setup and configure the water process, and performance models to generate the metrics required to make decisions, which are usually connected to the enterprise resource planning (ERP) software that enables automated scheduling repairs. The different models must be linked and updated in real-time to represent a complete digital-twin model (Liu et al. 2021).

Recently, the Internet of Things (IoT), information and communication technology (ICT) have enabled the facile development of a digital-twin model, which requires the appropriate filtration of information and a big data platform as the input/output of the digital-twin model. The proposed optimization procedure is divided into five stages, each containing different steps. The Methodology is based on routines specifically developed and presented in this study. The procedure is based on the programming in the Epanet toolkit to develop the self-calculation of different iterative procedures. Figure 1 illustrates the steps involved in this Methodology.

Step I focuses on data collection in the study area. Obtaining topographic modeling data using GIS tools is essential; these data include flow-recorded data, volume data, and consumption patterns. With all data acquired, the model is developed in Step II by Epanet (Bonilla et al. 2022). The model must be provided alongside the network physical data and the characteristics of the building (i.e. top elevation, number of floors, and eventual pump existence) to understand the pressure and the water-supply management. Once the model is completed, a calibration procedure is developed (Step III). The technique includes an iterative procedure in which the emitter values are changed to reach the water balance according to the billed and unbilled water and uncontrolled volume of water in the water network (Step IIIa.)

Leakages are included to simulate both the real and apparent losses. The leakages enable the discretization of the ratio, both real and apparent, using the following equations:

$$_{AL} = \frac{V_{AL}}{V_L} \tag{1}$$

$$_{RL} = \frac{V_{RL}}{V_L} \tag{2}$$

where $_{AL}$ is the ratio between the apparent and total leakages, $V_{AL}$ is the total volume of the apparent losses in m$^3$, $_{RL}$ is the ratio between the real and total leakages, and $V_{RL}$ is the total volume of the real losses in m$^3$. The apparent losses are uncontrolled leakages in water systems that cannot be measured (Ahmadzadeh et al. 2022).

Both consumption flow and apparent losses are included in the nodes of the model (Step IIIb). The values of the consumption nodes are considered as the distribution of the population. The population is considered by Thiessen polygons, which overlap with the BGRI polygons and enable the population value to be assigned to each consumption point. The discharged flow is defined as follows (Hamlehdar et al. 2022):

$$q_j = K_f \; p_j^{\gamma} \tag{3}$$

$$K_f = c \times \sum_{J=1}^{M} 0.5 \;\; \times L_{ij} \tag{4}$$

where $q_j$ is the flow discharged from each node in L/s; $K_f$ is the discharge coefficient; $p$ is the pressure in m w.c.; $\gamma$ *is* the pressure exponent that depends on the type of material used in the network (Ávila et al. 2022); $c$ is the discharge coefficient; $L_{ij}$ is the length of the pipe between the junctions in meters; *and i, j*, and $M$ are the nodes and number of pipes connected to node $j$.

Equations (1) and (2) enable the distribution of real losses at different consumption nodes. It is possible to use an iterative procedure (Step IIIb), which minimizes the simulated values (Step IIIc) compared to the measured values, using a programming tool from the Epanet toolkit. The initial value of the discharge coefficient ($K_f$) is $10^{-5}$ according to Adedeji et al. (2017), Ávila et al. (2022). The consumption demand and apparent losses are defined as uniform values. In contrast, the real losses are readjusted by the emitter coefficients. The iterative procedure is completed when the difference between the measured and simulated losses is less than the minimum defined value.

When the model is calibrated by completing Step III, the procedure continues until Step IV. This step is the development of the digital-twin operation, in which the model is connected to the rest of the variables that integrate the digital twin. Step IV includes the compatibility analysis of the model according to real data (Step IVa) and the development of the modification of incompatibilities (Step IVb), should they arise in the digital twin. When the model is accurate, the use of the proposal and water balance enables the development of an analysis to characterize sustainable improvements (Step V).

Different analyses have focused on energy, economic, and environmental issues. Energy balance considers the water balance and the possibility of using micro-hydropower systems. Knowledge of water balance considers the billed and unbilled values of the water company. This proposal includes active leakage control (ALC). It focuses on locating and repairing the broken points of a water system (i.e. pipes and nodes). It is a preventive action to avoid leakage; therefore, the water manager reduces the loss volume in the water-distribution system. The ALC is developed using district-metered areas (DMA). This enables the identification of areas with a higher volume of water loss and the prioritization of pipes for repair. The meshed system enables easy monitoring and control, and its development is based on Galdiero et al. (2015). Energy improvement is based on the location of the recovery system in the water system. As micro-hydropower reduces pressure in the system, energy recovery and reduction of leakages also occur.

The energy recovery is analyzed using PATs. The model considers energy recovery using the following equation:

Table 1. Targets linked to the improvement of SDGs.

| ID | Indicator | Target | Linked SDG | Sustainability Area | Water Cycle | Indicator Type |
|---|---|---|---|---|---|---|
| 1 | Quality tests conducted | 6.1; 6.3 | 3, 6, 11 | Social management | Water distribution and treatment | Health and hygiene; socio-cultural |
| 2 | Water quality (anomalous tests) | 6.1 | 2, 3, 4, 6, 11 | | | |
| 3 | Service interruptions | 6.1 | 2, 3, 6, 7, 9, 11 | | Water distribution | Health and hygiene, socio-cultural, and feasibility |
| 4 | Service continuity | 6.1 | 2, 3, 6, 7, 9, 11 | | | |
| 5 | Public resources | 6.1; 6.2 | 1, 3, 4, 6, 11 | | | |
| 6 | Regenerated water | 6.3; 6.4 | 2, 6, 11, 12 | Environmental management | Reused water | Environmental and feasibility |
| 7 | Inefficiencies in the use of water resources | 6.4 | 6, 11, 12 | | Caption | Environmental |
| 8 | Availability of water resources | 6.4 | 6 | | | |
| 9 | Energy recovery | 6.4 | 2, 6, 7, 8, 9, 11, 12 | Technical and environmental management | Reused water | Environmental and feasibility |
| 10 | Energy efficiency | 6.4 | 2, 6, 11 | Technical management | Water distribution | Feasibility |
| 11 | Energy consumption | 6.4 | 6 | Technical and economic management | Water distribution and treatment | Economic and viability |
| 12 | Water use | 6.4; 6.6 | 6 | Social and environmental management | Caption | Environmental and socio-cultural |
| 13 | Own facilities by people | 6.2 | 6 | Social management | Wastewater treatment and water service | Socio-cultural |
| 14 | Water licenses for captation | 6.4 | 6, 9, 12 | Environmental management | Caption | Environmental |
| 15 | Structural leakage ratio | 6.4 | 6 | Technical management | Water distribution | Feasibility |
| 16 | Leakage control | 6.4 | 6 | | | |
| 17 | Water losses | 6.4 | 2, 6, 8,12 | | | |
| 18 | Water resources from non-conventional origins | 6.4 | 2, 6, 9 | Environmental management | Caption and reused water | Environmental |
| 19 | Biodiversity of water resources | 6.6 | 6, 11, 14, 15 | Environmental management | Caption | Environmental |
| 20 | Renewable energy generated by the water system | 6.4 | 2, 6, 7, 8, 9, 11, 12 | Technical and environmental management | Caption, wastewater treatment, water distribution, water service, reused water, and treatment | Environmental and feasibility |
| 21 | Greenhouse emissions reduction | 6.6 | 3, 6, 7, 9, 11, 12, 13 | Environmental management | Wastewater treatment, water distribution, water service, and treatment | Environmental |
| 22 | Residual chlorine in the water | 6.1 | 3, 4, 6 | Social management | Water distribution and treatment | Health and hygiene; socio-cultural |
| 23 | Restriction of water service | 6.1 | 1, 3, 6, 11 | | Water distribution | Health and hygiene; socio-cultural |
| 24 | Average distance between taps | 6.1 | 3, 5, 6 | | | |
| 25 | Supply service coverage | 6.1 | 1, 2, 3, 4, 6, 9, 11 | | | |
| 26 | The resident population connected to the grid | 6.2 | 1, 2, 3, 4, 6, 11 | | Water service | Health and hygiene; socio-cultural |
| 27 | The resident population served by the WWTP | 6.2 | 3, 4, 6 | Social and environmental management | Wastewater treatment and water service | Health and hygiene; socio-cultural |
| 28 | The resident population served by on-site systems | 6.2 | 1, 3, 4, 6 | | Water service | Health and Hygiene; socio-cultural |
| 29 | Unserved resident population | 6.2 | 1, 3, 4, 6, 11 | Social management | Water service | Health and hygiene; socio-cultural |
| 30 | Interruption of wastewater collection and transport service | 6.2 | 2, 3, 4, 6, 11 | | | |
| 31 | Wastewater treated in the WWTP (quantity) | 6.3 | 3, 6, 11 | Social and technical management | Wastewater treatment | Socio-cultural and feasibility |
| 32 | Compliance of the WWTP with discharge requirements | 6.3 | 2, 3, 6, 11, 14, 15 | Social, technical, and environmental management | | Environmental, socio-cultural, and feasibility |
| 33 | Wastewater quality tests conducted | 6.3; 6.6 | 2, 3, 6, 11, 14 | | | |
| 34 | Water quality from raw sources | 6.3; 6.6 | 3, 6, 11, 14, 15 | Environmental management | Caption | Environmental |
| 35 | N, P, and BOD loads received by water sources | 6.3 | 3, 6, 11, 13,14, 15 | | Wastewater treatment | Environmental and feasibility |
| 36 | Cd, Hg, Cu, Pb | 6.3 | 3, 6, 11, 13, 14, 15 | | | Environmental |

(*Continued*)

Table 1. (Continued).

| ID | Indicator | Target | Linked SDG | Sustainability Area | Water Cycle | Indicator Type |
|---|---|---|---|---|---|---|
| 37 | Sludge production | 6.3 | 3, 6, 11 | Technical management | Wastewater treatment | Feasibility |
| 38 | Sludge use | 6.3; 6.4 | 6, 9, 11, 12 | | | Environmental and feasibility |
| 39 | Water discharge to the river | 6.3 | 3, 6, 11,14, 15 | | | |
| 40 | N and P reuse | 6.4 | 2, 6, 11, 12, 13 | Environmental management | Wastewater treatment and reused water | Environmental |
| 41 | Bodies of water affected by discharges | 6.6 | 6, 11, 13, 14, 15 | Technical and environmental management | Wastewater treatment | Environmental and feasibility |

$$E = \gamma Q H \eta \tag{5}$$

where $E$ is the recovered energy in kW, $\gamma$ is the specific weight of the fluid in $\frac{kN}{m^3}$, $Q$ is the flow in $m^3/s$, $H$ is the head recovered by the PAT in m, and $\eta$ is the global efficiency of the machine.

The viability analysis includes economic indicators that consider all costs and benefits. The feasibility was analyzed by considering the net present value (NPV), benefit/cost ratio (B/C), internal rate of return (IRR), and payback period (T) (Abdelhady 2021).

The NPV creates a balance between benefits and costs. This is defined as follows:

$$NPV = R - C - O - P \tag{6}$$

where R is the revenue in €, C represents the capital costs in €, O represents the operational costs in €, and P is the repositioning cost in €.

B/C relates the present value of benefits to total costs using the following equation:

$$B/C = \frac{R - O}{C + P} \tag{7}$$

The IRR is the discount rate that makes the NPV equal to zero. A project with a higher IRR value is better if the analysis shows a high value. Finally, T represents the number of years that enable the recovery of the initial investment (the payback period). The different targets used to measure the evolution of improvement in the SDGs are listed in Table 1.

The proposed management includes environmental improvement, considering the reduction of $CO_2$ and its relationship with the achievement of SDGs. Different targets are linked to improve and contribute to measuring these targets' evolution over time inside water systems. This table shows forty-one indicators that can define the environmental operation of the water-distribution system over time.

## 3 Results and discussion

### 3.1 Brief description of the case study

The case study analyzed is Santa Cruz, located in Madeira Island. Large difference topographic elevations throughout the network characterize the region. Figure 2 shows the Santa Cruz morphology based on the altimetry provided by the municipality of Santa Cruz (MSC). In an area of 81 km$^2$, the altitude varies from 0 m to over 1000 m. According to PORDATA, Santa Cruz is the second municipality with more inhabitants in Madeira Island. Located in the Atlantic Ocean, this island is characterized by its significant variable altimetry, and the consequent high slopes of the water distribution network. Figure 2(a) presents Santa Cruz morphology considering the altimetry provided. Figure 2(b) represents the water supply system, developing from a set of pipelines, reservoirs and sources or springs. The municipality has residential and touristic occupation being supplied by 42 reservoirs, mainly by gravity supply. The water distribution systems are aged, with 437 km of pipes, mainly HDPE (46%) and PVC (27%), and 91% of pipe's diameter is lower than DN140.

### 3.2 Water–energy balance

The proposed methodology was applied in this case study. It searches the best solution in the management to reduce the non-consumed water by the population. The establishment of active leakages control by the introduction of DMAs enables the improvement both water and energy balance. Besides, the procedure analyzed the implementation of control setup and micro-hydropower systems to improve the pressure management. The new control devices (flow control valves, pressure sensors and micro-hydro systems) reach the upgrading of the efficiency of the SCS, avoiding high-pressure variations and pipe breaks. This procedure helps managers to make decisions on the prioritization of system control and maintenance and refurbishment investments.

Table 2 shows the annual volume and unbilled/acquired ratio. This shows that more than 7 hm$^3$ have not been billed recently and represents 74% of the total acquired volume. The billed volume was uniform throughout the study period. Thus, the apparent losses did not change over time. The unbilled volume (UV) increased; therefore, the total loss also increased. If the unbilled authorized consumption (UAC) of 7 Mm$^3$/year is not billed, it represents 74% of the total billings. The billed volume has remained stable over the years, which indicates that the apparent losses should not vary substantially and may be due to errors in the measurement devices. The evolution of the UV indicates that the total losses increase significantly. The UAC component, corresponding to MSC expenses and intentionally unbilled water, may correspond to a significant portion of the UV. In conclusion, the portion with the greatest weighting increases the unbilled water volume. It contributes to real losses, which is unacceptable.

Santa Cruz WDS sub-subsystems are considered, creating new sub-subsystems and network sectorization by creating

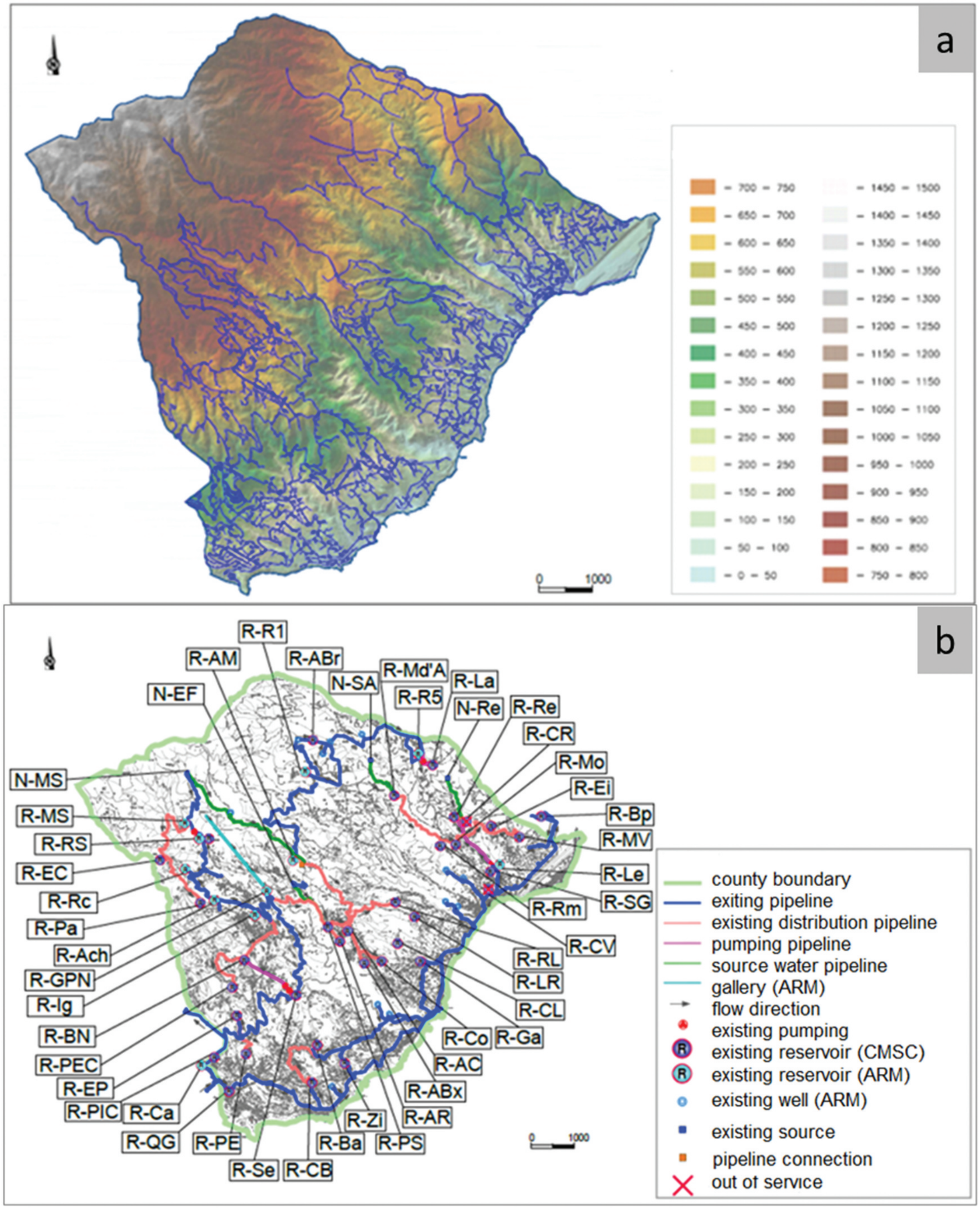

**Figure 2.** Case study—Santa Cruz System: a) morphology and b) water supply.

**Table 2.** Annual volumes in SCS.

| Year | Acquired Annual Volume | Billed Annual Volume | Unbilled Annual Volume | Unbilled/Acquired |
|---|---|---|---|---|
| (-) | (m$^3$) | (m$^3$) | (m$^3$) | (%) |
| 2010 | 7,211,432 | 2,810,567 | 4,400,865 | 61.0 |
| 2011 | 7,434,454 | 2,705,859 | 4,728,595 | 63.6 |
| 2012 | 7,688,409 | 2,656,678 | 5,031,731 | 65.4 |
| 2013 | 8,094,031 | 2,370,288 | 5,723,743 | 70.7 |
| 2014 | 8,011,062 | 2,406,423 | 5,604,639 | 70.0 |
| 2015 | 8,654,570 | 2,429,246 | 6,225,325 | 71.9 |
| 2016 | 8,774,399 | 2,481,348 | 6,293,051 | 71.7 |
| 2017 | 9,065,322 | 2,540,274 | 6,525,048 | 72.0 |
| 2018 | 9,233,381 | 2,444,474 | 6,788,907 | 73.5 |
| 2019 | 9,574,240 | 2,511,736 | 7,062,504 | 73.8 |

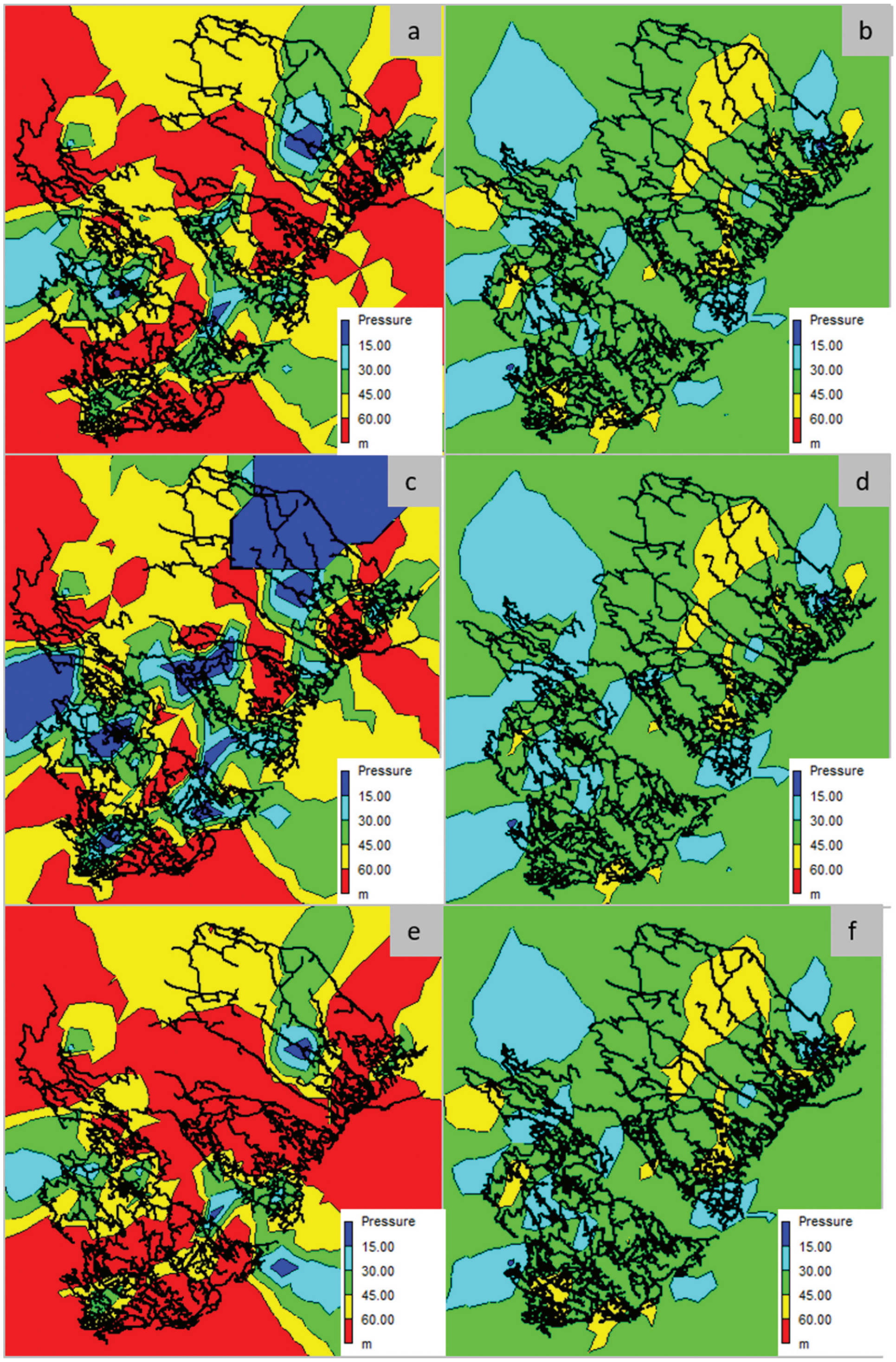

**Figure 3.** SCS simulation. a) the average pressure in the current scenario; b) the average pressure in the future scenario; c) maximum pressure in the current scenario; d) maximum pressure in the future scenario; e) minimum pressure in the current scenario; f) minimum pressure in the future scenario.

**Table 3.** Annual volumes in the Municipality of Santa Cruz (MSC).

| Scenario | Total Volume (TV) ($m^3$) | Billed Volume (BV) ($m^3$) | Unbilled Volume (UV) ($m^3$) | UV/TV |
|---|---|---|---|---|
| Existing scenario | 10,123,027 | 2,558,487 | 7,564,540 | 74.7% |
| Proposed solution | 6,778,348 | 2,558,487 | 4,219,861 | 62.3%<br>41.7% (to the Initial Volume of the existing situation) |

**Table 4.** Water and energy savings in SCS.

| Description | Total Values (TV) | Billed Values (BV) | Unbilled Values (UV) | UV/TV (%) |
|---|---|---|---|---|
| Proposed solution – volume ($m^3$) | 6,778,348 | 2,558,487 | 4,219,861 | 62.30% |
| Difference volume ($m^3$) | 3,344,679 | - | 3,344,679 | - |
| Water savings (€) | 1,423,065 | 435,045 | 988,018 | - |
| Energy savings (kWh/year) | 1,204,084 | 0 | 1,204,084 | - |
| Energy savings (€) | 118,000.28 | 0.00 | 118,000.28 | - |

**Table 5.** Flow control valve (FCV) calibration in SCS and investigation of the best pumps-as-turbines (PATs) locations.

| ID | DN (mm) | Q (l/s) | ΔH (m) | Q . ΔH (l.m/s) |
|---|---|---|---|---|
| QG | 150 | 23.0 | 43.47 | 999.81 |
| CB | 80 | 7.5 | 59.1 | 444.43 |
| PE | 80 | 6.0 | 50.29 | 301.74 |
| MV | 80 | 7.0 | 37.84 | 264.88 |
| RL | 80 | 7.0 | 27.75 | 194.25 |
| AB1 | 65 | 4.0 | 45.76 | 183.04 |
| RS | 80 | 3.0 | 50.11 | 150.33 |
| PC | 65 | 2.0 | 42.71 | 85.42 |
| CO | 80 | 2.5 | 29.22 | 73.05 |
| RO | 65 | 1.5 | 46.69 | 70.04 |
| MOI | 80 | 2.0 | 27.56 | 55.12 |
| EI | 65 | 1.5 | 29.66 | 44.49 |

DMAs. Figure 3 shows the pressure values in the average, peak, and static scenarios for current and future proposals.

The comparison between the current and proposed scenarios shows a reduction of the pressure in the system; therefore, advantages are achieved when the pressure and energy terms are considered. Table 3 compares the volumes verified in the existing situation and when the proposed solution is applicable.

The implementation of the proposed solutions (Figure 3 and Table 3) allows the reduction of the pressure and UV. These measurements enable a 44% reduction in UV above the new total volume and approximately 60% relative to the existing scenario. This enables a reduction of 3,344,679 $m^3$ in the total volume required. The model includes the application of ALC measures and controlling all the system volumes. Considering the data in Table 3 and an average annual energy consumption of 0.36 $kWh/m^3$ of water entering the system, an estimated energy saving of 1,204,084 kWh per year can be achieved, resulting in the proposed solution of the MSC WDS.

The model was calibrated using the database related to pressure and flow measurements. It enables the definition of an emitter coefficient to simulate the leakages as well as the definition of consumption patterns in the demand nodes. Once the model was verified, the digital twin was used introducing the different assumptions in terms of pressure reduction and micro-hydro solution.

The development of digital twins enables the determination of the value of losses and the resulting costs and savings. In further calculations, the average values for buying and selling water can be considered as 0.2954 €/$m^3$ and 0.8502 €/$m^3$, respectively, according to the data provided by the MSC. This estimate of economic savings is due to the reduction in water losses. The consumption volumes do not change and the apparent losses represent 20% of the consumption values. In addition, the buying cost to real water-loss volumes and average selling price to apparent losses were applied. The resulting savings for the MSC are listed in Table 4.

Therefore, energy savings greater than 1200 MWh are realized when this digital model is applied. It represents an annual value of 118,000 € exclusively from water that would not have to be wasted in the SC system.

Table 5 lists the FCVs considered in the proposed solution, which were located upstream of the existing tanks to regulate the entering flows. This change in SC system is designed to control the inlet flows and regulate the pressures in those locations. The following calculation aims to determine the viability of turbine implementation in the two pilot locations, because the cost associated with the additional elements is a fraction of the overall costs. The resulting energy could be sold or used, resulting in additional cost savings.

The analysis considers a constant flow over time. This enables the nominal operation of the recovery systems simulated by the model. The case study analyzed is in a QG tank with higher hydraulic power. According to the available head and flow, the chosen PAT is Etanorm 65–250, with its characteristic curve shown in Figure 4(a) (head curve) and 4b (efficiency curve).

In the study of QG behavior through inflows and outflows, an iterative process is performed to confirm the number of daily hours that the PAT would have to work to ensure no overflow or lack of available water volume occurs, considering that the working period of the turbomachine must not experience interruptions. The iterative procedure establishes that the PAT works for approximately 16 h daily, operating an annual volume of 496,437 $m^3$. It is installed with a power of 5.2 kW and annual recovered energy above 31 MWh. The use of these systems implies a reduction of more than 18 tons of $CO_2$, according to the relationship between generated power and $CO_2$ emissions (Han et al. 2022).

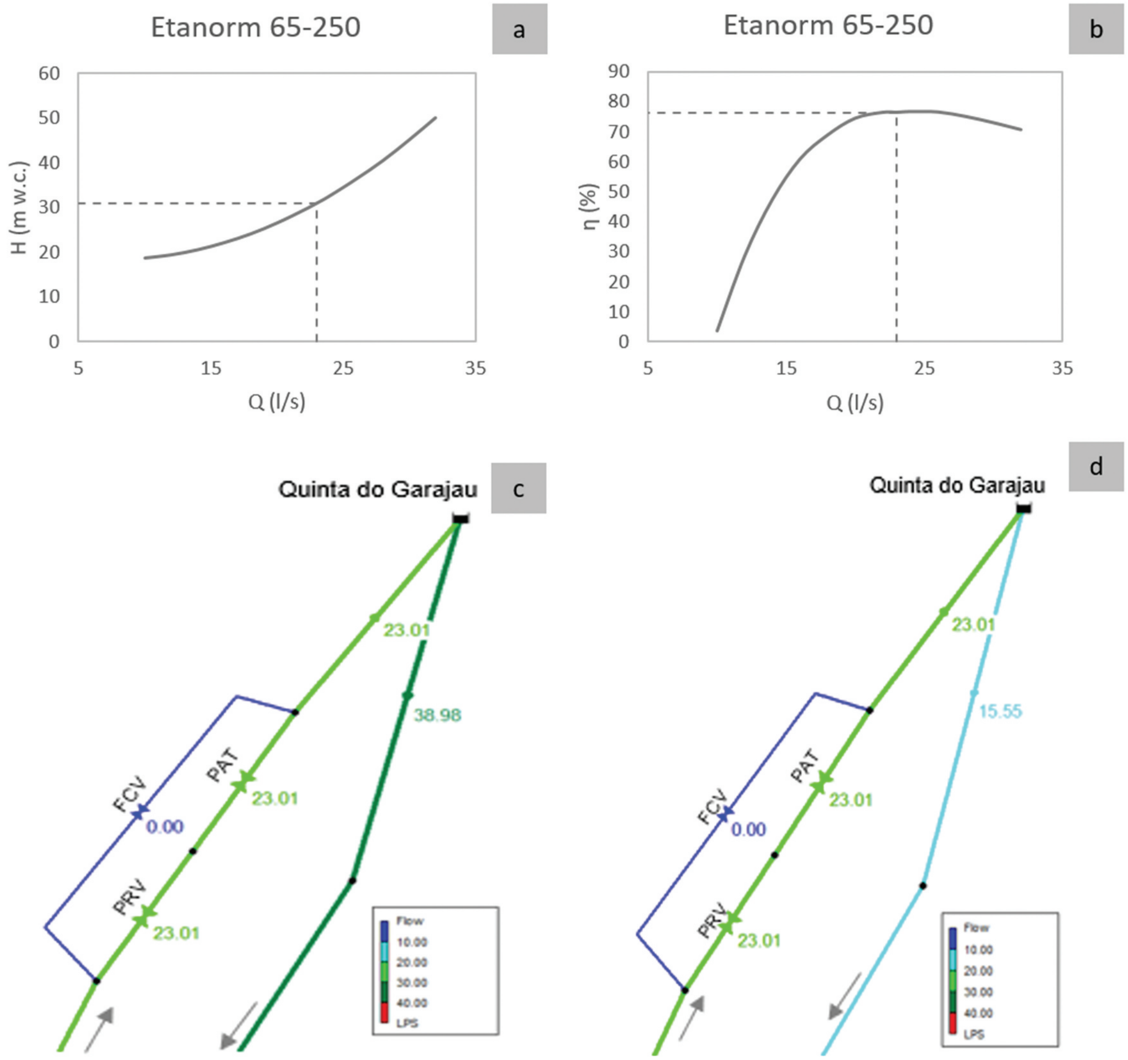

**Figure 4.** The PAT characteristics and performance: a) PAT head curve, b) PAT efficiency curve, c) detail model for a peak-demand hour in QG, and d) detail model for average value scenario in QG.

**Table 6.** Feasibility results.

| | | | | |
|---|---|---|---|---|
| Initial investment cost (€) | | | 15,000.00 | |
| Annual maintenance cost (€) | | | 300.00 | |
| Annual revenue (€/year) | | | 3050.74 | |
| Discount rate | 6% | 8% | 10% | 17.62% |
| NPV (€) | 16,550.8 | 12,007.2 | 8418.6 | 0.0 |
| B/C (-) | 7.5 | 9.1 | 11.2 | 26.3 |
| Payback period (years) | 7 | 8 | 9 | IRR |

## 3.3 *Viability and environmental analysis*

The viability of the recovery systems is analyzed by considering only the recovered energy as a source of income, meaning that no costs or benefits from the water losses and savings previously mentioned will be considered. For this economic analysis, 20 years is considered as the lifespan of the mechanical equipment of the PAT. The installation cost is 2% of the annual maintenance cost (Punys and Jurevičius 2022), and three different discount rates of 6%, 8%, and 10% are used. The energy value is considered 0,098 €/kWh from the ERSE database, as the hydraulic model development is based on the Santa Cruz 2018 water balance values. Table 6 presents the feasibility analysis results.

According to the presented results, an average of seven to nine years is required for the payback of the hydropower technology, considering its installation independent of the remaining changes in the Santa Cruz water network. This represents a worst-case scenario because in the present year, from 2022 onwards, due to the increasing energy costs it would represent a higher value, resulting in a higher value of annual revenue and, consequently, a lower payback period.

In a last situation, the implementation of the present study synchronized with ALC measures could reach an investment return period of 5.5 years, corresponding to the 2,536,268 €/year saved and to more than 7 $Mm^3$ water saving every year. If energy savings are also considered, a value of 2,787,240 € would be saved annually, reducing the payback period to less than five years and avoiding more than 500 tons of $CO_2$ emissions.

## 4 Conclusions

The development of a digital twin in the MSC system enabled to identify its weaknesses, locate and fix the hydraulic problems, solve the overall excessive pressure scenario, and prevent the lack of supply to some customers and avoid periodic ruptures occurring in the system. This research proposed a practical procedure for water managers to replicate their water systems developing a DT model, enabling the evolution of performance indicators and commensurate targets in the SDGs. This procedure identified forty-one indicators that can be applied.

In terms of water balance, after implementing the proposed solution, an annual saving of 3,344,679 $m^3$ would be realized, representing 1204 MWh in annual energy savings, representing an estimated economic reserves of more than 1.5 M€ and more than 530 tons/year of CO2 emissions. Furthermore, if ALC is performed in subsequent years until 15% is achieved – the theoretical optimum proposed level through the PEAASAR II Portuguese target – it would represent an estimated annual saving of more than 2.7 M€ and 7 $Mm^3$ of water.

In addition, the investigated source of micro-renewable energy upstream of a reservoir bears an insignificant cost when included in the overall network rehabilitation costs, achieving a significant amount of energy recovery and saving of 3050 €/year and 18 tons/year of $CO_2$ emissions.

The research proposes a conventional with AI tools and improvement methods in a digital twin model. The main goal allows the leakage reduction, the system efficiency increases and therefore, the improvement of the water balance and profits of the company. The strength of this research is focused in short-term requiring the development of tools that enable the measurement of different SDG targets through sustainable strategies. These strategies consider technical, social, and economic aspects to promote the incorporation of a weighted multi-criteria model. This DT enables water systems to adapt to climate change and increase their resilience. Under this research lines, the incorporation of different algorithms, to manage the data-driven in the water-energy management allows the evaluation of different SDGs targets over time.

## Abbreviations and symbols

| AL | Apparent Losses |
|---|---|
| ALC | Active Losses Control |
| AMI | Advanced Metered Infrastructures |
| B | Benefit |
| BGRI - Geographic Referenced Information Database | |
| BOD | Biochemical Oxygen Demand |
| BV | Billed values |
| C | Costs |
| CARL Current Annual Real Losses | |
| CMMS | Computerised Maintenance Management System |
| DMA | District Metered Area |
| DT | Digital Twin |
| ERSAR | Water and Wastewater Regulatory Entity |
| ERSE | Energetic Services Regulatory Entity |
| FCV | Flow Control Valve |
| GIS | Geographic Information Systems |
| IoT | Internet of things |
| ICT | Information and Communications Technologies |
| ILI | Infrastructure Leakage Index |
| IRR | Internal Rate of Return |
| MSC | Municipality of Santa Cruz |
| NPV | Net Present Value |
| PAT | Pump as Turbine |
| PEAASAR II | Portuguese Supply and Residual Water Strategic Plan |
| PI | Performance Indicators |
| PRV | Pressure Reducing Valve |
| RL | Real Losses |
| SCS | Santa Cruz Systems |
| SWG | Smart Water Grid |
| T | Payback Period |
| TV | Total values |
| UAC | Unbilled Authorized Consumption |
| UARL | Unavoidable Annual Real Losses |
| UV | Unbilled Values |
| WB | Water Balance |
| WDS | Water-Distribution System |
| WWTP | Wastewater Treatment Plant |

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