

# Zero discharge: An optimized strategy to improve the hydric deficit in the Mediterranean area by pumped hydro storage. Case study of Alicante, Spain

Modesto Pérez-Sánchez<sup>a,\*</sup>, Francisco-Javier Sánchez-Romero<sup>b</sup>, Francisco A. Zapata<sup>c</sup>,  
P. Amparo López-Jiménez<sup>a</sup>, Helena M. Ramos<sup>d</sup>

<sup>a</sup> Hydraulic and Environmental Engineering Department, Universitat Politècnica de València, Valencia 46022 Spain

<sup>b</sup> Rural and Agrifood Engineering Department, Universitat Politècnica de València, Valencia 46022 Spain

<sup>c</sup> Generalitat Valenciana, Valencia, Spain

<sup>d</sup> Civil Engineering Research and Innovation for Sustainability (CERIS), Instituto Superior Técnico, Department of Civil Engineering, Architecture and Environment, University of Lisbon, 1049-001 Lisbon, Portugal

## ARTICLE INFO

Handling Editor- Dr Z Xiying

### Keywords:

Wastewater reuse  
Water irrigation networks  
System sustainability  
Photovoltaic systems

## ABSTRACT

Alterations in annual temperature and precipitation patterns are imposing heightened strain on both urban and agricultural systems. The insufficiency of available water resources to satisfy the escalating demand necessitates a concerted effort to optimize alternative sources. In the context of agriculture, the utilization of treated water is currently executed on a sporadic basis. The elevated energy expenditures and the absence of regulatory frameworks in these systems contribute to a substantial portion of these resources being discharged into natural water bodies, or in the case of coastal municipalities, near the sea. This research endeavors to proffer a comprehensive strategy aimed at eliminating the discharge of treated water into the sea. It proposes the annual allocation of 16.7 hm<sup>3</sup> of treated water to irrigation communities grappling with acute water deficits. The strategy, when applied to a tangible case study, ensures the reliable provision and distribution of the entire designated volume. This approach takes into account the fluctuating agricultural demands through the implementation of hybrid systems boasting an installed capacity of 15 MW. Additionally, it establishes the deployment of pumped hydro-storage reservoirs to regulate and secure the requisite energy for distribution and the osmosis process involved in treating a portion of the reclaimed water, thereby presenting a high-quality solution amenable to agricultural consumption.

## 1. Introduction

Climate change is causing the distribution of resources, both in quality and quantity, to shift. This means that production systems that depend on natural events must adapt to them (Mohammed et al., 2022). Water scarcity is a reality, which should be considered in the new water management plans. The increase in water demand (i.e., urban, industrial or agricultural, as a result of population growth) is confronting water managers with the challenge of managing an increasing scarcity of water resources (Zobeidi et al., 2022). In this regard, the reuse of treated water can help mitigate this scarcity by providing an additional source of water and by providing the same drop of water for several uses (Bolinches et al., 2022).

The improvement of the wastewater management does not only

increase the water resource. It implies an improvement in the conservation of natural resources because the cost of purification does not end up in a discharge into the watercourse, but can be partly recovered in the water reused for irrigation or other uses (Partyka and Bond, 2022). The sustainability enhancement when the reuse is established improves the community resilience and therefore, it contributes to refining the achievement of some targets in the sustainable development goals (SDGs) (Obaideen et al., 2022).

The lack of water resources, the uncertainty of their temporal distribution due to climate change and the existence of densely populated urban areas near the coast mean that the focus is on waste water treatment plants (WWTPs) (Mora et al., 2022). The annual volume of these urban WWTPs is too high. Water managers of these infrastructures establish different uses to take advantage of this volume but it is not enough, and there is a high available volume not used. The global

\* Corresponding author.

E-mail addresses: [mopesan1@upv.es](mailto:mopesan1@upv.es) (M. Pérez-Sánchez), [fcosanro@agf.upv.es](mailto:fcosanro@agf.upv.es) (F.-J. Sánchez-Romero), [zapata\\_fra@gva.es](mailto:zapata_fra@gva.es) (F.A. Zapata), [palopez@upv.es](mailto:palopez@upv.es) (P.A. López-Jiménez), [helena.ramos@tecnico.ulisboa.pt](mailto:helena.ramos@tecnico.ulisboa.pt) (H.M. Ramos).

<https://doi.org/10.1016/j.agwat.2024.108684>

Received 28 September 2023; Received in revised form 9 January 2024; Accepted 9 January 2024

Available online 13 January 2024

0378-3774/© 2024 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Nomenclature	
<i>Indices (definition)</i>	
$A, B, C$	Coefficients of flow curve pumping head proposed by manufacturer
$AC_t$	Operation and maintenance cost for the year $t$ (€)
$AI_t$	Annual revenue for energy sales (€)
$\alpha$	Ratio between rotational speed and nominal rotational speed
$\gamma$	Specific weight of the fluid (kN/m <sup>3</sup> )
$C_{considered}$	Considered capacity (m <sup>3</sup> )
CO <sub>2</sub>	Carbon oxide emissions
CR	Capacity Ratio
$C_{theoretical}$	Theoretical capacity (m <sup>3</sup> )
DECR	Distributed Energy Consumption Ratio (kWh/m <sup>3</sup> )
DI	Demand Index
DTI	Demand transferred index
DVR	Distributed Volume Ratio
DR	Distribution Ratio
$\Delta t$	Interval time (s)
$E_4, E_3, E_2, E_1$ and $E_0$	Coefficients of flow curve pumping efficiency proposed by manufacturer
EDRp	Energy Distribution Ratio
$E_{FR_{jl}}$	Friction energy (kWh)
$E_k$	Friction energy in $k$ interval (kWh)
$E_{max}$	Maximum Energy consumed in any of the scenarios
$E_{RS_{jl}}$	Minimum energy required in a point to ensure the quality of the service (kWh)
$E_{SL_s}$	Energy consumed in $s$ scenario (kWh)
$E_t$	Annual energy for the year $t$ (kWh)
$E_{TA_{jl}}$	Available energy of recovery in a tap or line (kWh)
$E_{TN_{jl}}$	Minimum energy required in point or line to ensure the minimum pressure of irrigation (kWh)
$E_{TR_{jl}}$	Maximum theoretical recoverable energy in an irrigation point or line (kWh)
$E_{TR_{mj}}$	Recovered energy by a recovery system (kWh)
EWf	Energy Water Footprint (kWh/m <sup>3</sup> )
GCR	Global Capacity Ratio
GDR	Global Distribution Ratio
GIS	Geographical Information System
$H$	Pumped head (m w.c.)
$H_c$	Hypothesis considered for consumption point $d$
$H_{il}$	Recovered head by the $il$ recovery system (m w.c.)
$H_{mp}$	Manometric head of pumping (m w.c.)
$H_{reservoir}$	Piezometric level in the considered reservoir (m w.c.)
$H_{10i}$	Nominal demand curve por $i$ irrigation user
$i$	Each irrigation user
$IC_0$	Initial investment in the year 0 (€)
$il$	Each recovery system
$j$	Each reservoir considered in the system
$jl$	Each element of the system (line or node)
$k$	Each interval hour
$k_{d,i}$	Distribution coefficient according to de demand distribution hypothesis
$k_o$	Ratio between osmotized water and inlet water in osmosis procedure
$k_{RD}$	Real discount rate $k_{RD}=0.07$
LCOE	Levelized Cost of Energy (€/kWh)
$m$	Maximum number of reservoirs in the system
$M$	Mix coefficient
MRR	Manometric Regulation Ratio
$n$	Maximum number of pump stations in the system
$N$	Maximum number of machines in pumping station
$\eta_{il}$	Efficiency of the $il$ recovery system
$n_o$	Number of operating machines
NPV	Net Present Value (€)
$p$	Each pumping station
$P$	Instantaneous power (kW)
$P_{jl}$	Pressure in element $jl$ (m w.c.)
$P_{min_{jl}}$	Minimum pressure in the element to guarantee the pressure (m w.c.)
$P_{minS_{jl}}$	Minimum service pressure (m w.c.)
SDGs	Sustainable development goals
$Q$	Pumped flow (m <sup>3</sup> /s)
$Q_I$	Inlet Flow in the system (m <sup>3</sup> /s)
$Q_{jl}$	Circulating flow in element $jl$ (m <sup>3</sup> /s)
$Q_0$	Desalinated wastewater flow (m <sup>3</sup> /s)
$Q_{WWm}$	Regenerated wastewater flow used directly without considering the osmosis procedure (m <sup>3</sup> /s)
$s$	Each of the scenarios studied
$t$	Each year of study
$T$	Lifetime (years) $T = 25$ years
$t_{AI}$	Total of number interval over time ( $k$ ), in which the ratio $\frac{E_k}{V_k}$ is above zero $t_{AI} \leq 8760$
UGPR	Used Generated Power Ratio (Wp/m <sup>3</sup> )
$V_{d,i}$	Demanded volume for consumption point $d$ by the user $i$ (m <sup>3</sup> )
$V_{d,total}$	Total volume of the demand for the consumption point $d$ (m <sup>3</sup> )
$V_{distributed}$	Distributed volume in considered reservoir (m <sup>3</sup> )
$V_{DTV}$	Theoretically deliver volume (m <sup>3</sup> )
$V_I$	Annual available volume to be distributed in the irrigation system (m <sup>3</sup> )
$V_k$	Volume in $k$ interval (m <sup>3</sup> )
$V_{NDV}$	Non-Delivered volume (m <sup>3</sup> )
$V_{NES}$	Non-entered volume in the system (m <sup>3</sup> )
$V_O$	Annual desalinated wastewater volume used to be mixed with $V_{WWm}$ (m <sup>3</sup> )
$V_{pumped}$	Pumped volume (m <sup>3</sup> )
$V_t$	Total demanded volume by the system (m <sup>3</sup> )
$V_{WW}$	Annual regenerated wastewater volume used to be introduced in the osmosis procedure (m <sup>3</sup> )
$V_{WWm}$	Annual regenerated wastewater volume used without considering the osmosis procedure (m <sup>3</sup> )
$V_{WWr}$	Annual rejection regenerated wastewater volume (m <sup>3</sup> )
$V_{WWr}$	Total Annual regenerated wastewater volume generated by WWTP (m <sup>3</sup> )
$V_{\sum R_j}$	Annual volume demanded by consumption joints upstream (m <sup>3</sup> )
WWTPs	Water treatment plants
$z_{jl}$	Geometry level in element $jl$ (m)
$z_o$	Head level of the reservoir (m)

wastewater discharge was estimated at 400 billion m<sup>3</sup>/year (Hanjra et al., 2012). Particularly, Spain treated an estimated volume of wastewater close to 3375 hm<sup>3</sup>/year. Only 13% volume is currently reused (Jodar-Abellan et al., 2019). This volume of wastewater could

contribute to promoting the circular economy in the agricultural sector and improving the water balance in terms of water resources for the irrigation communities (Ungureanu et al., 2020).

The development of actions should improve the environmental

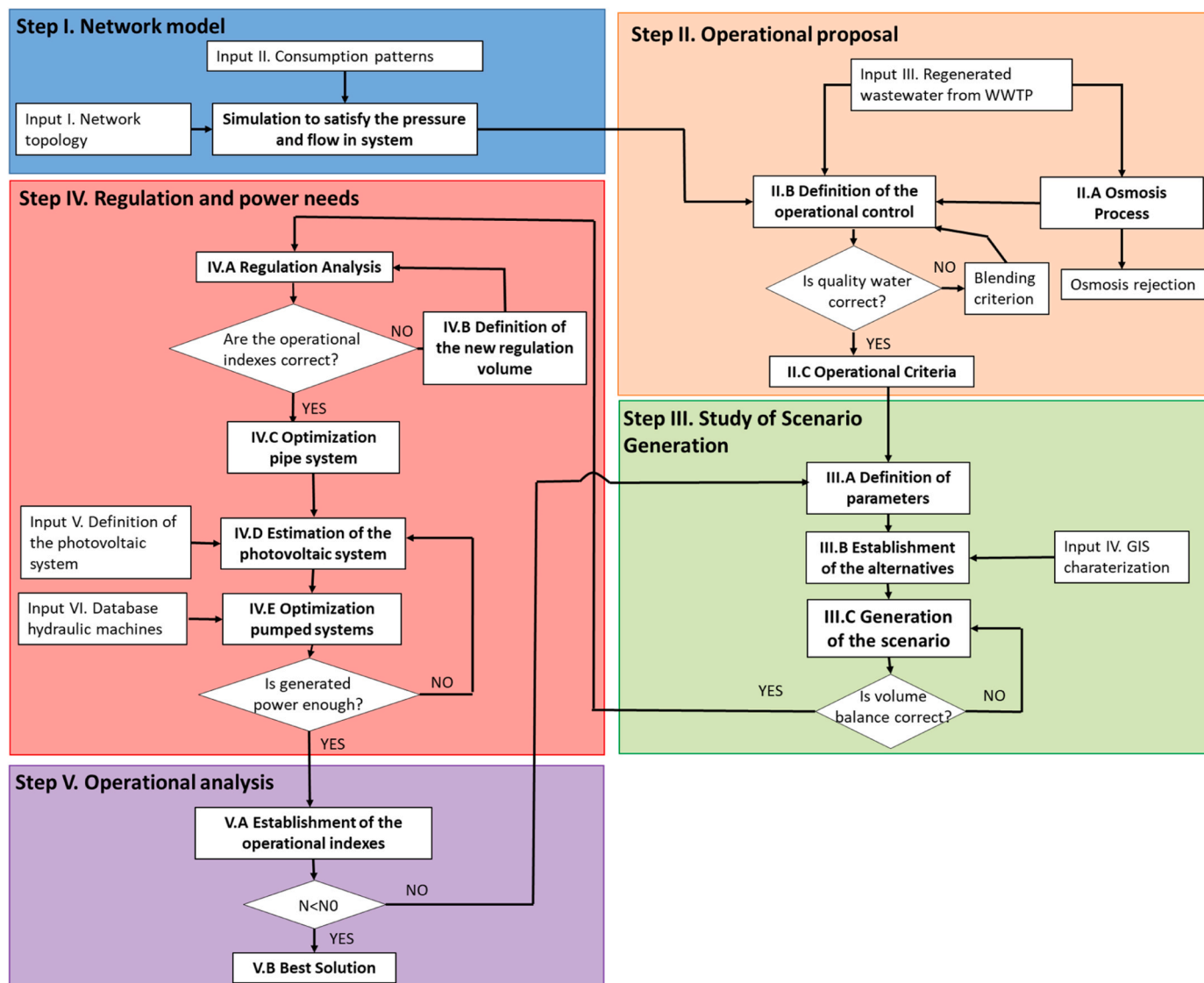


Fig. 1. Optimization procedure.

operation of the water systems, including the improvement of the technical, financial and environmental outcomes (Becken and McLennan, 2017). The operation of autonomous energy systems implies the possibility of developing isolated water systems using clean energy production (Dorji et al., 2012; Biswas et al., 2001). Some researchers proposed the use of batteries to store the excess energy (Tarroja et al., 2014). In other cases, the use of batteries is unfeasible in the facilities and the use of pumped-storage is combined with renewable systems, especially photovoltaic and hydropower systems (Canales et al., 2015). The incorporation of renewable systems when the facility works isolated could contribute to reducing the fossil resources to 70% (Millinger et al., 2012). These alternatives can supply enough energy to the pump station, when the flow can be injected into the network (Caniglia et al., 2016). It enables the reduction of the CO2 emissions in significance values (Vujanović et al., 2021).

WWTPs are located at the bottom of the urban areas since the sewage systems operate by gravity. It implies the internal procedure of depuration needs high values of energy to develop the purification process, showing range values between 0.34 and 2.51 kWh/m<sup>3</sup> (Trapote et al., 2014). When WWTPs collect effluents from cities or coastal municipalities, any reuse of these effluents requires higher energy consumption to reuse these waters for alternative uses (mainly irrigation or non-potable

urban uses such as street washing and/or garden irrigation), including the recharge of overexploitation of aquifers (Ríos et al., 2023). The Mediterranean cities (i.e., Barcelona, Valencia, Alicante, Naples, among others) are examples in which there are high reused volumes to be integrated into secondary uses but they need the use of a pump system to distribute the regenerated volume (Su et al., 2020). It implies that water-reuse projects should be evaluated from economic, technical and environmental point of views (Molinos-Senante et al., 2011).

In Spain, irrigation communities have invested significant efforts in enhancing their infrastructures, primarily through the modernization of their irrigation systems with localized irrigation methods (Azuz-Adeath and Rivera-Arriaga, 2009). This initiative has rendered previously uncultivated irrigated areas attractive for agricultural enterprises once more, thereby enhancing irrigation efficiency (Ministerio de agricultura, 2020). However, the expansion of cultivated land that was formerly abandoned, the emergence of climatic fluctuations necessitating increased water requirements for plantations, and the diminishing water resource reservoirs (e.g., the Tajo-Segura water transfer) during drought periods, all compel these entities to seek methods for integrating new resources into their systems (Zhan and Huang, 2004).

The formulation of effective strategies necessitates a meticulous sizing approach to estimate renewable energy generation (Sánchez

Romero, 2014). Optimization via various methodologies such as gray wolf algorithms (Tsakiris and Spiliotis, 2014), firefly-inspired algorithms (Mercedes Garcia et al., 2022), harmony methods (Picazo et al., 2018), or evolutionary algorithms (Vidović et al., 2023) has been proposed as a solution in certain published research. Moreover, analyses of other hybrid systems have been conducted to operate autonomously, facilitated by software like HOMER (Pérez-Sánchez et al., 2017). The integration of these facilities is pivotal for enhancing the operability of these systems and facilitating the incorporation of diverse water resources that might otherwise remain unused in conventional water systems, contingent on users bearing the costs of grid connection (Sánchez-Romero et al., 2022).

The scenarios presented typically involve consistent urban demands, resulting in a stable energy generation profile (Rossman, 2000). This simplicity streamlines the process of sizing and establishing managerial protocols concerning production, administration, and setting of operational parameters. However, when these principles are extended to agriculture, the complexity of the challenge escalates. This is primarily due to the fact that water requirements are subject to annual meteorological variations (e.g., temperature, precipitation, wind) and are contingent on crop type (annual or seasonal). In annual crop cycles, water demand is minimal in winter and reaches its peak during the summer months (Garcia et al., 2023).

Consequently, the systems developed and the strategies proposed must possess the capacity to adapt to these shifting patterns. Their objectives encompass ensuring a consistent supply, minimizing energy consumption, and, in the case of reclaimed wastewater utilization, regulating the entire volume generated by the treatment plant to prevent discharge into natural water bodies. In a novel approach, this research advocates for the incorporation of regenerated wastewater into agricultural water systems through hybrid systems. These systems provide the requisite energy for the wastewater treatment plant's operations, ensure water quality standards, and facilitate distribution to various irrigation communities. The overarching aim is to prevent wastewater treatment plants from discharging into the sea, thus mitigating eutrophication issues. The proposed methodology is replicable in any country, which has cities near the coast. In this line, different authors estimate that between 50% and 60% of the world's population lives in coastal areas (Azuz-Adeath and Rivera-Arriaga, 2009), 40% in the case of Spain (Ministerio de agricultura, 2020). This fact implies the need to address wastewater reuse by distributing these volumes from sea level to agricultural areas located at a higher elevation. For this reason, it is necessary to use pumping systems and energy systems to supply these pumping stations.

The research is aimed at both researchers working in water distribution systems and innovation departments of supply management companies. The proposed methodology tries to provide answers to questions such as: Is the total reuse of reclaimed water possible?; Can hybrid systems be incorporated into irrigation systems that imbricate with demand?; Is it possible to incorporate water resources that are not currently exploited, which reduce the water deficit in coastal areas?

## 2. Methodology

The envisaged procedure is partitioned into five discrete phases, each encompassing a multitude of individual steps, as illustrated in Fig. 1. This model mandates diverse inputs and iterative methodologies, which serve to determine the energy prerequisites and the dimensions of the infrastructure necessary to meet the water irrigation demand following the available volume.

### 2.1. Optimization stages

In pursuit of the optimization solution, Fig. 1 delineates the proposed methodology, segmented into five distinct stages: Network model (I), Operational Proposal (II), Study of Scenario Generation (III), Regulation

and power needs (IV) and Operational analysis (V).

### 2.2. Network model

The development of the model should adhere to the available information. Essential prerequisites include delineating the water topology and comprehending consumption patterns to initiate the initial operation of the system. Employing simulation via EPANET becomes imperative for ascertaining the minimal levels within various reservoirs and tanks to fulfill the water demand, thereby ensuring the maintenance of minimum pressure levels within the system. A meticulously calibrated methodology, as outlined by [34], facilitates the estimation of required flow rates at each consumption junction.

### 2.3. Operational procedure

This stage assumes paramount importance within the purview of the proposed strategy, as it lays down the fundamental blueprint, encompassing the utilization of regenerated wastewater and the implementation of water purification, specifically through the osmosis procedure. The utilization of regenerated wastewater can necessitate a desalination process, owing to the elevated salinity levels inherent in wastewater, rendering it unsuitable for direct irrigation use (Step II.A). The desalination could be necessary or not. It depends on water quality. If the sanitation system is located near the sea, the phenomenon of marine intrusion could occur in the sanitation system. When it occurs, the partial desalination of the volume is necessary to reach a minimum level of quality in the regenerated water to be used. Under the scheme delineated in Fig. 1, the osmosis process ensures the generation of osmosed water, which is subsequently blended with reclaimed water sourced from the treatment plant. This blending process yields the desired mixture, characterized by the optimal salinity levels conducive to irrigation, mixing desalinated water (without salinity) and water from wastewater treatment plants (water with high salinity).

The by-product of the osmosis process, known as reject water, undergoes a regenerative treatment utilizing a green filter. This green filter comprises bioreactors, surface flow wetlands, and subsurface flow wetlands, serving the pivotal function of eliminating nutrients, primarily nitrogen and phosphorus, known culprits in causing eutrophication at the discharge points of treatment plants. It is important to note that the analysis of the green filter falls beyond the primary scope of this research. References to sustainable methodologies for wastewater regeneration through natural processes can be found in the published literature [(Ministerio de agricultura, 2020)].

The osmosis procedure (Step II.B) is simulated in the developed model as:

$$V_I = V_{WW_m} + V_O \quad (1)$$

where  $V_I$  is the annual available volume to be distributed in the irrigation systems in  $m^3$ ;  $V_{WW_m}$  is the annual regenerated wastewater used directly without considering the osmosis procedure in  $m^3$ ;  $V_O$  is the annual desalinated wastewater used to be mixed with  $V_{WW_m}$ . The osmosis procedure is considered as

$$V_O = k_o V_{WW_T} \quad (2)$$

where  $V_{WW_T}$  is the annual regenerated wastewater volume used to be introduced in the osmosis procedure and  $k_o$  is the ratio between osmosed water and inlet water. The rejection volume ( $V_{RWW}$ ) is equal to

$$V_{RWW} = (1 - k_o) V_{WW_T} \quad (3)$$

The mix coefficient ( $M$ ) is defined as a function of the final salinity, which is defined as the following equation

$$Q_I = MQ_o + (1 - M)Q_{WW_m} \quad (4)$$

where  $M$  is the mix coefficient;  $Q_I$  is the inlet flow in the system in  $m^3/s$ ;  $Q_{WW_m}$  is the regenerated wastewater flow used directly without considering the osmosis procedure in  $m^3/s$ ;  $Q_O$  is the desalinated wastewater flow in  $m^3/s$ .

Defined the mixed ratio (Step II.B), the procedure evaluates if the water quality is according to the used constraints. If the restriction is satisfied, the procedure continues to Step II.C. This step defines the operational criteria. These criteria are based on defining the maximum and minimum flows in the different subsystems, as well as establishing the priority in the pumped systems. This priority is defined as a function of the water level in the different reservoirs.

According to inputs, the system should know the wastewater flow from the wastewater treatment plant over time, as well as the demand curve over time (consumption patterns) for the different consumption nodes. Each demand curve depends on the different crops, which are growing in the study area. The general curve, as a function of the irrigation needs, is denominated nominal demand curve and it is identified as  $H_{10i}$  ( $i$  is each irrigation user), assuming a daily distribution of monthly volumes over 20 h a day. The distribution from reservoir to irrigation user is considered on 20 h. This means being on the safe side, increasing the flow rates demanded and considering that there may be four hours of downtime for system maintenance each day. Based on this demand, the study includes a variation of the demand curve that will be described in Step III, to determine the flexibility and resilience of the system.

#### 2.4. Scenario Generation

The third block of the procedure is focused on the automatic generation of scenarios. The objective is to develop operating situations that take into account the variation of the demand curve between consumption nodes, as well as the volumes demanded, to meet the objective that the unused volume is kept to a minimum.

The generation of the different scenarios is configured by different parameters, which is based on demand over time and consumption of the different users (Step III.A), defining the following indexes: demand index ( $DI$ ) and demand transferred index ( $DTI$ ).

The Demand Index ( $DI$ ) is defined as the weighted average of irrigation volumes about the demand hypothesis considered. This index characterizes the scenario concerning the demand situations and their annual distribution.

$$DI = \frac{\sum(V_d \cdot H_c)}{V_t \cdot 10} \quad (5)$$

where:  $H_c$  is the demand hypothesis curve to discharge in the reservoir, which supplies the irrigation user. The suffix  $c$  varies between 0 and 10.  $H_0$  implies the input volume to the irrigation volume is constant over time. It could be considered when the regulation capacity of the irrigation community is higher.  $H_{10}$  the discharge volume is according to the curve of the irrigation needs, assuming the irrigation community does not have a regulation capacity of its volume.  $V_{d,i}$  is the demanded volume for consumption point  $d$  by the user  $i$ , defined by the expression:

$$V_{d,i} = k_{d,i} \cdot V_{d,total} \quad (6)$$

and  $k_{d,i}$  is the distribution coefficient according to the demand distribution hypothesis;  $V_{d,total}$  is the total volume of the demand for the consumption point  $d$ ;  $V_t$  is the total demanded volume by the system. It is defined as

$$V_t = \sum V_{d,i} \quad (7)$$

$DI$  values vary between 0 and 1. When  $DI$  is equal to 0, it means that all demand points operate with a hypothesis  $H_0$  (24-hour annual average). When the  $DI$  value is 1, it means that all demand points operate with a hypothesis  $H_{10}$  (monthly average at 20 h according to the

irrigation demanded curve). Intermediate values represent other ways of delivering the demanded volumes.

The demanded transfer index ( $DTI$ ) to  $R_j$  is defined as the ratio between the difference in volumes supplied from total volume capacity, which is defined as  $\sum R_j$  ( $j$  is the different reservoirs considered in the system) and the volume demanded by consumption joints upstream of them concerning their minimum difference.

$$DTI = \frac{V_{\sum R_j} - V_{d,i}}{(V_{\sum R_j} - V_{d,i})_{\min}} \quad (8)$$

$DTI$  represents the increase in volumes that are redistributed from the demand  $d_i$  ( $i$  identify the different irrigation users. The demand ( $d$ ) can connect to different users ( $i$ ) to entities at higher elevations and that must be transferred by pumped systems to be distributed from downstream reservoirs ( $R_j$ ).  $DTI$  is always greater or equal to 1, and the maximum value depends on the  $\sum R_j$  and  $V_{d,i}$ .

Step III: B is focused on locating the different alternatives of the different reservoirs, pump systems and recovery systems by GIS tool (Zhan and Huang, 2004). Knowing the different location alternatives, the scenario is defined (Step III.C), which depends on the combination between  $DI$  and  $DTI$ . The generation is established according to different  $DI$  and  $DTI$  values for each variation of the demand hypothesis ( $H_c$ ,  $c$  varies from 0 to 10) for each consumption user. For each generation, the balance volume between input and output should be established to go to Step IV.

#### 2.5. Regulation and power optimization

Step IV.A estimates the regulation needs in the system, according to different scenarios defined in step III.C and different alternatives (III.A). Once the circulating flows in the system have been established, the variation of water height in the ponds and the necessary capacity are determined through a volumetric balance according to the following model. The iterations of the different capacities of the reservoirs, according to geometry are modeled following the methodology proposed by (Sánchez Romero, 2014). It allows the establishment of the water levels and volumes in the basin of the reservoir according to its basic geometric characteristics (i.e., perimeter and bottom area and maximum height of water for the Normal Maximum Level). In the different iterations (Step IV.B), the geometric characteristics of the reservoir are corrected to adjust the necessary capacity and depend on the characteristics of the selected locations. In the last iteration, the final fitting of the ponds in the selected locations has been carried out, and the real geometric characteristics have been obtained. According to pumping stations, an iterative regulation strategy is based on the Newton-Raphson optimization method (Tsakiris and Spiliotis, 2014). This method optimized the rotational speed to minimize the flow and pressure requirements.

The head and efficiency curves for the pump machine are defined by the following equations:

$$H = \alpha \left( A + B \frac{Q}{\alpha} + C \frac{Q^2}{\alpha^2} \right) \quad (9)$$

$$\eta = E_4 \frac{Q^4}{\alpha^4} + E_3 \frac{Q^3}{\alpha^3} + E_2 \frac{Q^2}{\alpha^2} + E_1 \frac{Q}{\alpha} + E_0 \quad (10)$$

where  $\alpha$  is the ratio between rotational speed and the nominal rotational speed,  $Q$  is the flow rate in  $m^3/s$ ;  $H$  is the pumped head for a given rotational speed in m w.c. and  $\eta$  is the efficiency of the machine and  $n$  is the number of installed pumps machines.  $A, B, C, E_4, E_3, E_2, E_1$  and  $E_0$  define the characteristics curves provided by the manufacturers.

The instantaneous power is defined by

$$P = \gamma g n_0 Q H \quad \eta \quad (11)$$

where  $\gamma$  is the specific weighted  $\text{kN/m}^3$ ,  $g$  acceleration of gravity in  $\text{m/s}^2$  and  $n_0$  number of operating machines. The optimization procedure reaches de best operational points of the machine in terms of energy requirements for each interval  $k$  by minimizing instantaneous power requirements by iterative regulation strategy based on the Newton-Raphson optimization method (Tsakiris and Spiliotis, 2014). For each interval, the  $\alpha$  value is calculated to optimize the pump operation points, determining the optimal number of machines ( $n$ ) and establishing a flow rate between pumps, when in the system are two or more pumps. The optimization procedure is subject to the following restrictions:  $0.75 \leq \alpha \leq 1.25$  and  $1 \leq n_0 \leq N$ , where  $N$  is the maximum number of machines in pumping station analyzed.

The hydraulic variables are defined as the operational points in each interval of time. The following optimized parameters in the system are (the order is established according to priority):

1. To maximize the value of the distributed volume ratio. It guarantees all water volume of the WWTP is used
2. To maximize the value of the capacity ratio. It guarantees the minimum value of the reservoir capacities.
3. To optimize the rotational speed for minimizing the flow and pressure requirements. It guarantees the minimum energy consumption
4. To maximize the self-consumption from photovoltaic systems

The iterations are considered analyzing the different indexes, which are focused on hydraulic, energy and economic values to compare different alternatives and know the real behavior of the system. The characterization of the system response is defined by different ratios. These are defined as:

Capacity Ratio ( $CR$ ). Its purpose is to determine whether or not the basins operating in the system are oversized. Its range is between 0 and 1. Values close to zero show that the pond under study is oversized, while values close to unity show that it is optimized in terms of regulation for the scenarios analysed. The Capacity Ratio for each basin is defined as follows:

$$CR = \frac{C_{theoretical}}{C_{considered}} \quad (12)$$

where  $C_{theoretical}$  is the theoretical capacity, which is necessary for each analysed scenario in  $\text{m}^3$  and  $C_{considered}$  is the considered capacity in this alternative in  $\text{m}^3$ .

When all reservoirs are considered, the procedure can define the global capacity ratio (GCR). It represents the use of the volume capacity when all reservoirs are considered. This index shows whether the methodology overstates or understates the overall capacity of the system. However, the value obtained depends on the weighted capacity ratios of the rest of the reservoirs, maintaining the trend of those with the highest capacity.

Distributed Volume Ratio ( $DVR$ ). The purpose of this index is to indicate the discharge into the watercourse since it cannot be distributed. Its value ranges between 0 and 1. Correct operation of the system must establish  $DVR$  values equal to 1.

$$DVR = 1 - \frac{V_{NES}}{V_{wwT}} \quad (13)$$

where  $V_{NES}$  is the volume non-entered in the system, and therefore it cannot be distributed instead of used to distribute;  $V_{wwT}$  is the total volumen generated by WWTP in  $\text{m}^3$ .

Distribution Ratio ( $DR$ ). Its objective is to measure in a dimensionless way the degree of supply of the demanded volume according to the established scenario. It takes into account the volume that the system has not been able to deliver to the demands ( $V_{NDV}$ ) and the volume that it should theoretically deliver according to the calculation scenario ( $V_{DTV}$ ). It takes values between 0 and 1, being the ideal value equal to 1 because it guarantees that all the demand of the calculation scenario is supplied.

It is defined as:

$$DR = 1 - \frac{V_{NDV}}{V_{DTV}} \quad (14)$$

when all demands are considered, introducing the different volumes, the global distribution ratio ( $GDR$ ) can be defined.

Manometric Regulation Ratio ( $MRR$ ). This adimensional ratio shows the relationship between the manometric head injected into the system considering the volume pumped by the different pumping groups and the piezometric level of distribution from each of the basins. It takes a positive value, being in ideal conditions equal to 1. In this case, as there is part of the volume of water that is not distributed (rejection) and there are different pumping units at different heads, as well as different regulation and distribution basins, it will always be greater than unity. However, the closest values indicated show that less energy is required in the system.

$$MRR(adimensional) = \frac{\sum_{p=1}^n H_{mpk} V_{pumpedk}}{\sum_{j=1}^m H_{reservoirj} V_{distributedk}} \quad (15)$$

where  $p$  is each of the pumping stations;  $n$  is the maximum number of pump stations in the system;  $H_{mp}$  is the manometric head of pumping in each hour ( $k$ ) in  $\text{m w.c.}$ ;  $V_{pumped}$  is the volume pumped in hour ( $k$ ) in  $\text{m}^3$ ;  $j$  is each of the reservoirs;  $m$  is the maximum number of reservoirs in the system;  $H_{reservoirk}$  is the piezometric level of reservoir  $j$  concerning the level of the WWTP in hour  $k$  in  $\text{m w.c.}$ ;  $V_{distributed}$  is the volume distributed in reservoir  $j$  in hour  $k$  in  $\text{m}^3$ .

Energy Distribution Ratio ( $EDR$ ). It establishes the adimensional ratio between the energy consumed by each pumping system ( $p$ ) for each of the scenarios analysed and the maximum energy consumed by the system. It therefore shows the proportion of energy consumed that each of the pumping systems uses to operate.

$$EDR_p(adimensional) = \frac{E_{St_s}}{E_{max}} \quad (16)$$

where  $E_{St_s}$  is the energy consumed in the pumping system, analysed in each of the scenarios studied ( $s$ ) in  $\text{kWh}$ ;  $E_{max}$  is the maximum energy consumed in any of the scenarios in  $\text{kWh}$ .

Distributed Energy Consumption Ratio ( $DECR$ ). It establishes the relationship between the energy consumed taking into account the volume of water distributed. It is defined as the following expression:

$$DECR \left( \frac{\text{kWh}}{\text{m}^3} \right) = \frac{\text{Consumed Energy}(\text{kWh})}{\text{Distributed volume}(\text{m}^3)} \quad (17)$$

Used Generated Power Ratio ( $UGPR$ ); the purpose of this ratio is to establish a relationship between the power required to be installed in the system in  $\text{Wp}$  and the volume that is distributed to the different entities in  $\text{m}^3$ . It is determined by the following expression, and it is recommended that it be as low as possible, since it indicates the  $\text{kW}$  needed to distribute each cubic meter of water.

$$UGPR \left( \frac{\text{Wp}}{\text{m}^3} \right) = \frac{\text{Installed Solar Power}(\text{Wp})}{\text{Distributed volume}(\text{m}^3)} \quad (18)$$

For each defined alternative, which shows correct operational indexes, the optimization procedure is developed according to different criteria (i.e., environmental, technical and economical). Finally, the system chooses the best diameter for each pipe according to the Levelized Cost of Energy ( $LCOE$ ), guaranteeing the correct operation of the pipe.

**Table 1**  
Expressions to develop the energy balance.

Energy	Equation	ID
Total ( $E_t$ )	$\gamma Q_{ji} (z_o - z_{ji}) \Delta t / 3600$	(22)
Friction ( $E_{FR_{ji}}$ )	$\gamma Q_{ji} (z_o - (z_{ji} + P_{ji})) \Delta t / 3600$	(23)
Theoretical Necessary ( $E_{TN_{ji}}$ )	$\gamma Q_{ji} P_{min_{ji}} \Delta t / 3600$	(24)
Required $E_{RS_{ji}}$	$\gamma Q_{ji} P_{min_{S_{ji}}} \Delta t / 3600$	(25)
Theoretical Available ( $E_{TA_{ji}}$ )	$\gamma Q_{ji} (P_{ji} - P_{min_{ji}}) \Delta t / 3600$	(26)
Theoretical Recoverable ( $E_{TR_{ji}}$ )	$\gamma Q_{ji} (P_{ji} - \max(P_{min_{ji}}; P_{min_{S_{ji}}})) \Delta t / 3600$	(27)
Theoretical Recovered ( $E_{TR_{mjl}}$ )	$\gamma Q_{ji} H_{il} \eta_{il} \Delta t / 3600$	(28)

$$LCOE\left(\frac{\epsilon}{kWh}\right) = \frac{IC_0 + \sum_{t=1}^{t=T} \frac{AC_t}{(1+k_{RD})^t}}{\sum_{t=1}^{t=T} \frac{E_t}{(1+k_{RD})^t}} \quad (19)$$

where  $IC_0$  is the initial investment in € in the year 0. It studies the investment of the grid facilities to reach the supply points;  $AC_t$  is the operation and maintenance costs in € for the year  $t$ ;  $E_t$  is the annual energy in kWh for the year  $t$ ;  $T$  is the lifetime in years;  $k_{RD}$  is the real discount rate.

Energy Water Footprint ( $EFW$ ). It is defined as the friction energy by unit distributed in the network. This parameter identifies the trend of the decrease as a function of the increase in the diameter considered, calculating the average of the values greater than zero.

$$EFW\left(\frac{kWh}{m^3}\right) = \frac{\sum_{k=1}^{j=t_{AI}} \frac{E_k}{V_k}}{t_{AI}} \text{ where } \frac{E_k}{V_k} > 0 \quad (20)$$

where  $t_{AI}$  is the total number interval over time (k), in which the ratio  $\frac{E_k}{V_k}$  is above zero.  $t_{AI}$  is always lower than 8760.

Net Present Value (NPV), which is defined as the following equation.

$$NPV = -IC_0 + \sum_{t=1}^{t=T} \frac{(AI_t - AC_t)}{(1+k_{RD})^t} \quad (21)$$

where  $IC_0$  is the investment cost in €;  $AI_t$  is the annual revenue from energy sales in €.

Step IV.D established the analysis of the photovoltaic systems. It is focused on maximizing solar energy capture per square meter through solar irradiance. The method is based on the methodology defined by (Mercedes Garcia et al., 2022). This endeavor involves dividing the area into four distinct sub-blocks. The first sub-block involves computing hourly irradiance throughout the year, enhancing the analytical model proposed by (Picazo et al., 2018). The irradiation is estimated for a plane when the manager knows the solar parameters (i.e., day, latitude, angle declination and sunset time). The diffuse, direct and global irradiance estimates for floating photovoltaic panels, which are used in this methodology to reduce the evaporation of water reservoirs, improve the efficiency compared to ground solar photovoltaic (Vidović et al., 2023) and reduce the used area for the infrastructures. Once the estimation of the photovoltaic system is considered according to regulation analysis (Step IV.A and Step IV.B), the optimization procedure (Step IV.C) is developed to choose the best pump to define the different pump stations. In this step, an energy balance is developed according to (Pérez-Sánchez et al., 2017). The energy balance is used to analyse the different energy indicators in the system, as well as to analyse the possibility of installing micro-hydropower systems. Different equations are established in Table 1 to establish the particular analysis for any line or consumption point.

The different variables of Table 1 are:  $\gamma$  is the specific weight of the fluid in  $kN/m^3$ , which is equal to the ratio 9.81/3600;  $E_t$  is the total energy supplied in the system in kWh;  $E_{FR_{ji}}$  is the friction energy, which

is lost in the water system in kWh;  $E_{TN_{ji}}$  is the minimum energy required in a hydrant or line to ensure the minimum pressure of irrigation in the more unfavorable point in kWh;  $E_{TA_{ji}}$  is the available energy for recovery in a tap or line in kWh;  $E_{RS_{ji}}$  is the minimum energy required in a point to ensure the quality of the service in kWh;  $E_{TR_{jl}}$  is the maximum theoretical recoverable energy in an irrigation point, hydrant or line of the network in kWh;  $E_{TR_{mjl}}$  is the recovered energy by a recovery system considering the efficiency of the pump working as turbines (PATs) systems;  $Q_{il}$  is the circulating flow in an element (i.e., line or consumption point) over time in  $m^3/s$ ;  $z_o$  is the head level of the reservoir in m;  $z_{ji}$  is the geometry level in m;  $P_{ji}$  is the pressure in the element  $jl$  (line or node);  $P_{min_{ji}}$  is the minimum pressure in the element to guarantee the pressure in the more unfavorable point in m w.c.;  $P_{min_{S_{ji}}}$  is the minimum service pressure in any consumption point in m w.c.;  $H_{il}$  is the recovered head by the recovery system ( $il$ ) in m w.c.;  $\eta_{il}$  is the efficiency of the recovery system for this flow  $Q_{ji}$ ;  $\Delta t$  is the considered interval time in s.

Once the solar photovoltaic system is minimized according to the demanded power by the pumping station through an iterative process, step IV finishes and the procedure continues to step V. This step defines all estimates for the different alternatives by an iterative procedure for considering the best solution. It is established when  $DVR$  and  $DR$  are maximized, therefore their values are 1. Considering the solutions, in which  $RVD$  and  $DR$  are 1, the method chooses the solution with  $LCOE$  values lower. This solution englobes the best recovery system. These indicators are shown in Table 1 and the optimization procedure calculates them in each iterative procedure of the selection of the machine.

The methodology outlined above was programmed, developing the *APLIRE*D tool (Sánchez-Romero et al., 2022) by this research. This tool interfaces with the *EPANET* Toolkit (Rossman, 2000) in the development of the hydraulic models for the time-dependent analysis of the network.

## 2.6. Materials and case study

This methodology was applied to a real case study. It is located in Alicante (Spain) (Fig. 2a). A total annual volume equal to  $16.7 \text{ hm}^3$  should be used to improve the availability of the water resources around 13,747 ha. agricultural demand is mainly focused on the cultivation of vegetables and table grapes. There are three discharge points according to three different demands. These points discharge in different consumption joints (D01, D02 and D03, Fig. 2b).

Fig. 2b shows the main scheme of the water system proposed to use the regenerated water. Four different pump systems are proposed, which are PS01, PS02 and PS03 operated by solar photovoltaic systems. PS00 is connected to the grid but the excess of generated solar power is injected into the grid. The final compensation of the network consumption with these overages is zero. The osmosis system is powered by the PS01 system when solar radiation is present. This system also stores potential energy in the reservoir (DP04) to power the osmosis system. In addition, PS01 uses excess photovoltaic energy to accumulate volume in DP04. This volume is operated by a turbine (RS01) during hours when the PV system is not operating. The energy generated is used to power the pumping system PS02. The floating PV systems that operate as a single generator are located in the reservoirs DP01, DP02 and DP06. PS02 pumps irrigation flow to a reservoir called DP06. This reservoir is distributed to irrigation communities located on this level, particularly to the demand curve called D03. These irrigation communities supply 3524 ha and the excess of the energy in the inlet of the communities' reservoirs is recovered using a PAT system, called RS02. DP06 also supplies to pump system called PS02. This pumped station injects volume to reservoir DP07. This reservoir distributes different flows to high-level areas of D02 as well as it distributes volume to reservoir DP08. This pond supplies the demand of 7073 ha in different irrigation communities, which are defined by the demand curve D02. The excess energy between reservoirs DP07 and DP08 is recovered by the micro-hydropower system called RS03 by PAT systems. The total length of the

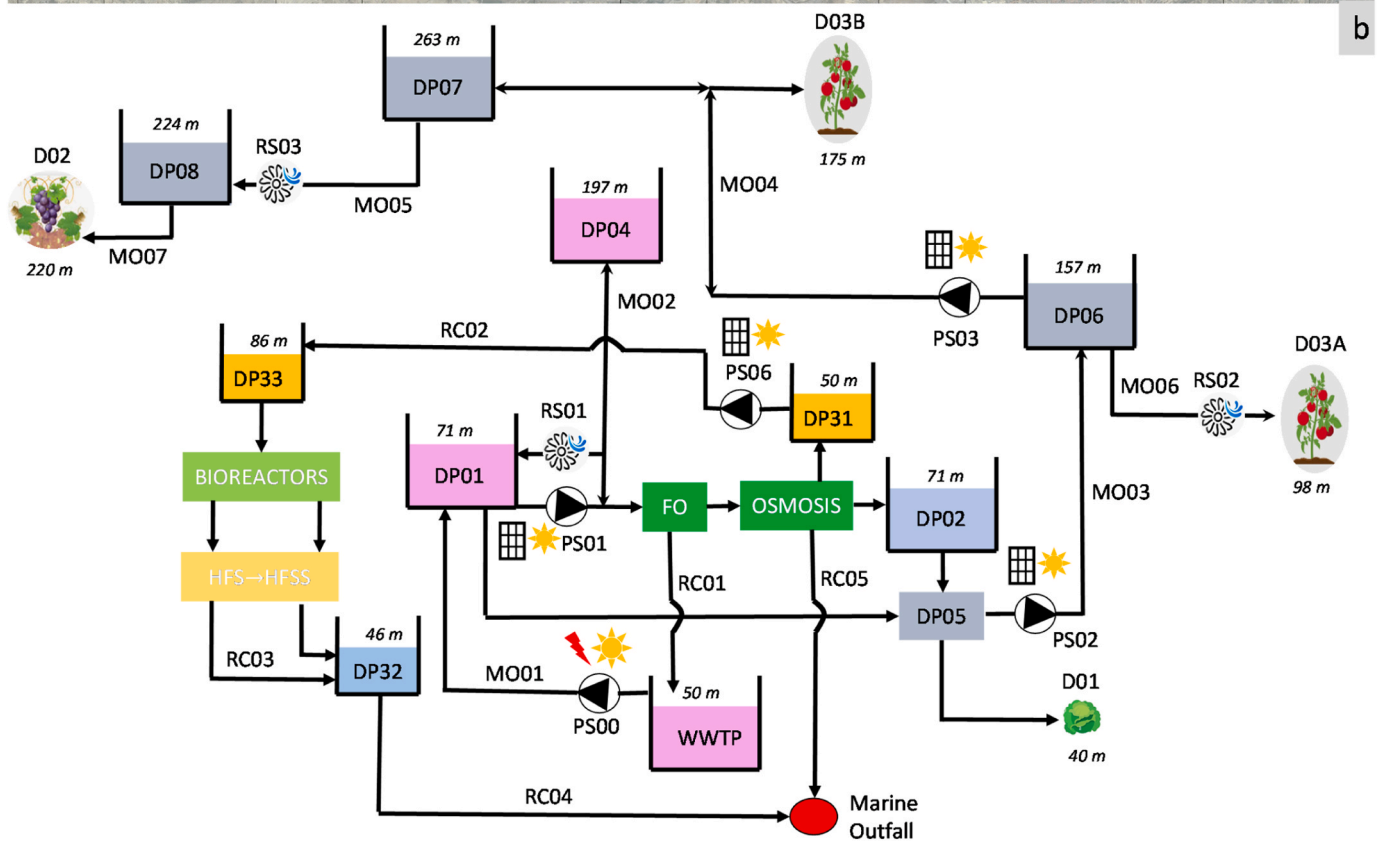
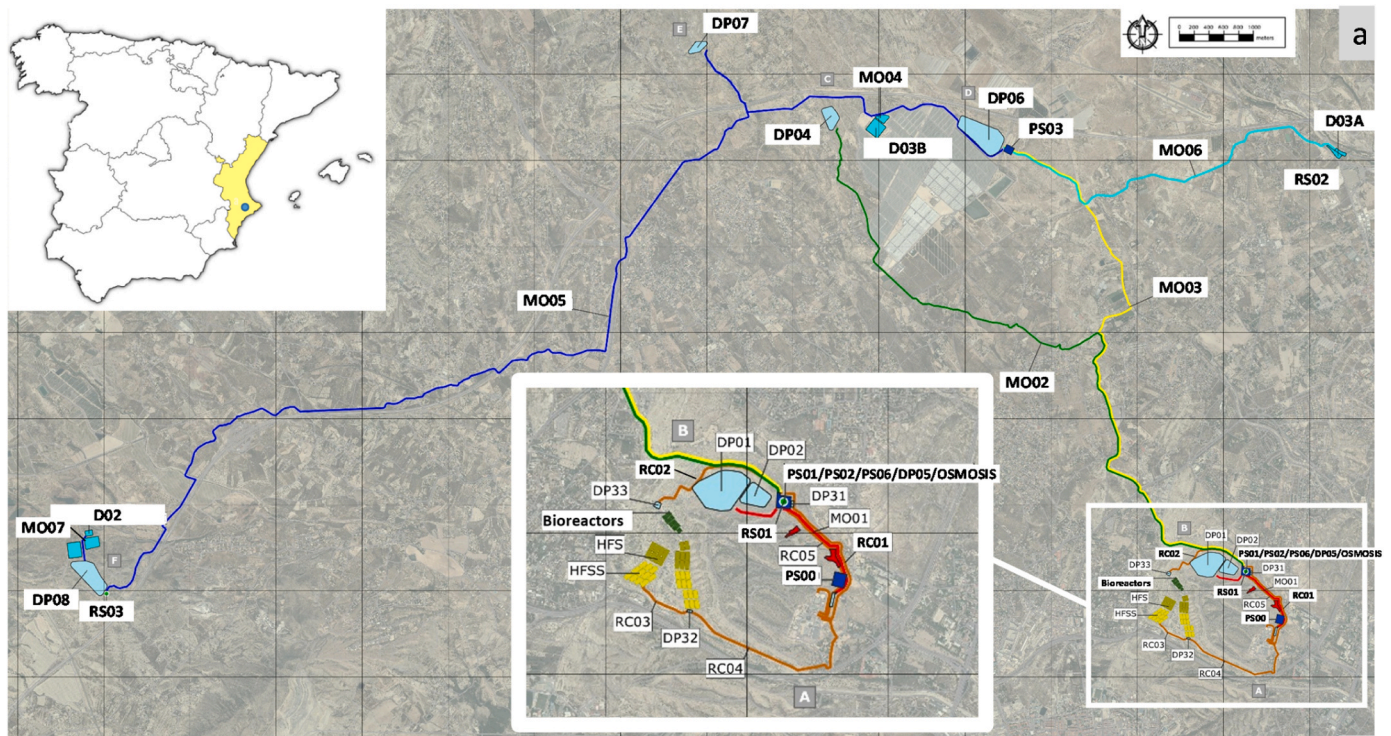


Fig. 2. The solution adopted for the case study (a). Scheme of the case study (b).

pipes, which connect different reservoirs, pump systems and consumption joints is 45.3 km. Hourly inlet flow is shown in Fig. 3a. It oscillates between 0.31 to 0.96 m<sup>3</sup>/s, being the average 0.55 m<sup>3</sup>/s. The demand curves are shown from Fig. 3b to Fig. 3d. The irrigation campaign covers the whole year given the diversity of crops. These data were the average obtained values between 2017 and 2022.

### 3. Results and discussion

The previous analysis (Step I) showed the minimum levels established to supply the demand in the different consumption joints in terms of pressure and volume. Table 2 shows the minimum levels, which should locate the different reservoirs.

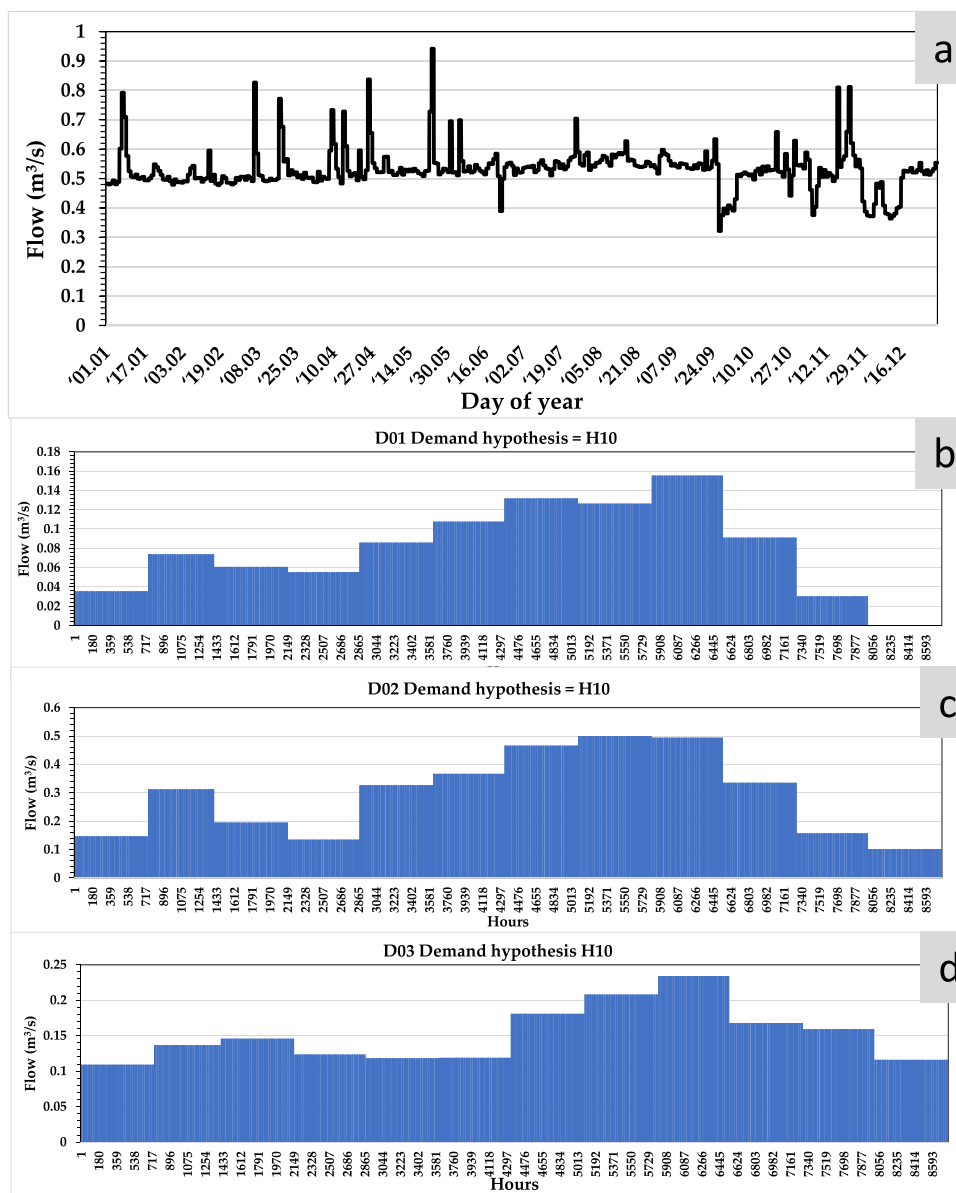


Fig. 3. (a) Inlet flow from WWTP. (b) Hourly demanded curve for D01; (c) Hourly demanded curve for D02; and (d) Hourly demand curve form D03.

Table 2  
Minimum, maximum levels and volume for different reservoirs of the system.

ID Reservoir	Minimum Level (m)	Maximum Level (m)	Volume (m³)
DP01	61	71	550,000
DP02	58	71	150,000
DP04	190	197	150,000
DP05	50	54	7500
DP06	149.5	157	650,000
DP07	253	263	80,000
DP08	211	224	550,000

The osmosis procedure established the mixed ratio, considering the available volume of WWTP is 16.7 hm<sup>3</sup> according to Fig. 4a. It defines the volume (gray area in Fig. 4a), which could be reached according to the osmosis procedure and mix criteria to get the mixed volume with low salinity. This volume is 13.8 hm<sup>3</sup> when nominal values are considered and it could oscillate between 13 and 14.6 hm<sup>3</sup> each year. The annual volume of osmosis rejection is 2.5 hm<sup>3</sup>, and it is treated in green wetlands. The osmosis procedure is necessary since the regenerated water of

WWTP contains around 4000 μS/cm and irrigation communities required a maximum value of 1500 μS/cm.

A first analysis of the system, considering the demand curve and input flows was developed to define the operational criteria for both pumped systems, and recovery systems. The energy balance was evaluated hourly throughout the year, considering 8760 h. These ranges are shown in Fig. 4b and they are results of a first iteration procedure to establish these ranges. Once, the regulation analysis was established (Step II.B) and operational criteria (Step II.C) were defined, the scenario generation was carried out according to DI and DTI.

Considering a periodic operation, 572 different scenarios were generated by combining the demand distribution hypotheses (1–52) and 11 demand situations. These scenarios correspond to typical operating conditions. The system is required to function correctly and respond to various requirements for these scenarios. A multi-year calculation was established to stabilize the system concerning the initial calculation levels. Initially, it was assumed that the reservoirs started with a water level, and a multi-year calculation was performed until the system stabilized. System stabilization was achieved when the initial level at the beginning of the annual simulation (1st January) was

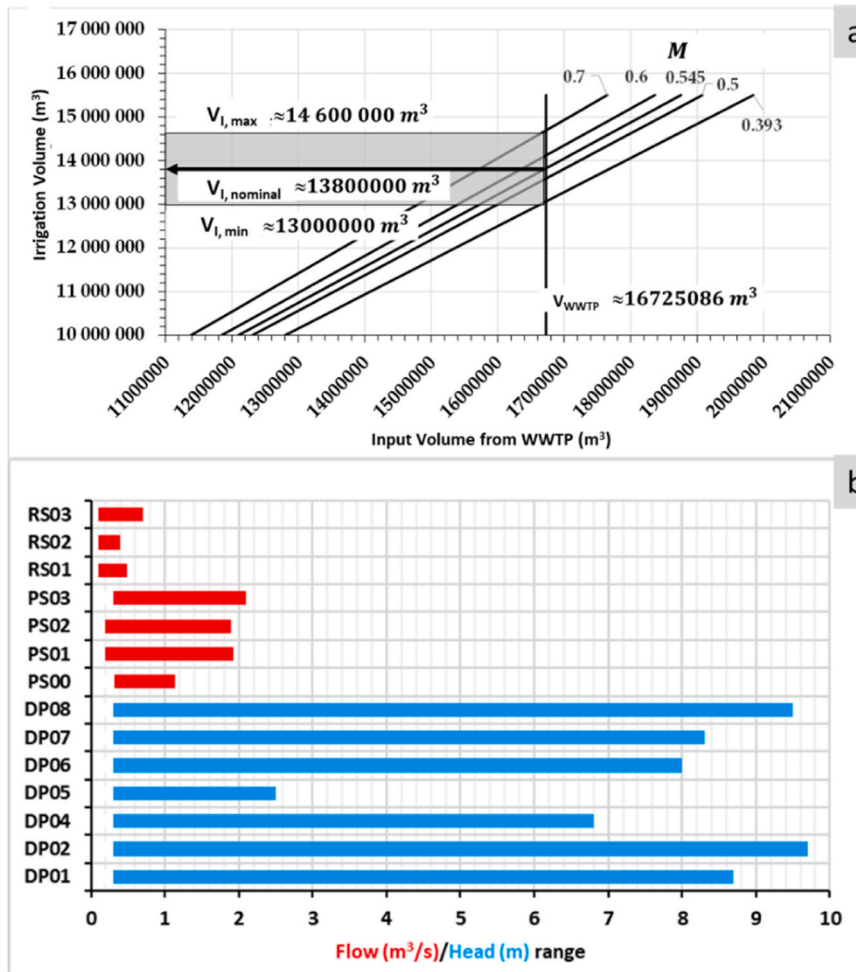


Fig. 4. (a) Irrigation volume as a function of mix coefficient ( $M$ ) and input volume of the WWTP; (b) Operational criteria for reservoirs (DPxx), pumps systems (PSxx) and recovery systems (RSxx).

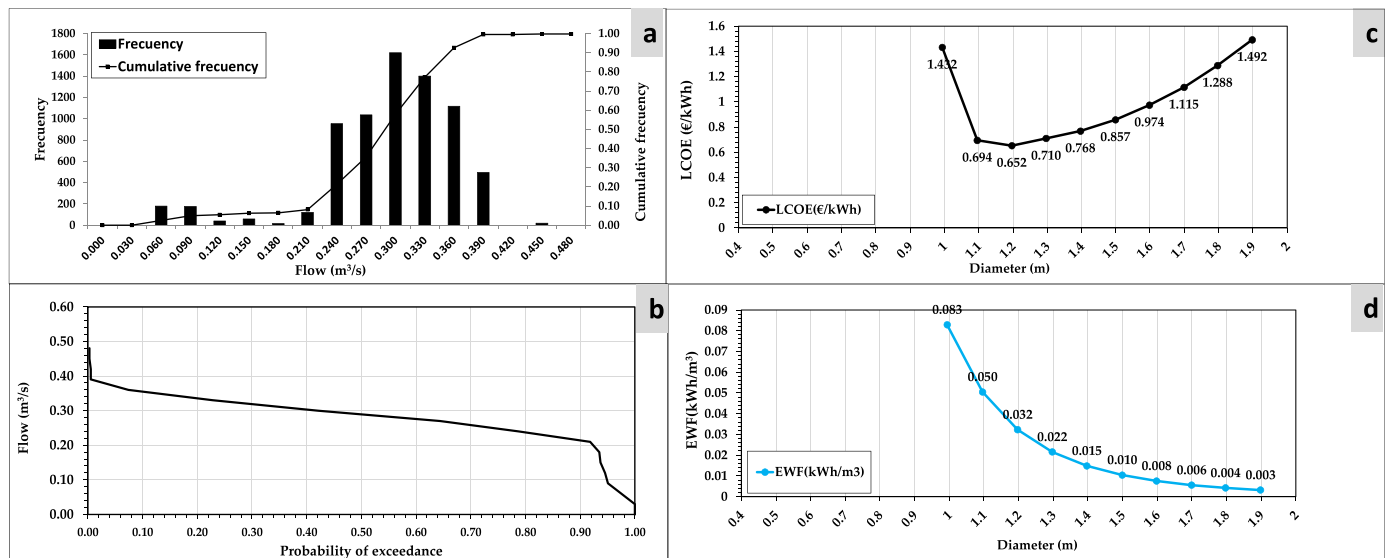


Fig. 5. (a) Example of flow frequency for MO05; (b) Probability of flow exceedance for MO05; (c) LCOE and NPV values for MO03; and (d) Example of EWF for MO03.

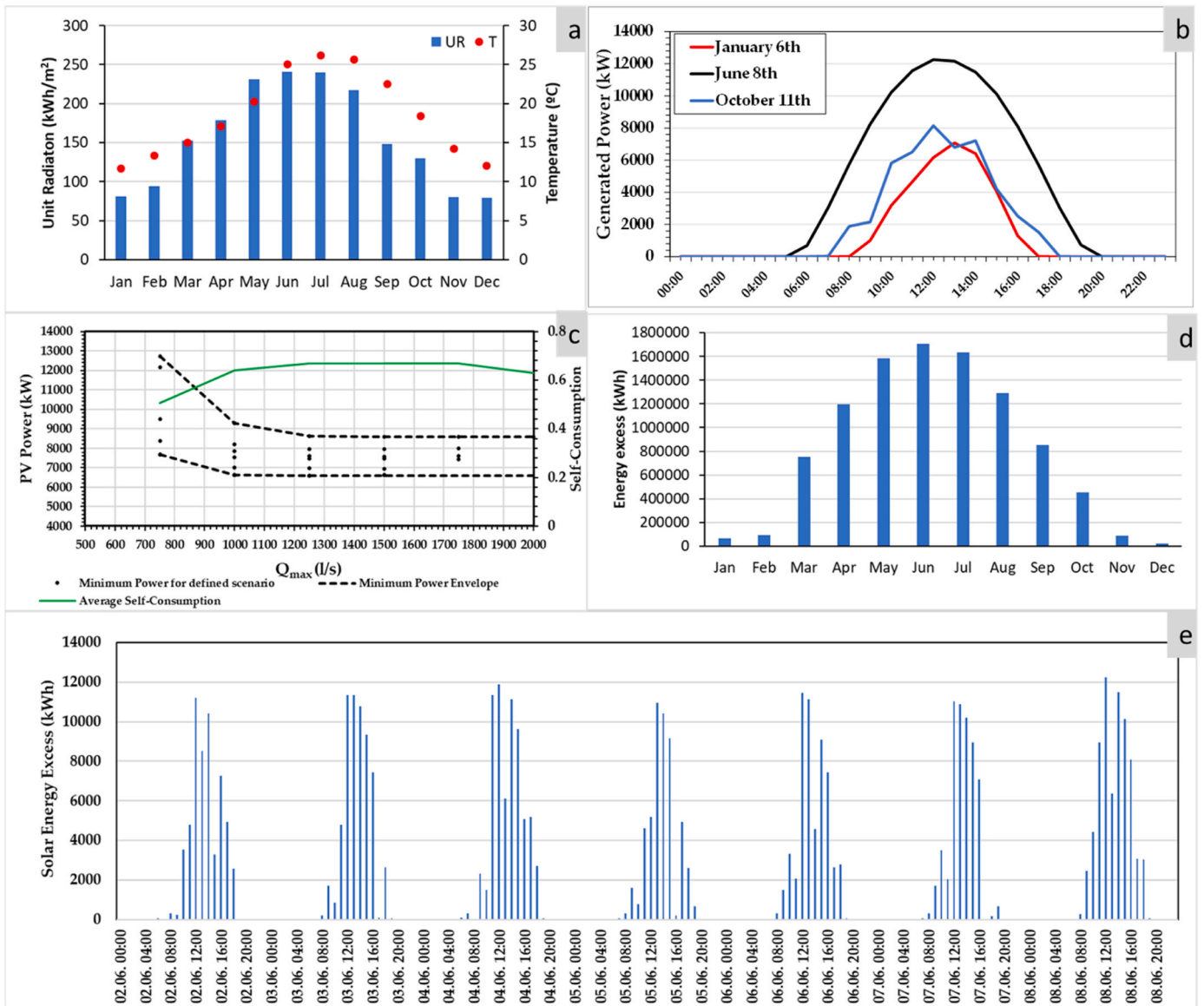


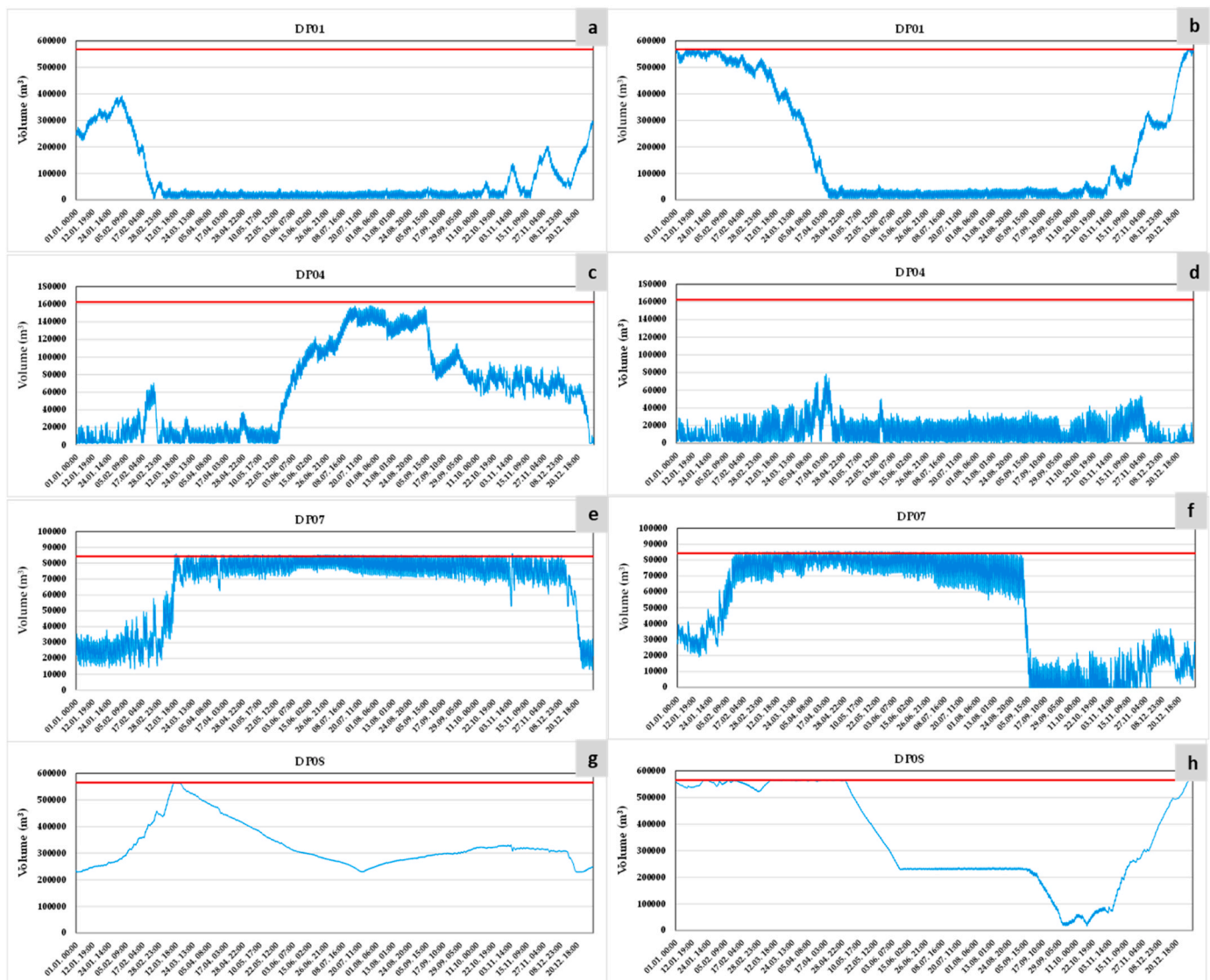
Fig. 6. (a) Unit radiation and average temperature for the case study; (b) Generated power for different days; (c) Example of analysis of needed PV power as a function of flow for distributed ratio; (d) Monthly solar energy excess; and (e) Example of hourly excess between 2nd and 8th June.

equal to the final level (31st December). It was verified that the system stabilized from the second year onwards, and calculations were made for these scenarios over a total of 3 years, with the results of the last year representing the system’s operation for that scenario. Besides, the proposed strategy also considered transient situations, called non-periodic operations. 1353 calculation scenarios with non-periodic operation were generated. These scenarios were made by combining the 123 demand distribution hypotheses, which were enumerated between 53 and 176. Each demand distribution hypothesis was combined with the 11 different demand situations. These scenarios corresponded to non-typical operating conditions. It assumed that the system operated in a periodic operating scenario, and the operating conditions were disrupted, shifting to a non-periodic operating scenario. This disruption was maintained throughout one year, after which the system returned to a periodic operating scenario and it was stabilized to a typical operating situation. Finally, the strategy considered the situation of the operation of RS01. Once again, the 572 scenarios in periodic situations and the 1353 scenarios in non-periodic situations were addressed, studying the system’s behavior and evaluating the system’s regulation to assess its performance in response to zero discharge. Therefore, 3850 scenarios

were evaluated to define the behavior of the water systems in regulation terms. Once the regulation was satisfied the pipe optimization was developed considering the different indexes defined in step IV.C. The size-optimized procedure considers the investment costs of the pipes by LCOE value.

Fig. 5a shows the analysis of flow frequency developed in the optimization procedure. It enables to analysis of the operation of each pipe for each scenario, defining the probability of flow exceedance (Fig. 5b) when the diameter is defined. For this chosen diameter, the Levelized Cost of Energy (LCOE), Net Present Value (NPV) and Energy Water Footprint (EWF) values were defined (Figs. 5c and 5d). LCOE and NPV values considered  $T$  equal to 25 years and  $k_{RD}$  equal to 0.07. The selected diameter is conditioned to meet the minimum LCOE value of the series of diameters analysed in each line (Fig. 5c). For each line, there is a value of LCOE and NPV. Therefore, the values are relative values applied to the line under study. In the case of NPV, the values are negative because it is a particularized and individualized analysis for each line. Therefore, the methodology takes the maximum NPV value that usually coincides with the minimum LCOE value.

The selection of diameters enabled the establishment of the



**Fig. 7.** (a) Reservoir DP01 when scenario S001 is analysed without RS01; (b) Reservoir DP01 when scenario S001 is analysed with RS01 activated; (c) Reservoir DP04 when scenario S001 is analysed without RS01; (d) Reservoir DP04 when scenario S001 is analysed with RS01 activated; (e) Reservoir DP07 when scenario S001 is analysed; (f) Reservoir DP07 when scenario S572 is analysed; (g) Reservoir DP08 when scenario S001 is analysed; and (h) Reservoir DP08 when scenario S572 is analysed.

photovoltaic needs according to the consumed power by the different pump stations. Analysed the radiation for each hour over the year, the needs of generated power were recognized to satisfy the irrigation demand and zero discharge of the WWTP.

Fig. 6a shows the input data used (i.e., unit radiation and temperature). These data enabled the calculus of the hourly generated solar power over the year (Fig. 6b), showing the difference of the solar generation over time. For example, solar generation is reduced a 32% if January is compared to June. Fig. 6c shows an example in which the strategy can define the involved, which determines the minimum power to install as a function of the pumped flow in one of the pump stations. The involve contains the different analysed scenarios. This encompasses enabling the definition of the nominal pumped flow to satisfy the distributed ratio (*DR*) in the water system, as well as the minimum photovoltaic power to install. The proposal can define the average self-consumption for each flow and installed power for the analysed scenarios.

Fig. 6d shows the result analysis of the proposed tool, which defines the excess of generated solar energy. It shows the proposed strategy can minimize the photovoltaic system installed in the case study, reducing

the generated energy excess between November and February, maintaining the distribution ratios and discharge distribution ratios equal to one in periodic operation and very close to one in the non-periodic scenarios. December showed an excess equal to 2.38%, while June showed 60.12%. An example of this hourly distribution of excess is shown in Fig. 6e. The knowledge of this distribution enables the management of the green compensation of the consumption in PS00, which is supplied by the grid to pump all volume of the WWTP.

Once the photovoltaic system is defined in power terms, the different pump systems was chosen using a database, optimizing their operation according to operational curves (i.e., head and power curves) to reach the best efficiency point in the system. Besides, the strategy establishes the operation of different recovery systems, to define and estimate the operational curve. The analysis enables the definition of the operation of all elements of the system, including the operation hours of the osmosis system throughout the day to guarantee the quality of the water. The analysis of the different scenarios shows the diverse behavior of the reservoirs and therefore, it enables the definition of the different technical indexes described in the previous section. An example, Fig. 7 shows the different behavior of some reservoirs when the scenario changed and

**Table 3**  
Distributed Volume Ratio (DVR), Global Distribution Ratio (GDR) and relationship between alternatives.

Id	Alternative	PV power (MW)	Volume DP01 (m <sup>3</sup> )	Q <sub>PS01</sub> (m <sup>3</sup> /s)	DVR			GDR			DVR relationship	GDR relationship
					Min	Max	Average	Min	Max	Average	Average	Average
1	1	15	650,000	1.79	0.944	1.000	0.981	0.944	1.000	0.984	1.000	1.000
2	2	15	650,000	1.79	0.919	0.971	0.950	0.920	0.977	0.954	0.969	0.970
3	2	15	650,000	2.70	0.920	0.971	0.951	0.920	0.978	0.955	0.969	0.972
4	2	18.75	650,000	1.79	0.922	1.000	0.976	0.923	1.000	0.977	0.995	0.993
5	2	18.75	400,000	1.79	0.906	0.995	0.963	0.909	1.000	0.966	0.981	0.982
6	2	18.75	200,000	1.79	0.895	0.981	0.951	0.897	0.996	0.954	0.969	0.969
7	2	18.75	200,000	2.70	0.900	0.987	0.955	0.900	1.000	0.959	0.973	0.975
8	3	15	60,000	1.79	0.863	0.900	0.887	0.863	0.918	0.896	0.905	0.911
9	3	15	60,000	2.70	0.865	0.903	0.889	0.866	0.923	0.898	0.907	0.913
10	3	18.75	60,000	1.79	0.889	0.951	0.929	0.891	0.965	0.934	0.947	0.950
11	3	18.75	60,000	2.7	0.889	0.953	0.930	0.889	0.969	0.936	0.947	0.952

**Table 4**  
Used Generated Power Ratio (UGPR), Distributed energy consumed ratio (DECR) and manometric regulation ratio (MRR).

Id	UGPR (Wp/m <sup>3</sup> )			DECR (kWh/m <sup>3</sup> )			MRR		
	Min	Max	Average	Min	Max	Average	Min	Max	Average
1	1.086	1.150	1.104	0.910	1.002	0.970	1.528	1.687	1.622
2	1.111	1.180	1.138	1.203	1.317	1.253	1.742	2.028	1.911
3	1.110	1.180	1.136	1.201	1.316	1.253	1.780	2.069	1.952
4	1.357	1.470	1.390	1.203	1.325	1.259	1.772	2.025	1.924
5	1.357	1.493	1.407	1.204	1.321	1.255	1.752	2.037	1.929
6	1.362	1.513	1.425	1.197	1.320	1.254	1.743	2.050	1.927
7	1.357	1.507	1.416	1.200	1.320	1.254	1.786	2.089	1.971
8	1.182	1.258	1.212	1.370	1.493	1.423	1.816	2.269	2.097
9	1.176	1.254	1.209	1.371	1.493	1.423	1.850	2.316	2.136
10	1.406	1.523	1.453	1.377	1.501	1.433	1.909	2.258	2.110
11	1.401	1.526	1.450	1.376	1.501	1.432	1.946	2.299	2.151

the hydrostorage pump system was established.

The analysis of the levels of the proposed strategy through the tool makes it possible to know at all times the level of all the reservoirs according to the calculation scenario. This knowledge is crucial for the management of wastewater reuse systems because if conditions change (water quality, mixing conditions, solar radiation, demand curve), the water manager will be able to define criteria for action, with prior knowledge of the system's response in a simulated manner that will help them to optimize decision-making. Figs. 7a to 7d show the behavior of the control reservoirs (DP01 and DP04) is different when the hydro storage pump system is activated. The use of RS01 enables the PS02 operating at different hours when there is no radiation. It implies the pumped volume can reach 20% of the total annual volume, using the renewable energy generated by RS01. It enables the reduction of the installed photovoltaic power and it increases the operation guarantee without solar radiation.

Fig. 7e and f compared a reservoir (i.e., DP07) for different scenarios (DI and DTI are different). It shows the annual behavior of the reservoir varies. DP08 shows similar results and the significance of the analysis of scenarios as a function of the DI and DTI.

The different alternatives were simulated to compare the different indexes proposed (Step V). This case study develops 11 different alternatives in terms of reservoir location and operation. The procedure established the comparison between them considering all scenarios. Table 3 shows the values for the different proposed indexes. It shows the best solution is Id= 1. This alternative established the DVR value between 0.944 and 1, being the average value equal to 0.981 when the 1925 scenarios were analysed. When the GDR was analysed this alternative also showed the best results, being the range between 0.944 and 1. A comparison with the current situation is not possible as the water is currently discharged into the sea and is not usable for irrigation. Comparing with other systems does not make sense as it depends on the

topography of the systems (Garcia et al., 2023). A study of alternatives is shown in Table 3. It allows water managers to evaluation of the indicators operating in the same topography with different solutions for the location of reservoirs, lengths of pipelines, and manometric head but maintaining the volume distributed and the demand scenarios.

Energy ratios were examined and they are shown in Table 4. The best alternative is Id= 1 for these indicators again showing the best values in terms of requirement power, energy consumed and manometric head regulation. The energy ratio oscillated between 0.91 and 1.002 kWh/m<sup>3</sup>, minimizing the manometric head ratio to 1.528 considering the water distribution is developed to different levels, which are located at heights equal to 90 and 210 m and water is taken from a height equal to 45 m.

Finally, the strategy can show the different indicators. Fig. 8 shows the development of the strategy for water managers to improve the management of water systems, as well as the optimization of the indicators for the best solution. Fig. 8a shows the capacity ratio (CR) when DP01 is analysed. It shows the capacity of the reservoir was optimized by this proposed procedure, showing CR above 0.95 when DI and DTI are above 0.35 and 1.3, respectively, being the minimum value 0.65, when all consumption nodes demanded the ideal demand curve in average values H<sub>0</sub>. Similar values could be seen when CR was analysed in DP06 (Fig. 8b). The CR ratio was above 0.9 when DI were above 0.4, being able to supply the distribution of the irrigation communities with values of DTI between 1 (nominal conditions) and 2.44.

Fig. 8c shows the high answer of the DP06 reservoir to distribute different demanded volumes in any situation, when DI and DTI oscillated between their minimum and maximum values. Fig. 8d shows DR when DP08 was analysed. This reservoir showed DR values equal to 1 for DI lower than 0.81 and any DTI value. The minimum value for DTI was 0.96 considering DI equal to 1 and DTI between 1 and 1.5. Fig. 8e shows the capacity of the proposal to analyse the energy distribution ratio for

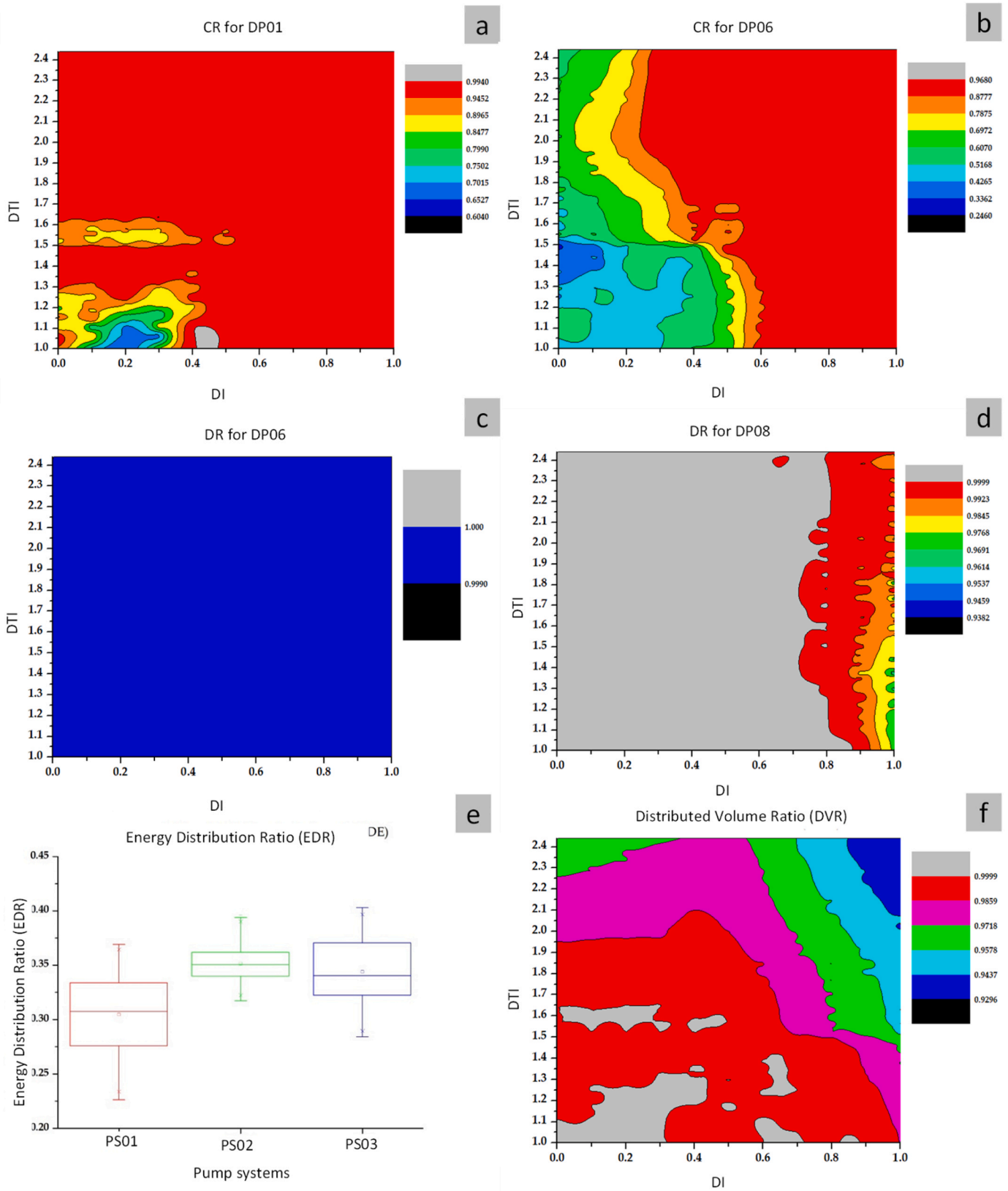


Fig. 8. (a) CR for DP01; (b) CR for DP06; (c) DR for DP06; (d) DR for DP08; (e) EDR for pump systems; and (f) Distributed Volume Ratio (DVR).

all pump systems in any scenario. The procedure discretized the EDR value for each pump system, showing values between 0.23 and 0.40 as a function of the analysed pump system.

Fig. 8f shows the key to the strategy. It shows the distributed volume

ratio (DVR) according to the variation of DI and DTI. Excellent results were defined by the proposal because the objective was satisfied (zero discharge when DVR is equal to 1) when DI was lower than 0.5 for any DTI value. If DTI was lower than 1.9, the resilience of the system was

**Table 5**  
Energy values when recovery systems are activated in the proposal.

	Annual volume operated with RS01 from DP04 to DP01 (hm <sup>3</sup> )	Annual volume pumped by PS02 using energy of RS01 (hm <sup>3</sup> )	Annual recovered energy by RS01 (MWh)	Ratio pumped flow with PS02 (m <sup>3</sup> /s)	Annual Recovered energy by RS02 (MWh)	Annual recovered energy by RS03 (MWh)
Max	5.625	2.743	1790.76	[0.1836-0.2028]	493.74	769.66
Mín	3.681	1.842	1150.34	[0.1763-0.1930]	210.17	48.54
Average	4.425	2.193	1398.47	[0.1800-0.1984]	371.48	312.17
Median	4.467	2.217	1412.02	[0.1806-0.1985]	398.37	301.30

able to achieve the goal ( $DVR=1$ ) when  $DI$  was between 0.5 and 0.7. If Fig. 8f is analysed the minimum value was 0.96 and it was achieved for the stress situation ( $DI$  above 0.95 and  $DTI$  above 2.2).

Finally, Table 5 shows a summary of the highlights supported by the recovery systems, which were analysed in the proposal strategy. The pumped hydro storage system RS01 operated between 3.68 and 5.62 hm<sup>3</sup> each, as a function of the considered scenario. It implied an annual recovered energy between 1150.34 and 1790.76 MWh. This energy enabled the activation of the PS02 system when the photovoltaic system is turned off, pumping between 0.1763 and 0.2028 m<sup>3</sup>/s. The average value of annual recovered energy in RS02 and RS03 was 398.37 and 301.3 MWh, respectively.

#### 4. Conclusions

Climate change is causing an escalation in water deficits in specific regions, such as the Mediterranean. Consequently, the diminishing water resources resulting from factors, such as reduced water transfers and the intrusion of saline water into underground boreholes are compelling the exploration of novel sources for integration into distribution systems. In the context of wastewater utilization, it serves two primary objectives: mitigating water deficits and curbing the environmental repercussions associated with discharging treated water into the sea. The methodology postulates a zero-discharge framework wherein water, having undergone partial osmosis to attain an irrigation-appropriate quality level, becomes available for utilization by irrigation communities.

The research represents a significant stride in advancing the sustainability of irrigation systems through the implementation of regenerated wastewater systems. As a novel, the optimized system introduces new resources to be used in irrigation systems by hybrid systems. The approach enables the extrapolation of this methodology in coastal areas, which are around 50% of the world's people and it is a solution to reduce the hydric deficit caused by climate change. The strategy sets forth a comprehensive approach, encompassing the development of a tool for demand forecasting, renewable energy generation, pump system management, and the osmosis process to produce irrigation water of requisite quality. The tool can adapt the operation of the system as a function of the water salinity from WWTPs by changing the mixing of water (i.e., desalination and non-desalinated). Different objective functions will allow water managers to adapt as a function of the different variables. Besides, the methodology evaluates the behavior of the system in a periodic state, therefore it can analyse the behavior of the water system when the demand of the irrigation communities changes.

This proposed strategy incorporates the selection of the most optimal solution based on sustainable metrics, which assess the system from technical, environmental, and economic standpoints. Uniquely, this strategy establishes operational criteria aimed at minimizing wastewater discharge while maximizing the distribution of this resource to cater to the needs of irrigation communities following demand indices. Furthermore, it is designed to seamlessly integrate renewable systems to ensure net-zero energy consumption from the grid.

The concurrent utilization of solar pumping with floating panels, micro-hydro generation, and the storage of potential energy in elevated ponds demonstrates its viability from a resource efficiency standpoint.

This methodology was effectively applied to an actual case study situated in Alicante, and its applicability can be extended to other irrigation regions equipped with purification systems, which are located in coastal municipalities. It will enable the integration of these waters into their water cycles in a sustainable manner. Future research endeavors should concentrate on achieving a more precise parameterization of irrigation community demands to enhance regulation. This, in turn, will facilitate a more targeted optimization effort aimed at minimizing the volumes utilized and optimizing the photovoltaic system. The incorporation of these resources will necessitate irrigation communities to confront new management paradigms.

#### Funding

Funding for open access charge: CRUE-Universitat Politècnica de València. The authors would like to acknowledge the grant PID2020-114781RA-I00 funded by MCIN/AEI/10.13039/501100011033.

#### CRedit authorship contribution statement

**Zapata Francisco A.:** Conceptualization. **Ramos Helena M:** Visualization. **López-Jiménez P. Amparo:** Visualization. **Sánchez-Romero Francisco-Javier:** Validation, Software, Methodology, Conceptualization. **Pérez-Sánchez Modesto:** Writing – review & editing, Writing – original draft, Software, Methodology, Funding acquisition, Conceptualization.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

The data that has been used is confidential.

#### Acknowledgment

The research was developed along on research stay of the corresponding author called "THE IMPROVEMENT OF THE ENERGY EFFICIENCY IN WATER SYSTEMS USING MICROHYDROPOWERS SYSTEMS AND OTHER RENEWABLE SYSTEMS".

#### References

- Azuz-Adeath, I., Rivera-Arriaga, E., 2009. Descripción de la dinámica poblacional en la zona costera mexicana durante el periodo 2000-2005. *Pap. De. Poblac.* 15, 75–107.
- Becken, S., McLennan, C. Lee, 2017. Evidence of the water-energy nexus in tourist accommodation. *J. Clean. Prod.* 144, 415–425. <https://doi.org/10.1016/j.jclepro.2016.12.167>.
- Biswas, W.K., Bryce, P., Diesendorf, M., 2001. Model for empowering rural poor through renewable energy technologies in Bangladesh. *Environ. Sci. Policy* 4, 333–344. [https://doi.org/10.1016/S1462-9011\(01\)00031-4](https://doi.org/10.1016/S1462-9011(01)00031-4).
- Bolinches, A., Blanco-Gutiérrez, I., Zubelzu, S., Esteve, P., Gómez-Ramos, A., 2022. A method for the prioritization of water reuse projects in agriculture irrigation. *Agric. Water Manag.* 263, 107435 <https://doi.org/10.1016/j.agwat.2021.107435>.
- Canales, F.A., Beluco, A., Mendes, C.A.B., 2015. A comparative study of a wind hydro hybrid system with water storage capacity: conventional reservoir or pumped

- storage plant? *J. Energy Storage* 4, 96–105. <https://doi.org/10.1016/j.est.2015.09.007>.
- Caniglia, B., Frank, B., Kerner, B., Mix, T.L., 2016. Water policy and governance networks: a pathway to enhance resilience toward climate change. *Sociol. Forum* 31, 828–845. <https://doi.org/10.1111/socf.12275>.
- Dorji, T., Urmee, T., Jennings, P., 2012. Options for off-grid electrification in the Kingdom of Bhutan. *Renew. Energy* 45, 51–58. <https://doi.org/10.1016/j.renene.2012.02.012>.
- García, C., López-Jiménez, P.A., Sánchez-Romero, F.J., Pérez-Sánchez, M., 2023. Assessing water urban systems to the compliance of SDGs through sustainability indicators. Implementation in the valencian community. *Sustain. Cities Soc.* 96, 104704 <https://doi.org/10.1016/j.scs.2023.104704>.
- Hanjra, M.A., Blackwell, J., Carr, G., Zhang, F., Jackson, T.M., 2012. Wastewater irrigation and environmental health: implications for water governance and public policy. *Int. J. Hyg. Environ. Health* 215, 255–269. <https://doi.org/10.1016/j.ijheh.2011.10.003>.
- Jodar-Abellán, A., López-Ortiz, M.I., Melgarejo-Moreno, J., 2019. Wastewater treatment and water reuse in Spain. Current situation and perspectives. *Water* 11, 17–22. <https://doi.org/10.3390/w11081551>.
- Mercedes García, A.V., Sánchez-Romero, F.J., López-Jiménez, P.A., Pérez-Sánchez, M., 2022. A new optimization approach for the use of hybrid renewable systems in the search of the zero net energy consumption in water irrigation systems. *Renew. Energy* 195, 853–871. <https://doi.org/10.1016/j.renene.2022.06.060>.
- Millinger, M., Mårilind, T., Ahlgren, E.O., 2012. Evaluation of Indian rural solar electrification: a case study in Chhattisgarh. *Energy Sustain. Dev.* 16, 486–492. <https://doi.org/10.1016/j.esd.2012.08.005>.
- Ministerio de agricultura, 2020. pesca y alimentación Análisis y Prospectiva-Serie Pesca no5 Demografía de la población costera en.
- Mohammed, I.N., Bolten, J.D., Souter, N.J., Shaad, K., Vollmer, D., 2022. Diagnosing challenges and setting priorities for sustainable water resource management under climate change. *Sci. Rep.* 12 (1), 15. <https://doi.org/10.1038/s41598-022-04766-2>.
- Molinos-Senante, M., Hernández-Sancho, F., Sala-Garrido, R., 2011. Cost-benefit analysis of water-reuse projects for environmental purposes: a case study for Spanish wastewater treatment plants. *J. Environ. Manag.* 92, 3091–3097. <https://doi.org/10.1016/j.jenvman.2011.07.023>.
- Mora, A., Torres-Martínez, J.A., Capparelli, M.V., Zabala, A., Mahlkecht, J., 2022. Effects of wastewater irrigation on groundwater quality: an overview. *Curr. Opin. Environ. Sci. Heal.* 25, 100322 <https://doi.org/10.1016/j.coesh.2021.100322>.
- Obaideen, K., Shehata, N., Sayed, E.T., Abdelkareem, M.A., Mahmoud, M.S., Olabi, A.G., 2022. The role of wastewater treatment in achieving sustainable development goals (SDGs) and sustainability guideline. *Energy Nexus* 7, 100112. <https://doi.org/10.1016/j.nexus.2022.100112>.
- Partyka, M.L., Bond, R.F., 2022. Wastewater reuse for irrigation of produce: a review of research, regulations, and risks. *Sci. Total Environ.* 828, 154385 <https://doi.org/10.1016/j.scitotenv.2022.154385>.
- Pérez-Sánchez, M., Sánchez-Romero, F., Ramos, H., López-Jiménez, P.A., 2017. Optimization strategy for improving the energy efficiency of irrigation systems by micro hydropower: practical application. *Water* 9, 799. <https://doi.org/10.3390/w9100799>.
- Picazo, M.Á.P., Juárez, J.M., García-Márquez, D., 2018. Energy consumption optimization in irrigation networks supplied by a standalone direct pumping photovoltaic system. *Sustain* 10. <https://doi.org/10.3390/su10114203>.
- Ríos, I.H., Cruz-Pérez, N., Chirivella-Guerra, J.L., García-Gil, A., Rodríguez-Alcántara, J. S., Rodríguez-Martín, J., Marazuela, M.Á., Santamarta, J.C., 2023. Proposed recharge of island aquifer by deep wells with regenerated water in Gran Canaria (Spain). *Groundw. Sustain. Dev.* 22, 100959 <https://doi.org/10.1016/j.gsd.2023.100959>.
- Rossmann, L.A., 2000. EPANET 2: User's Manual. U.S. EPA, Cincinnati.
- Sánchez Romero, F.J., 2014. Criterios de Seguridad En Balsas De Tierra Para Riego. Universitat Politècnica de València, Valencia (Spain).
- Sánchez-Romero, F.J., López-Jiménez, P.A., Pérez-Sánchez, M., 2022. APLIRE. (<http://aplicat.upv.es/exploraupv/ficha-tecnologia/patente-software/42308>).
- Su, C., Madani, H., Liu, H., Wang, R., Palm, B., 2020. Seawater heat pumps in China, a spatial analysis. *Energy Convers. Manag.* 203, 112240 <https://doi.org/10.1016/j.enconman.2019.112240>.
- Tarroja, B., AghaKouchak, A., Sobhani, R., Feldman, D., Jiang, S., Samuelsen, S., 2014. Evaluating options for balancing the water-electricity nexus in California: Part 2-greenhouse gas and renewable energy utilization impacts. *Sci. Total Environ.* 497–498, 711–724. <https://doi.org/10.1016/j.scitotenv.2014.06.071>.
- Trapote, A., Albaladejo, A., Simón, P., 2014. Energy consumption in an urban wastewater treatment plant: the case of Murcia region (Spain). *Civ. Eng. Environ. Syst.* 31, 304–310. <https://doi.org/10.1080/10286608.2013.866106>.
- Tsakiris, G., Spiliotis, M., 2014. A Newton-Raphson analysis of urban water systems based on nodal head-driven outflow. 18, pp. 882–896. [doi:10.1080/19648189.2014.909746](https://doi.org/10.1080/19648189.2014.909746).
- Ungureanu, N., Vlăduț, V., Voicu, G., 2020. Water scarcity and wastewater reuse in crop irrigation. *Sustain* 12, 1–19. <https://doi.org/10.3390/su12219055>.
- Vidović, V., Krajačić, G., Matak, N., Stunjek, G., Mimica, M., 2023. Review of the potentials for implementation of floating solar panels on lakes and water reservoirs. *Renew. Sustain. Energy Rev.* 178, 113237 <https://doi.org/10.1016/j.rser.2023.113237>.
- Vujanović, M., Wang, Q., Mohsen, M., Duić, N., Yan, J., 2021. Recent progress in sustainable energy-efficient technologies and environmental impacts on energy systems. *Appl. Energy* 283, 116280. <https://doi.org/10.1016/j.apenergy.2020.116280>.
- Zhan, X., Huang, M.L., 2004. ArcCN-Runoff: an ArcGIS tool for generating curve number and runoff maps. *Environ. Model. Softw.* 19, 875–879. <https://doi.org/10.1016/j.envsoft.2004.03.001>.
- Zobeidi, T., Yaghoubi, J., Yazdanpanah, M., 2022. Farmers' incremental adaptation to water scarcity: an application of the model of private proactive adaptation to climate change (MPPACC). *Agric. Water Manag.* 264, 107528 <https://doi.org/10.1016/j.agwat.2022.107528>.