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Treated wastewater reuse for irrigation: A feasibility study in Portugal

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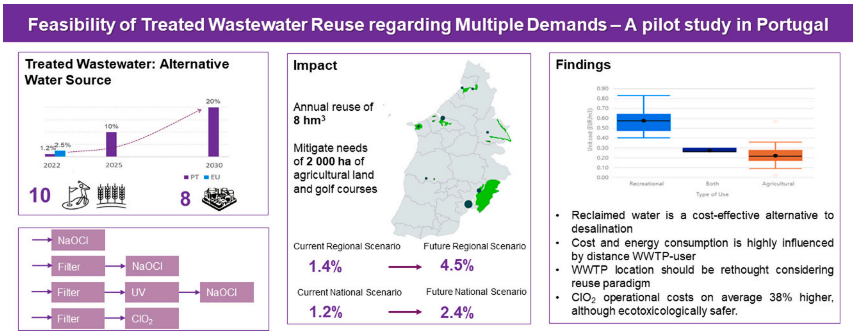
HIGHLIGHTS

- Eight selected Portuguese WWTP enable an annual reuse of 8 hm^3.
- This wastewater reuse programme could double Portuguese current marks (+1.2 %).
- Agricultural uses are foreseen to cost 0.02–0.57€/m^3.
- Recreational uses cost 0.43–0.83€/m^3 due to higher user distances and lower volumes.
- Distance to users and annual water consumption were shown as main cost determinant.

GRAPHICAL ABSTRACT



- Reclaimed water is a cost-effective alternative to desalination
- Cost and energy consumption is highly influenced by distance WWTP-user
- WWTP location should be rethought considering reuse paradigm
- ClO_2 operational costs on average 38% higher, although ecotoxicologically safer.

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ABSTRACT

In an increasing water scarcity and climate-vulnerable global context, treated wastewater represents a vital alternative water source, thereby enhancing resource sustainability. Despite its potential, only roughly 2.5 % of the treated wastewater is reused in the European Union, with Portugal's reuse rate being only 1.2 % in 2022. Considering this framework, this study evaluates the feasibility of increasing wastewater reuse in Portugal by focusing on the Tagus River and Ribeiras do Oeste Basins. The regional assessment identified eight key wastewater treatment plants (WWTP) with significant potential for irrigation reuse in the agriculture and tourism sectors. Analysing costs, quality requirements, and technological options, this study considered five treatment lines, incorporating filtration and disinfection methods. The findings indicate that reclaimed water costs may range from 0.02€/m^3 to 0.83€/m^3, being competitive with other water sources and significantly lower than desalination processes (up to 1.66€/m^3). Distribution investments and energy consumption are primary cost drivers, suggesting a relocation of WWTP closer to end-users as a cost-saving strategy. The proposed reuse

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projects could quadruple regional reuse rates and double the national rate, mitigating water needs for over 2000 ha of agricultural land and golf courses. This study underscores the importance of treated wastewater reuse in addressing water scarcity, advocating for WWTP decentralisation, strategic investments and policy interventions to achieve cost-effective goals. The methodologies and insights presented offer valuable guidance for other regions facing similar challenges, promoting a paradigm shift towards circular water resource management.

1. Introduction

Integrated water resource management faces a significant challenge due to climate changes amid rising concerns over water scarcity and drought. The impacts are particularly pronounced in the Mediterranean region, where climate change and population expansion are anticipated to raise irrigation demands by 74 %, worsening the already strained region (Fader et al., 2016). As water scarcity intensifies, the search for sustainable water sources becomes imperative. Reclaimed wastewater surges as a secure alternative to conventional water sources, that can reduce dependence on water bodies (Garcia and Pargament, 2015).

Despite this undeniable reality, wastewater reuse in the European Union remains very limited, with an average reuse rate of only 2.5 % (European Water Association, 2022), explained by the conservative thinking promoted by financial, administrative, and social acceptance challenges (Bolinches et al., 2022). However, some countries have managed to achieve higher rates, such as Cyprus (95 %) (WaterEurope, 2021) and Malta (60 %) (NURSECOAST, 2023), with Spain (13 %) (Jodar-Abellan et al., 2019) and Italy (4 %) striving for it (Re et al., 2020). Portugal, despite facing similar climatic challenges, has not yet significantly invested in water reclamation. Current reuse rates stand at 1.2 % (ERSAR, 2022), notably low compared with the government targets set to achieve a 10 % reuse rate by 2025 and 20 % by 2030 (Governo de Portugal, 2019).

Given this context, the agricultural and recreational sectors emerge as key areas for potential growth in wastewater reuse due to their substantial water demands and the critical role of irrigation in Mediterranean agriculture. In 2015, the agricultural sector alone used about 75 % of Portuguese water resources, similar to other South European countries (FAO, 2024). Developing strategies to enhance water-use efficiency and resilience is crucial for sustaining agricultural productivity and reducing dependency on external sources. Reclaimed water is a *Water-Energy-Food Nexus* carrier that can serve as a complementary water source, promoting circular economy principles by reusing nutrients in soils and reducing reliance on chemical fertilizers (Garcia and Pargament, 2015), hence decreasing the burden on food production (Radini et al., 2021).

The European Regulation 2020/741 established guidelines for the reuse of treated wastewater reuse, setting quality requirements for various agricultural irrigation purposes, and guaranteeing its safe usage in European countries (Mannina et al., 2022). This regulation came in line with the European goals to achieve environmental protection, and maintain the freshwater sources quality (Bieroza et al., 2021). This happens since treated wastewater reuse in agricultural soils allows both water and nutrient reuse (e.g., nitrogen, phosphorus) (Mannina et al., 2023), limiting its discharge on pressured aquatic environments and promoting the urban water cycle circularity. Besides, these practices decrease the costs associated with fertilization through the application of natural fertigation (Ofori et al., 2021), a farm-to-fork practice that alleviates the pressure under the Water-Food-Ecosystem Nexus (Marinelli et al., 2021). Nonetheless, by encouraging the use of alternative water sources for irrigation, Regulation (EU) 2020/741 indirectly reduces the reliance on aquifer and freshwater extraction, thereby contributing to the preservation of natural water bodies and promoting hydrological balance (Manganiello et al., 2024). Although more detailed studies are required to determine the overall carbon footprint balance, water reclamation has exhibited the potential to reduce the actual societal carbon footprint, mostly the one related to food production (Lahlou et al., 2022).

It is paramount to provide policymakers and water resource managers with all information regarding the availability and economic viability of water reclaim projects. Previous studies highlight the importance of robust methodologies for assessing the feasibility and help prioritize wastewater reuse projects based on scientific evidence. Studies have developed various indices that evaluate wastewater reuse considering criteria based on crop water and nutrient needs, WWTP water volumes (Vivaldi et al., 2022), crop type, climate conditions, water policies, proximity to WTTP (Paul et al., 2019), effluent quality, and rainfall (Penserini et al., 2024), although risk analysis is frequently overlooked. Economic considerations are also critical, as the viability of water reclaim projects depends heavily on the associated costs and the willingness of end-users to pay for reclaimed water. Pistocchi et al. (2017) provided an overarching study at the European level on the costs of reclaiming and transporting treated wastewater for reuse, but the macro-level analysis eventually neglects locally relevant features, such as existing irrigation infrastructure, effluent quality and fit-for-purpose treatments adapted to the user needs.

The study aims to design a first methodology integrating technical, cost and risk assessments to address Portugal's wastewater reuse gap by using the case of Tagus River and Ribeiras do Oeste Basins. Focusing on major water consumers in drought-prone agricultural and tourism sectors demonstrates the undeniable reclaimed water's role in sustainable water planning in Portugal and beyond. This granular approach allows for an accurate and actionable evaluation of the feasibility of wastewater reuse projects, identifying key WWTPs capable of supporting large-scale irrigation. Additionally, the study uses the economic findings to challenge traditional WWTP placement strategies, advocating a paradigm shift towards circular water resource management.

2. Materials and methods

To tackle this increasing need for reclaimed water production, a comprehensive methodology was designed. The process starts with the selection of WWTP based on characterization data (e.g., quality, flow, possible reclaimed water consumers), for which were determined both the supplying water capacity and the potential consumer's consumption requirements (i.e., quality, flow). Based on that knowledge, treatment trains were considered, together with the associated supply networks. In the final step, investment, operational costs and risks were assessed to allow a comparison and selection of the proposed solutions.

2.1. Data collection and WWTP prioritisation

The initial phase of this work consisted of a data-driven prioritisation exercise that supported the selection of pivotal case studies for in-depth study. All the 100 WWTP managed by AdTA were characterized using several key properties: maximum potential production rate (hm^3/year), effluent pollution load (TSS, BOD, N, NH_4 and P), quality of treated wastewater and treatment system. Simultaneously, each area of influence distancing 5 km from the WWTP was analysed through remote sensing imagery and territorial management instruments, to identify major irrigation users (i.e., agriculture, recreational). In an effort to align potential supply with demand, the WWTP with higher potential production rates located near major water consumers were subset, resulting in the selection of eight key WWTP (Alverca, Atouguia da Baleia, Charneca, Fervença, Nazaré, Rio Maior, Turcifal, Vila Franca de

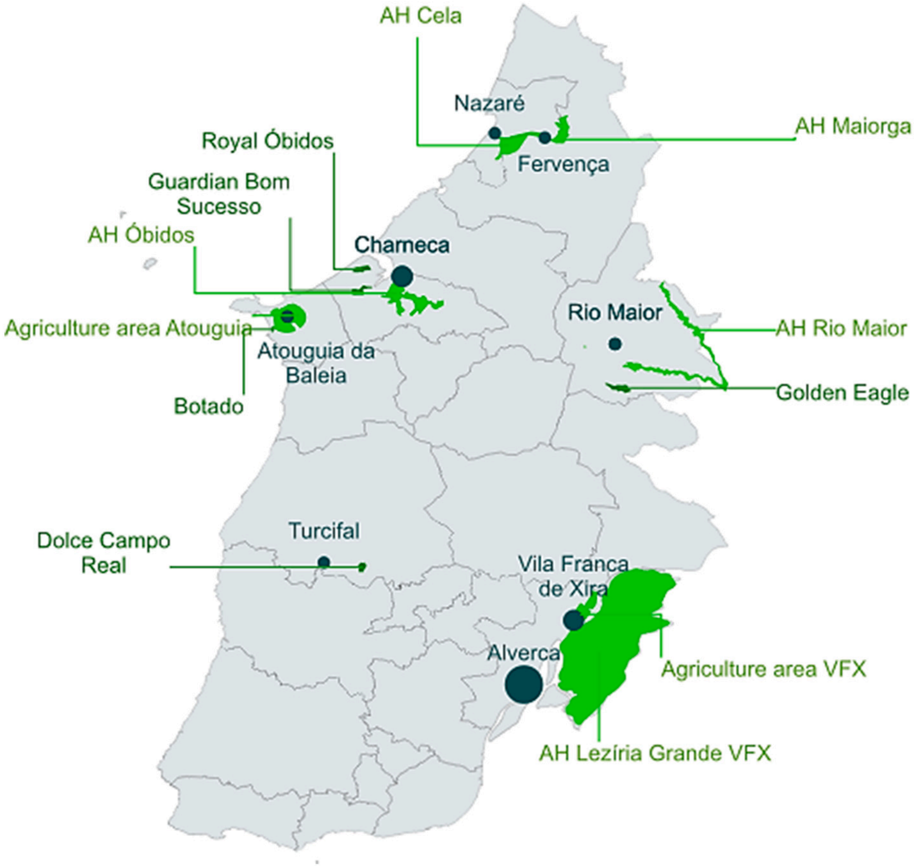

Fig. 1. Location of the eight WWTP studied and respective potential users analysed.

Table 1
Description of WWTP characteristics. EAAS – Extended aeration activated sludge, CAS – Conventional activated sludge, SBR – Sequence Batch Reactor, F – Filter, UV – Ultraviolet, NaOCl – Sodium Hypochlorite, $FeCl_3$ – Iron Chloride.

WWTP	Influx Flowrate (m^3/day)	Treatment System	Average BOD (mg O_2/L)	Average TSS (mg/L)	Average N (mg/L)	Average P (mg/L)	Particularities
Charneca	5255	EAAS	11	11	31	3	Existent reclaimed water system (F + UV + NaOCl) with a treating capacity of 720m^3/d.
Atouguia da Baleia	2517	SBR + UV	7	13	8	2	Existent reclaimed water system (F + UV + NaOCl) with a treating capacity of 600m^3/d.
Rio Maior	2510	EEAS	11	15	7	2	Presence of disturbing industrial effluent discharges.
Turcifal	1175	EAAS + Anoxic tank	8	11	12	3	Ecological flow needs in the receiving body were considered.
Nazaré	2447	SBR + NaOCl	26	30	29	3	Inefficient treatment system.
Fervença	3430	CAS + NaOCl	9	11	38	5	Effluent quality is compared to class D of reclaimed water quality.
Vila Franca de Xira	8174	$FeCl_3$ + CAS	8	12	31	3	–
Alverca	16,575	CAS + $FeCl_3$	13	30	38	3	Presence of disturbing industrial effluent discharges. High concentration of ammonia.

Xira), that became individual case-studies (Fig. 1).

2.2. Case studies characteristics

The selected WWTP (Table 1) show diverse profiles, with significant variances in inflow rates (1175 m^3/d – 16,575 m^3/d), treatment systems and effluent quality, which highlight the need for tailored approaches to optimize wastewater reuse.

The potential users associated with these WWTP (Table 2) predominantly require quality class B water, according to the Regulation (EU) 2020/741. The difference in irrigation needs and proximity to WWTP are undeniable, particularly when comparing agriculture with golf users, based on the distribution and use of treated wastewater.

2.3. Techno-economic model

For each selected WWTP, multiple treatment systems and distribution networks were evaluated according to the different user scenarios, through a dedicated methodology. This assessment considered factors such as investment, operational and energy cost, quality robustness, technical readiness, microbiological quality, and organic byproduct formation risk.

Table 2
Characteristics of potential reclaimed water users.

WWTP	User	Area (ha)	Pipe length to WWTP (km)	Crops	Minimum Quality Class*	Irrigation Needs (hm^3)
Charneca	Agriculture	1200	7	Fruit trees and vegetables	B	2.81
	Golf	55	9	–	B	0.40
Atouguia da Baleia	Agriculture	237	1	Vegetables (brassicas, roots)	B	0.69
	Golf	7	3	–	B	0.05
Rio Maior	Golf	75	8	–	B	0.53
Turcifal	Golf	28	5	–	B	0.20
Nazaré / Fervença	Agriculture 1	356	6 / 0.2	Pome fruit trees, brassicas and potatoes	B	1.17
	Agriculture 2	454	1 / 2	Vegetables (brassicas, corn, potato), fruit trees, pastures	B	1.30
Vila Franca de Xira	Agriculture 1	470	2	Cereals, tomato for processing	C	3.01
Vila Franca de Xira / Alverca	Agriculture 2	9257	8 / 17	Rice, vegetables, forage	B	91.90

* Quality class according to the Regulation (EU) 2020/741.

2.3.1. *Irrigation requirements and water storage*

For each case study, the potential user's water consumption requirements were determined according to the different uses: agriculture or recreational spaces (golf sector).

Agricultural water consumption needs were determined using historical data from users, where available, or estimated based on river basin reference crop requirements for dry years (APA, 2016a; APA, 2016b; DGADR, 2018) and reported cultivated areas (DGADR, 2021). Distribution and irrigation losses were factored in, which considered an efficiency of 85 % for modern collective irrigation systems, in addition to aspersion or drip irrigation efficiencies of 75 % and 90 %, respectively (APA, 2016a; APA, 2016b). Monthly distribution figures were not available by the users and hence had to be estimated. Since a wide range of crops are cultivated at each site, with staggered sowing periods, an extended irrigation campaign was considered, from April to October, peaking in July and August. Water storage infrastructure was only considered in cases with reservoirs already available, being in the form of dams (AH Óbidos – 5.8 hm^3) or ponds (Atouguia da Baleia – 0.06 hm^3).

In the case of golf courses, regional average consumption figures were used (Almeida and Velosa, 2021), ranging from 7084 m^3/ha to 10,011 m^3/ha. The monthly distribution was determined using FAO's crop water requirements approach [$(ET_o \times K_c) - Re) \times Area$] (Doorenbos and Pruitt, 1977). The effective precipitation (Re) was calculated as the actual precipitation with a runoff coefficient of 50 %, and the constant crop coefficient (K_c) took the value of 0.8, in line with the United States Golf Association guidelines (Gross and Hartwiger, 2016). Monthly precipitation and evapotranspiration (ET_o) used average values from the latest river basin management plan (APA, 2022a). The already existent irrigation ponds in the golf courses were treated as reservoirs for the reclaimed water, using literature sizing considerations (Swistock, 2022).

2.3.2. *Reuse potential*

Estimated water needs were compared with the theoretical reclaimed water production capacity of each corresponding WWTP. The reuse capacity was approximated by subtracting the volume of reclaimed wastewater used for internal WWTP processes from the average treated wastewater volume, with a 5 % water loss being considered.

Additionally, in cases where there is a significant contribution of the treated wastewater discharge to the maintenance of the aquatic ecosystem, ecological flow requirements for the receiving water body were also accounted for. Although the needs of the ecosystem should be studied on a case-by-case basis, data has not been reported for any of the basins under analysis. Hence, Tennant's method was selected for assessing ecological flows in the river basins, corresponding to 10 % of the river's average yearly flow (Tennant, 1975; APA, 2022b), which was approximated to 10 % of the WWTP average effluent flow.

2.3.3. *Design flow*

To define the design flow for treatment and distribution systems, two scenarios were considered: I) the reuse capacity is always higher than the irrigation requirements; II) there are months in which the reuse capacity does not fulfil entirely the irrigation needs, requiring that all flow is used for reclaimed water production.

For the first case, the treatment system was designed for the maximum daily flow required by potential consumers, while the distribution system was designed for the 90th percentile of daily user needs, to avoid oversizing and associated costs. For the second case, where the entire effluent flow from the treatment plant is committed to producing reclaimed water, the treatment system design flow was considered the 90th percentile of the daily wastewater inflow, only for supply months, while the transportation system was designed for the 90th percentile of reuse potential, which excludes other uses also during supply months.

2.3.4. *Treatment system*

Reclaimed water quality requirements followed European and Portuguese legislation for agriculture and recreational irrigation (EU Regulation 2020/741 and Decree-Law n°. 119/2019), adjusted to the type of irrigation and cultivated crops. Different treatment scenarios were proposed and evaluated to ensure the necessary quality and robustness, considering WWTP historical monitoring data, existing main treatment trains, and user requirements. This assessment considered factors such as investment and operational costs, quality robustness, technical readiness and disinfection byproduct formation. Simpler solutions, that maximized water security goals while minimizing costs, were also suggested in a *fit-for-purpose* approach, where lower water quality was acceptable (class B and C – EU Regulation 2020/741).

It was concluded that following secondary or tertiary treatment processes, at least a disinfection step is necessary to comply with the microbiological parameters stipulated in the European regulation. After a thorough literature review, technologies deemed as the most feasible were selected and designed according to the needs of each case study, resulting in four different treatment lines that comply with the defined treatment goals: (I) Disinfection by Sodium Hypochlorite (NaOCl); (II) Disinfection by Sodium Hypochlorite after mechanic filtration (F + NaOCl); (III) Mechanic filtration before disinfection by ultraviolet radiation and sodium hypochlorite (F + UV + NaOCl); (IV) Mechanic filtration before disinfection by chlorine dioxide (F + ClO_2). Each treatment train is focused on solving typical problems in reusing treated wastewater. Solution (I) is proposed for treated wastewater that does not follow the legal pathogen maximum requirements but does guarantee the solid matter concentration limit. On the other side, solution (II) aims to minimize both the microbiological content and the solid matter content. Besides, it can be used to reduce the microbiological content in

Table 3
Likelihood and Severity descriptors and respective description.

Descriptor		Description
Likelihood		
1	Very Unlikely	It has not happened in the past and is highly unlikely to happen in the next 5 years (or another reasonable period)
2	Unlikely	This has not happened in the past but could happen in exceptional circumstances in the next 5 years (or another reasonable period)
3	Possible	It may have happened in the past and it may happen in the next 5 years (or another reasonable period)
4	Probable	Happened in the past and/or is likely to happen in the next 5 years (or another reasonable period)
5	Almost Certain	Happened in the past and/or is almost certain to happen in most circumstances within the next 5 years (or another reasonable period)
Severity		
1	Insignificant	Hazard or dangerous event results in no or negligible health effects when compared to standard levels
2	Reduced	Hazard or dangerous event may result in reduced health effects (e.g., temporary symptoms such as irritation, nausea, headache)
4	Moderated	Hazard or dangerous events can potentially result in health effects that limit daily life (e.g., acute diarrhoea, vomiting, upper respiratory tract infections, minor trauma)
8	High	Hazard or dangerous event may result in illness (e.g., chronic diarrhoea, chronic respiratory problems, neurological problems; May lead to complaints and legal problems
16	Catastrophic	Danger or dangerous events can result in serious illnesses (e.g., severe poisoning, neoplasms and tumours) or even loss of life

wastewater with a high risk of formation of disinfection byproducts, since the filtration process reduces the oxidable content in the wastewater, increasing disinfection efficiency. The addition of the UV process to the solution (III) follows the latter premise of reducing the disinfection byproduct formation and therefore minimizing the potential risk use. Lastly, solution (IV) uses chlorine dioxide (ClO_2), which doesn't produce organic disinfection byproducts since it doesn't combine with nitrogen nor with natural organic matter (Abdighahroudi et al., 2021), producing a potentially safer reclaimed water, with a higher disinfection reliability. This solution is ideal for cases where transmittance of treated wastewater is reduced (<50 %), These different solutions all aim to remove pathogens and/or solid matter, although differing in terms of potential risk and reliability of the produced reclaimed water. For each case study, the most adequate solutions were considered based on WWTP treatment quality, user quality requirements and risk.

Disinfectant doses were estimated based on the needed logarithmic removal, solid content, and nitrogen concentration of the treated wastewater, as well as taking into account the existence or not of a complementary UV disinfection: 1–8 mg Cl/L (NaOCl); 0.5–1 mg ClO_2/L (ClO_2); 30 or 60 mJ/cm^2 (UV) (Metcalf et al., 2007; Metcalf et al., 2014; Kesar and Bhatti, 2022). To guarantee the maximization of the mixing power, without an increase in operational costs, static mixers were selected due to their technical and economic advantages (Valdés et al., 2022). To ensure a minimum contact time of 30 min, the construction of a reservoir to act as a buffer is foreseen when the transportation time to the user is lower than 30 min. Concerning the filtration step, conventional processes were preferred to ultrafiltration membrane technologies due to their lower operation costs, namely because of energy consumption. More specifically, disc filters were chosen given their capacity to retain smaller-sized solids, which represent most of the solid content in this water type (Cornacchia et al., 2022).

Although mandatory, it is important to regularly monitor the reclaimed water composition, especially in situations of direct contact with living beings, or possible food adsorption, mostly due to the possibility of byproduct production. That being, it is recommended to also analyse the byproducts formation, with higher concern in wastewater that may possess a high presence of natural organic matter (NOM) and nitrogen. Based on that, a risk analysis was conducted for each solution (per case study), following an adapted version of the World Health Organization recommended methodology for wastewater safety (Fewtrell and Bartram, 2001) and having the *Water Reuse Risk management for Agricultural Irrigation Schemes Technical Guidance* in mind (Maffettone and Gawlik, 2022). The hazardous events of each case study were defined (e.g., failure to guarantee the maximum solids content, failure to guarantee the pathogen logarithmic removal and trihalomethanes production), after which the risk was quantified based on the severity and likelihood (Table 3). To try to get a better risk definition, the likelihood was determined based on 5 years and accounted for the different contact types (i.e., direct/indirect, continued/discontinued) to better determine which contention barriers could be suitable to be applied for the risk mitigation.

Table 4
Risk descriptor and respective description.

Risk	Description
High (32 to 80)	The event may result in acute and/or chronic illnesses or loss of human life. Measures must be adopted to minimize the risk.
Average (13 to 32)	The event may result in negative, but moderate, health effects (e.g., fever, headache, diarrhoea, minor irritations). Measures must be taken to minimize the risk.
Low (<13)	There is no predicted danger to human health. No action is required at this time.

The risk was then determined (Risk = Probability x Severity) and categorized based on three categories: High, Average or Low (Table 4). Based on the risk categorization it is possible to determine the strength of the containment barriers and measurements needed to be applied. In high-risk situations, measures are mandatory, while on average are recommended and if low risk is determined no actions are needed.

This risk analysis methodology aims to develop a first expeditious approach for water reclaim risk assessments, given the scarcity of base data for identifying hazards and risk management focused on the consumption of reclaimed water. Ergo, the authors acknowledge the need to develop a more detailed risk assessment covering the entire life cycle of the reclaimed water (production and consumption), at a large exposure time, identifying the hazards for operators and others not covered here. Besides, it is crucial to identify the pathogens that might be predominant and perform an epidemiological assessment to support the severity determination.

2.3.5. Distribution system

The assessment of possible distribution systems involved conducting a hydraulic analysis of potential pipeline routes, considering elevation profiles and distances to determine the most efficient layout; selecting pipe diameters based on required flow rates; and choosing pumps that meet the required pressure and flow conditions while minimizing energy consumption; and running iterative simulations to test different scenarios, adjusting the design to achieve the best trade-off between cost and performance. Several distribution layouts were hence assessed for each case study, considering the installation of new pipelines on roadways or the repurposing of existing ones. Velocity was limited to a minimum of 0.3 m/s, to prevent sedimentation and biofilm growth (Cowle et al., 2020) and to a maximum of 2,0 m/s for agricultural uses (Costa Miranda, 2011) and 1.5 m/s for other uses (Mariano, 2014) and ensured through calculations using Manning-Strickler equation.

2.3.6. Cost estimations

Water reuse costs are dependent on site-specific factors, being influenced by the volume, distance, water quality, regulatory requirements, selected treatment system, pumping and storage requirements, as well as external costs and the existence of subsidies

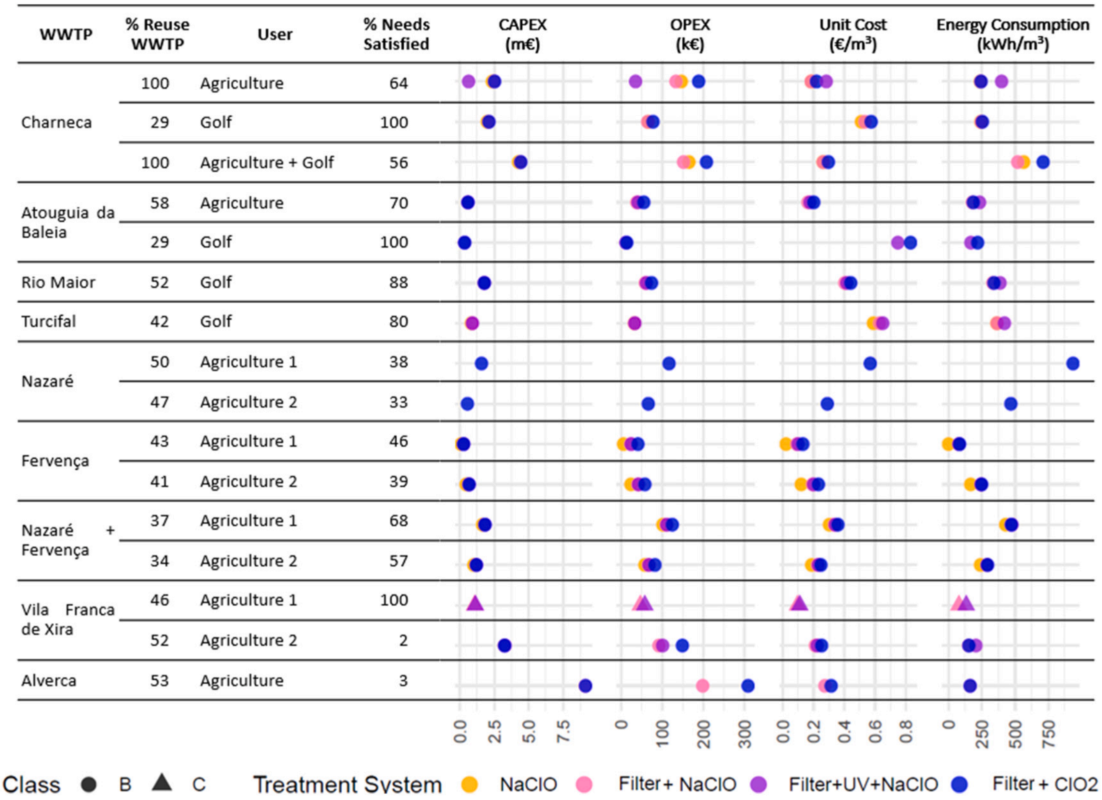

Fig. 2. Summary of results for the 8 WWTP pilot case studies. The symbols represent the values obtained for different treatment system simulations.

(National Research Council, 2012).

In this work, capital expenditure (CAPEX) comprised the investment for both the treatment systems and the supply network, including civil construction and project design costs. The investment cost for treatment equipment was determined based on consultation of market prices provided by several international suppliers. Pipelines and pumping station costs were based on current prices and estimated by adapting pre-existing functions (Covas, 2020). OPEX included costs of energy, reagents, personnel, and quality monitoring, determined using AdTA internal values. Unit cost calculation (€/m^3) assumed a 30-year planning period with a 6 % discount rate, and replacement of equipment (treatment system and distribution pumps) after 15 years. Furthermore, inflation rates were also accounted for, using sectorial average values between 2010 and 2021 (1.8 % for human resources, 3.8 % for energy and 1.6 % for infrastructure, reagents and monitorisation). Unit costs were also adjusted accordingly, assuming a 10 % tariff update every 5 years.

3. Results and discussion

This work showed that a new methodology for assessing water reuse potential may be successfully designed in water-scarce regions. Indeed, reusing wastewater from the eight selected WWTP would enable annual reuse of 8 hm^3, quadrupling regional reuse rates and doubling the national rate to 2.4 %, which could mitigate water needs for over 2000 ha of agricultural land and golf courses. This presents an opportunity to alleviate pressure on local water resources and enhance the resilience of the tourism and agricultural sectors.

Across 17 user scenarios, 56 proposals were evaluated (Fig. S1), predominantly (82 %) focusing on class B reclaimed water quality (EU Regulation 2020/741). Fig. 2 depicts the summary of the results, highlighting several important insights into the feasibility and cost dynamics of wastewater reuse in Portugal.

Higher percentages of water reuse in WWTP (58 % in Atouguia and 100 % in Charneca) correspond to scenarios where storage infrastructure is available, emphasizing the importance of these facilities in achieving higher reuse rates and ensuring consistent water availability. In contrast, more common reuse values (between 31 % and 53 %) reflect situations without storage, where supply-demand imbalances inhibit the supply of all user needs. In general terms, golf course irrigation needs appear to be easier to satisfy due to their lower water requirements, whereas agricultural irrigation is more dependent on the crop area and the WWTP's capacity.

CAPEX is relatively stable across different treatment systems, while OPEX and unit costs vary, especially for technologies like UV disinfection and chlorine dioxide. These technologies, while effective and safer from an ecotoxicology perspective, increase operational costs due to higher energy consumption (e.g., UV) and reagent costs (e.g., ClO_2). This reinforces the need for careful selection of treatment methods for balancing cost, energy consumption, risk, water quality requirements and public health. According to the performed risk assessment, these mentioned technologies allow a significant decrease in the reclaimed water reuse risk. Case studies where nitrogen is not removed on the main treatment process exhibited increased consumption risk when NaOCl is used due to the possible formation of genotoxic compounds (e.g., trihalomethanes) (Clayton et al., 2019). For instance, WWTPs with lower water quality, such as Nazaré, Rio Maior, and Alverca (Table 1), only considered the most reliable treatment systems (Filter + UV + NaOCl or Filter + ClO_2) to mitigate risks caused by byproduct formation or inefficient/unreliable treatment. This approach, while reducing the possibility of implementing potentially cheaper options, highlights how critical factors like water quality and risk management influence the overall feasibility and sustainability of water reuse projects.

Contrary to many coastal locations in south Portugal where seawater intrusion is noticed (Figueiredo et al., 2021) the salt concentrations observed in the present case studies were within the normal values for irrigation, leaving out the need for more advanced treatments (e.g., membrane), which inevitably results in lower costs (Bellver-Domingo

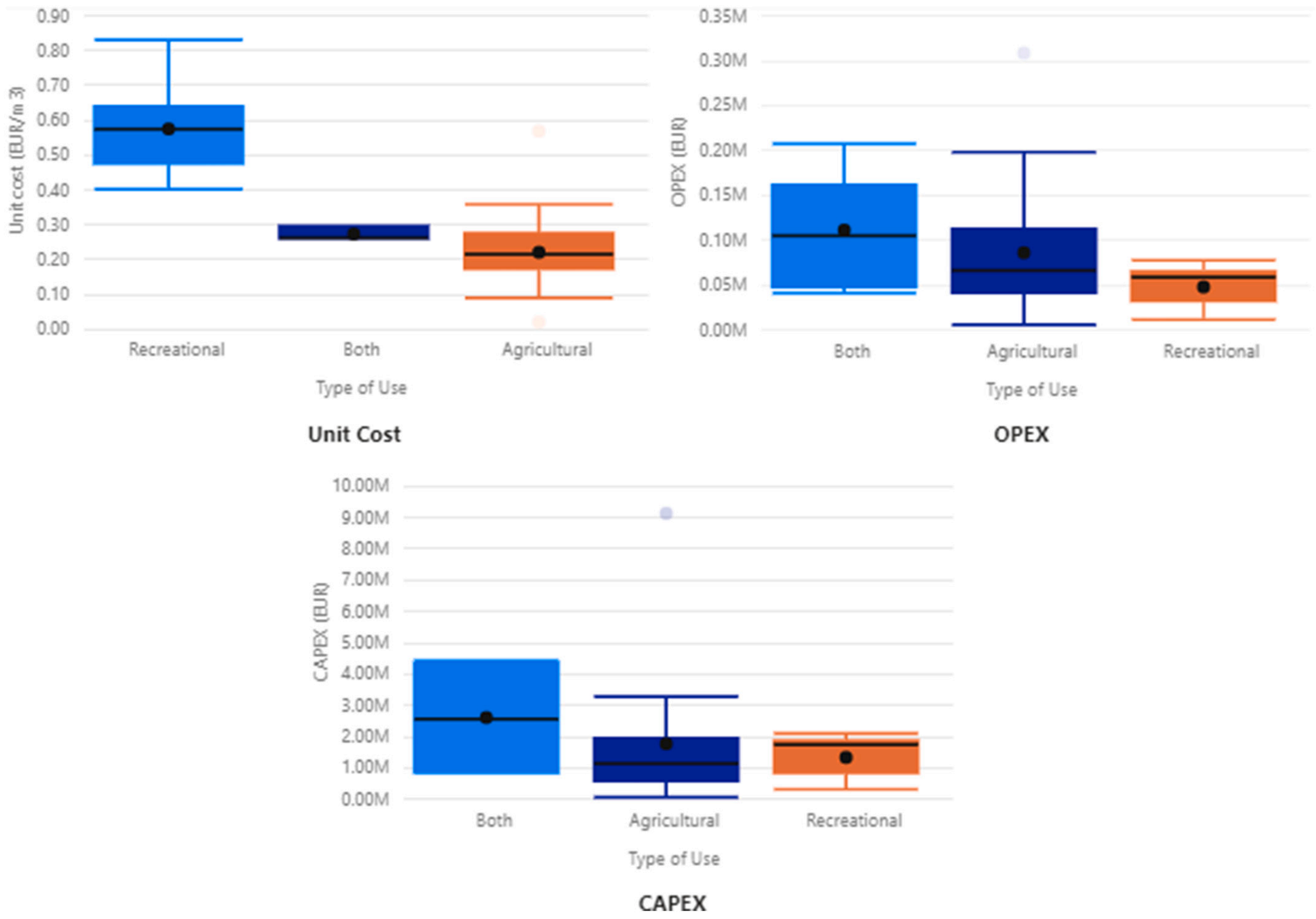

Fig. 3. Boxplots comparing unit cost, OPEX and CAPEX by type of user. The circles mark the average.

et al., 2019).

3.1. Unit cost analysis

This study sheds light on costs associated with water reuse projects in Portugal. For class B quality, the estimated cost ranges from 0.02€/m^3 to 0.83€/m^3, with an average of 0.31€/m^3, encompassing tertiary treatment and distribution, which is in line with the predictions of JRC for the region (Pistocchi et al., 2017). These figures are comparable to those found in Valencia (0.39€/m^3–0.74€/m^3) (Hernández-Chover et al., 2022) and Italy (0.01€/m^3–0.48€/m^3) (IMPEL, 2018), and lower than average drinking water costs in the region (0.84€/m^3 in Lisbon and 0.87€/m^3 in Leiria) (APFN/Millenium, 2022). Only Cyprus, with significant government subsidies, charges as low as 0.07€/m^3 for agricultural uses and 0.23€/m^3 for golf course irrigation (KDP 48/2017, Cyprus Government). However, one should be wary that in Portugal the

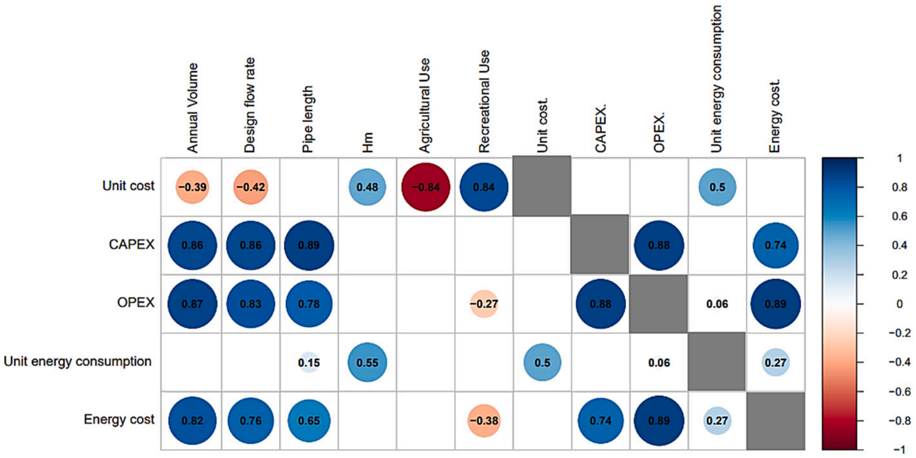

Fig. 4. Correlation matrix plot of water reuse project parameters. Blue shades denote positive correlations, while red shades indicate negative correlations. The darker the shade, the stronger the correlation.

negligible cost of groundwater abstraction could hinder the adoption of such projects (APA, 2023; OECD, 2010). It should also be noted that these values do not account for environmental externalities, which have been shown to offset tariffs and make reuse projects economically viable (Abu-Ghunmi et al., 2016; Molinos-Senante et al., 2011).

Desalination has a global average levelized cost of water of 2.40€/m^3, including transportation, but may be expected to decline in the upcoming years, down to 1.05€/m^3 in 2050 (Caldera and Breyer, 2020). Desalination costs are predicted to decrease with decarbonisation and increasing renewable energy production, but this technology may present some environmental problems (Nasrollahi et al., 2023). This is, despite the advantages in terms of availability to meet water needs in extreme situations, desalination is not optimal for generalised agricultural irrigation since costs may outweigh agricultural benefits (Chang et al., 2021; Reznik et al., 2017). Thus, while direct comparisons are challenging due to differing project parameters, it is evident that reclaimed water offers an interesting cost-effective solution. Therefore, as a rule of thumb, irrigation projects should prioritize existing reclaimed water sources over investing in desalination.

Fig. 3 depicts the variability in costs for different types of users. Agricultural uses show higher operational expenses, explained by the tendentially larger scale of the projects, while capital expenditures are similar across uses. Recreational uses, such as the irrigation of golf courses, incur higher unit costs (0.43€/m^3 to 0.83€/m^3) than agricultural uses (0.02€/m^3 to 0.57€/m^3). This can be explained since the studied golf courses tend to be located further from the WWTP, covering distance and heights 56 % and 50 % higher, on average. Furthermore, these users tend to require a lower volume of reclaimed water due to the smaller irrigated areas.

The values calculated for agriculture users stand in stark contrast with the irrigation water tariffs practised among water-use associations, in which the volumetric tariff averages 0.02€/m^3 (Rodrigues et al., 2021; OECD, 2010). Thus, the viability of the tariff is linked to the user's ability to access other conventional or non-conventional water sources, their adaptability in contexts of water stress, and the possibility of accessing external funding sources.

3.2. Key-cost influencing variables

As anticipated, distance and water volume requirements were identified as the main cost determinants (Fig. 4), with investments in the distribution network playing a pivotal role. Distribution was estimated to account for an average of 79 % of the initial investment and 41 % of the operational costs. These findings are crucial to the ongoing debate (Oniki et al., 2018; Zhang et al., 2023) on the optimal strategy for WWTP location. Traditionally, WWTP were located as close as possible to receiving water bodies to minimize costs, since sewage was preferably drained by gravity. However, this approach is here shown to lead to higher reuse costs, due to the need for extensive pumping and long-distance transport, requiring significant energy usage. The circular use of water and resources warrants a paradigm shift, advocating for the strategic relocation of WWTP to minimize costs and energy consumption. While acknowledging the impact of the proximity to WWTP on property values (Iftekhar et al., 2018), numerous studies have underscored their importance for a more circular society, in the interest of many stakeholders (Harris-Lovett et al., 2018). The quest for decentralized WWTP, on-site located, gains a new boost under a new framework of proximity between wastewater production and water reuse needs, namely in Mediterranean countries where water availability for agriculture is an undeniable asset.

In addition to the distribution system, energy consumption is also a significant component of treatment costs, with technologies like ultraviolet (UV) treatment causing an average 33 % increase in total energy requirements. This reinforces the need for alternative energy production systems supplying the WWTP, to reduce energy costs and externalities (Cevik and Ninomiya, 2022) and enhance the viability of these projects. In the specific case of chlorine dioxide, reagent consumption also contributes to the operational costs, resulting in an additional 38 % cost, on average, than counterpart solutions. As shown in Fig. 2, this directly translates into the higher OPEX costs observed for all solutions that incorporate chlorine dioxide. However, the risk assessment performed indicates that the increased cost of certain technologies, as is the case of chlorine dioxide, can still represent a worthwhile investment considering the trade-off for improved safety and reliability in production.

4. Conclusions

The general absence of measures and preparedness for treated wastewater is evident in most Mediterranean countries and Portugal is no exception. Portugal's natural orography implies high energy costs in water pumping, leading to scenarios where viability might be conditioned by public funding considering the users' low willingness to pay. This study sets a new starting point for discussions on pricing and tariffs within the region, illustrating how reclaimed water costs vary according to different needs and technical variables. Although the findings apply to the Portuguese context, the methodology holds potential for adaptation and application in other regions facing water scarcity. Moreover, the emphasis on the importance of a new strategy based on decentralized WWTP and the role of energy consumption in cost considerations will contribute to broader discussions on water planning and water reuse strategies, as well as to a paradigm shift towards a circular economy.

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CRediT authorship contribution statement

Inês Areosa: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tiago A.E. Martins:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Rita Lourinho:** Project administration, Funding acquisition. **Marcos Batista:** Project administration, Funding acquisition. **António G. Brito:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Leonor Amaral:** Writing – review & editing, Supervision, Project administration, 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

Results data will be made available on request, while raw data will remain confidential and will not be shared.

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