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How much does reclaimed wastewater cost? A comprehensive analysis for irrigation uses in the European Mediterranean context

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ABSTRACT

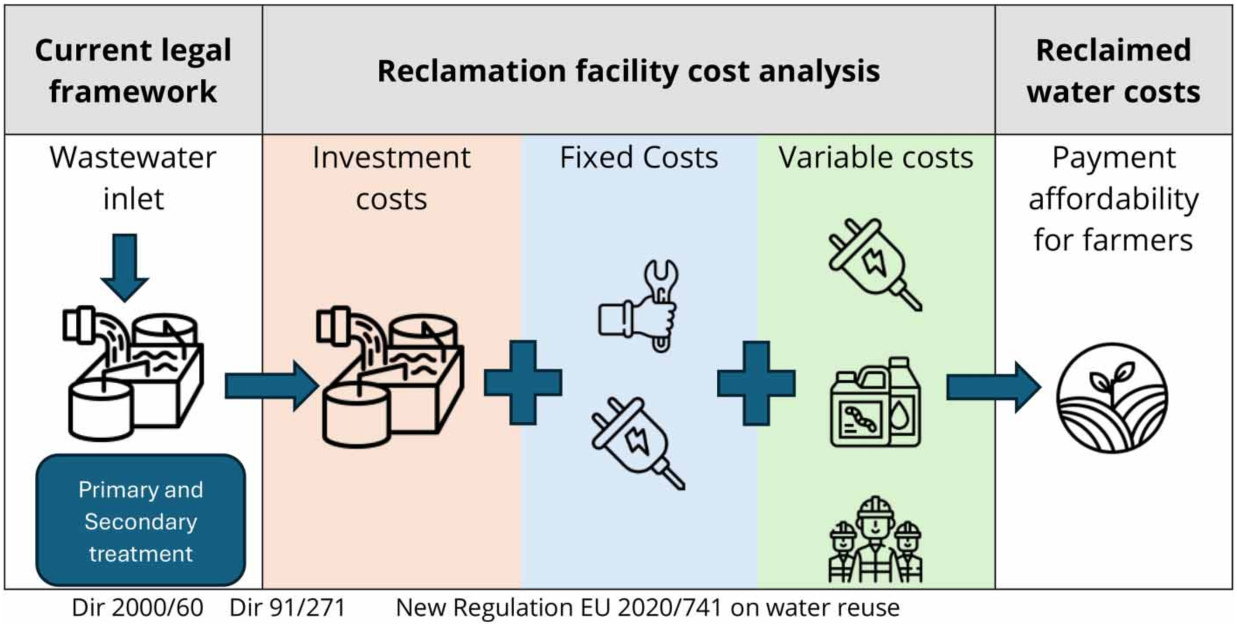
The new European Union regulation on the minimum requirements for the use of reclaimed water for irrigation entered into force in June 2023, thereby imposing concerns regarding the costs of this non-conventional resource for potential users in the context of increasing water scarcity in the Mediterranean region. This research offers a comprehensive cost assessment of reclaimed water production based on the financial information gathered from wastewater treatment plants located on the Mediterranean coast of Andalusia (Southern Spain). The results offer valuable information for policy-makers, water operators, and potential users to assess the economic viability of utilising reclaimed water as an alternative source to scarce conventional resources.

Key words: cost assessment, irrigation, payment affordability, reclaimed water, sustainability, wastewater

HIGHLIGHTS

- A comprehensive cost analysis of reclaimed water is provided under the current EU regulation.
- Cost-recovery principle requires detailed information on water reclamation costs.
- Results offer valuable information to guarantee future viability of this resource.
- Payment affordability for potential users needs to be considered.

GRAPHICAL ABSTRACT



INTRODUCTION

Reclaimed water use, a powerful climate change adaptation measure, has become a significant non-conventional source of water to guarantee a sustainable future for a variety of production sectors. Although agricultural and landscape irrigation, as well as industrial and cooling processes, are usually identified as the main potential applications (Lautze *et al.* 2014), reclaimed water is also utilised for a wide variety of purposes, such as environmental enhancement, non-potable urban uses, groundwater recharge, and indirect potable reuse. Even though the costs of the production of reclaimed water, which are linked to tertiary and advanced (disinfection) treatment, lead to higher prices of this non-conventional water compared with the prices of conventional water, its use gains a special significance in regions with increasing water scarcity and extreme droughts, such as Mediterranean countries. Moreover, conventional water resources in this region are generally overexploited and the future of strategic high water demanding sectors, such as agriculture, are seriously compromised (Poustie *et al.* 2020; Hristov *et al.* 2021).

In the context of the European Union (EU), the role of water reuse has largely been addressed from the point of view of the implementation of circular economy (CE) principles in the water sector with the aim of reducing the use of, and the pressure on, natural resources (including energy) and recycling both the water and nutrients present in the wastewater as much as possible (European Commission 2012). Further to the CE action plan, EU policy on droughts and water scarcity also calls for action in the sector of water reuse (European Commission 2015). In an effort to meet these policy objectives, the EU has recently approved the new Regulation EU 2020/751 on water reuse for irrigation both to open the market to the technologies and services related to water reclamation and to increase water reuse projects (Berbel *et al.* 2023).

As previously noted, the use of reclaimed water is mainly driven by scarcity, therefore those regions with the highest percentage of water reuse are mainly located in arid areas, such as Israel, Cyprus, and California (USA) (Angelakis & Gikas 2014). All these territories share similar characteristics in terms of high water scarcity, economic development, and the existence of a highly competitive irrigation sector. Several studies, such as Raso (2013), Pistocchi *et al.* (2017), and Hristov *et al.* (2021), have stated that Spain has the highest potential use of reclaimed water in volumetric terms within the EU, with agriculture as its main potential user. Therefore, Spain constitutes a perfect example for the analysis of the potential use of reclaimed water for irrigation, although the current use of this non-conventional water resource remains limited. Specifically, this work focuses on the case study of the Mediterranean Andalusian Basins (located in Southern Spain) where reclamation rates have risen from 7% in 2022, up to 17% in 2023, and to 30% in 2024. This rate is expected to undergo a significant increase in the coming years as the region has been suffering from a long and severe drought since 2021.

Although the use of reclaimed water for irrigation has become a major issue in the current context of increasing water scarcity in Spain and other regions of the world, studies offering a comprehensive analysis of production costs remain scarce (Mesa-Perez *et al.* 2020). From among these few studies, it is relevant to mention the work of Melgarejo *et al.* (2015), which aims to offer an economic study of a variety of alternative processes and related costs for reclaimed water and desalinated water in a case study in Spain. However, this study lacks a comprehensive financial viability analysis and payment affordability studies for irrigators and decision-makers. Recent studies have focused on technological and water quality aspects (Ayache *et al.* 2023; Dittmann *et al.* 2024), crop growth and agronomy aspects (Poustie *et al.* 2020), and on consumer perceptions and acceptance of products irrigated with this non-conventional source (Ellis *et al.* 2022). To the best of our knowledge, there are no studies offering a comprehensive cost analysis of reclaimed water production for irrigation purposes.

This research aims to fill this gap by offering a comprehensive cost analysis of the production of reclaimed water for irrigation that complies with the quality standards set by the current EU and national regulations on water reuse. The analysis presented herein has been built upon the information gathered from the interviews and upon cost data from six public and private reclamation plants located in the Andalusian Mediterranean region. Our analysis provides information on both variable and fixed-cost components, together with a projection of costs for different plant scales (from 1 up to 10 Mm^3/year of treatment capacity). Therefore, the main contribution of this study is to offer a comprehensive cost analysis of water reclamation for irrigation purposes that takes into account the recently approved regulations on water reuse. These results offer valuable information for policy-makers, irrigators, water companies, and investors in the EU context and worldwide for the analysis of the financial viability of this resource, as well as for the design of suitable cost-recovery price settings that guarantee the recovery of costs as required by the EU legal framework. Moreover, based on the results of Expósito *et al.* (2024), our study also offers a brief discussion on the payment affordability for irrigators based on the water productivity of the crop mix in the region and on the cost of alternative water sources, such as desalination.

Lastly, it is worth noting that our analysis focuses on all operating costs of tertiary treatment and disinfection. Despite these treatments being non-mandatory in the urban water cycle, the EU regulation on minimum requirements for agricultural water reuse establishes quality standards that require tertiary treatment and disinfection if those reclaimed resources are allocated to food production (Reg 2020/741). Currently, the costs of those treatments must be assumed by the irrigators themselves following the cost-recovery principle in the EU Water Framework Directive. It should also be borne in mind that investment amortisation costs are considered in our analysis, although Spanish public authorities (e.g., national and/or regional governments) usually totally or partially finance the investment costs related to the construction of both conventional wastewater treatment plants (WWTPs) and additional tertiary and disinfection treatments.

After this introduction, the rest of the article is structured as follows. The subsequent section offers an overview of the current status of water reuse in Spain, followed by a description of the case studies and materials used herein. The next section describes the estimation and calculation methods employed, followed by the estimated costs obtained. A brief discussion on the results is then offered, which includes issues related to irrigators' affordability and the costs of alternative water sources. The final section summarises several concluding remarks.

Status of water reuse in Spain in the EU context

Although reclaimed water has historically been utilised for agricultural irrigation in Spain, it was not until the 2005–2008 drought period that its use became regulated and promoted by Royal Decree (Royal Decree 1620/2007), which established the legal framework for the use of reclaimed water (Iglesias *et al.* 2010). However, the high reuse goals set by previous national plans have failed to materialise, and the expansion of the sector has remained very limited in recent decades (Figure 1).

According to data from the Spanish Association of Water Supply and Sanitation Companies (AEAS), the current treatment capacity at the national level is 8,130 Mm^3/year, while the volume of treated wastewater totals 4,097 Mm^3/year. The Spanish National Institute of Statistics (INE) estimates a use of reclaimed water in Spain of up to 507 Mm^3/year, which has practically remained constant at approximately 1.3 Mm^3/day in the last 15 years (Figure 1), accounting for 12% of the treated volume.

In this context, the Spanish National Plan for Purification, Sanitation, Efficiency, Savings, and Reuse (MITECO 2021) aims to significantly increase these figures by incorporating the use of reclaimed water into the third-cycle hydrological plans (2022–2027) of all Spanish river basins. Although the impacts of this National Plan have yet to materialise, from our point of view the two most relevant considerations regarding this new governmental instrument are the following: (1) Encourage the use of reclaimed water to reduce pressures on conventional resources in surface and groundwater bodies; (2) Eliminate

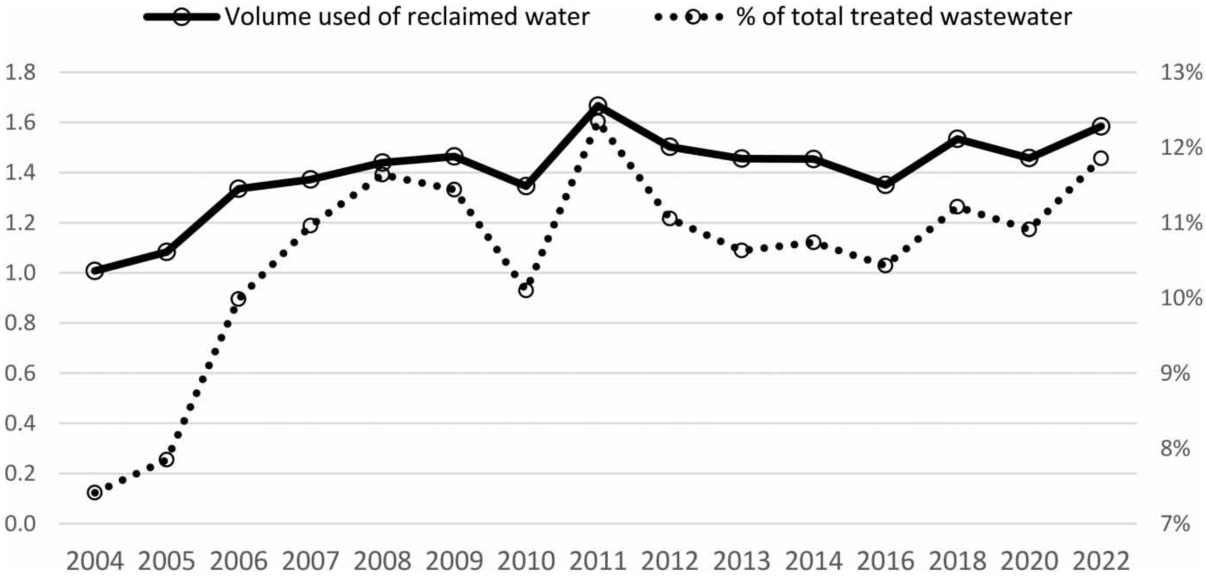


Figure 1 | Use of reclaimed water in Spain (2004–2022). *Note*: Volume used of reclaimed water in Mm^3/day (left-hand axis) and volume of reclaimed water as a % of total treated wastewater (right-hand axis). *Source*: Authors' own.

institutional and financial barriers that limit the use of reclaimed water, through the improvement of the regulatory and financial frameworks for reuse, and (3) Review and adapt RD 1620/2007 to the EU regulation 2020/741 (European Union 2020).

The Royal Decree 4/2023 (11 May 2023) has recently approved an adaptation of the legal framework to facilitate the administrative process of allocating reclaimed water rights. In our opinion, the definition of water property rights and the regulatory framework are of major significance towards facilitating water reuse. There is a wide variety of models of property rights worldwide: unlimited long-term private property (e.g., Australia), private property with certain limitations (e.g., USA, depending on the State), private concession limited in time (e.g., Spain, France, Portugal), and totally public property (e.g., Israel).

In the EU context, two regulations with a high impact in the water reuse sector deserve to be mentioned: Regulation EU 2020/741 and the revision proposal of the Urban Wastewater Treatment Directive (UWWTD) 91/271 (European Union, 1991). The use of reclaimed water is limited by the need for the suitable protection of health and the environment and a certain minimum quality of said water is required. The recently approved Regulation EU 2020/741 introduces minimum quality requirements for the reuse of urban wastewater depending on the type of reuse. It also requires the definition of risk management and transparency plans, while simultaneously supporting the opening of market opportunities. Nevertheless, the real impact of this regulation on the expansion of water reuse is limited by water scarcity and crop profitability (Berbel *et al.* 2023), as is discussed in subsequent sections. Regulation EU 2020/741 entered into force on 26 June 2023 without the need for legal transposition, and the Spanish government is therefore expected to have fulfilled the adaptation requirements to ensure its full implementation.

Figure 2 illustrates the regulatory system for the use of reclaimed water in all its phases. Regarding the recovery of costs, the figure indicates that, up to point 'A' (entrance to the reclamation facility or exit from secondary treatment), the cost is assumed by the urban cycle users since they are responsible for the quality of discharge according to standards set by the Directive 91/271, while tertiary treatment becomes the responsibility of the reclaimed water users (e.g., irrigators). However, the revision proposal of Directive 91/271 might change this cost distribution since point 'B' would become the new 'responsibility frontier' between the urban users and the reclaimed water users. This can therefore lead to a scenario where tertiary treatment costs are internalised by the urban cycle, thus lowering the cost of reclaimed water for potential users.

On the other hand, Directive 91/271 has been successfully implemented at the EU level, with 98% of urban water being treated, although little or no such treatment is available in small cities. After 30 years of application, work is finally being carried out on its review and the EU Commission's proposal includes significant innovations regarding the use of reclaimed water, since, as indicated, the quality of the effluents and the internalisation of costs of tertiary treatments would be changed. Table 1 presents the expected changes in Directive 91/271. Following the definitions of Directive 91/271, secondary

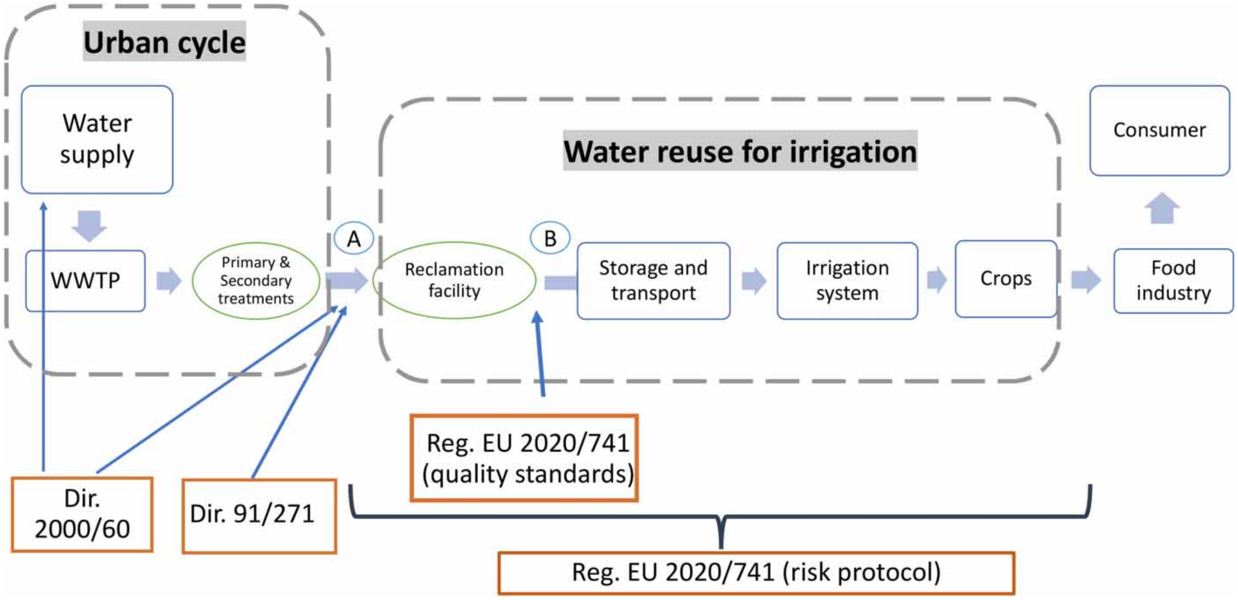


Figure 2 | Water cycle and regulations in the EU context. *Source*: Authors' own.

Table 1 | Expected changes in the Revised Directive 91/271/EEC on wastewater treatment in urban areas

Type of treatment	Directive 91/271	Expected changes
Secondary	>2,000 eq. inhabitants	>1,000 eq. inhabitants
Tertiary	>10,000 eq. inhabitants in sensitive areas	>100,000 eq. inhabitants >10,000 eq. inhabitants in sensitive areas
Quaternary	n.a.	>10,000 eq. inhabitants in sensitive areas

Source: Authors' own.

treatment generally implies involving biological treatment with a secondary settlement or other processes in which the requirements established in Annex I are respected (Article 2(8)). Tertiary treatment generally consists of nutrient removal, and either chemical or physical disinfection (Annex I lays down the thresholds for nutrient reduction). Lastly, quaternary treatment aims to carry out micropollutant removal via ozonation and/or filtering with activated carbon or advanced techniques, such as nanofiltration and the use of membranes. At this point, it is worth noting that, hitherto, there has been no legal obligation to treat micropollutants.

The impact of this regulation could be more pronounced in urban agglomerations with equal to or greater than 100,000 equivalent inhabitants, where tertiary treatment and disinfection costs would be internalised by the urban cycle, meaning zero costs for the users of reclaimed water (at the exit of the treatment plant). This is currently the case of urban agglomerations (with more than 10,000 eq. inhabitants) that discharge in sensitive areas of special environmental protection. However, final users (e.g., irrigators) would still have to take charge of not only the management, but also the costs of storage, transport, analysis, and distribution.

In the specific case of Spain, the allocation of water rights consists of a temporal concession defining the use (e.g., public supply, irrigation) and other conditions (e.g., location of abstraction and point of discharge). Public supply companies must return treated water to the environment once the WWTP reaches the quality requirements set by Directive 91/271. Reclaimed water can be obtained for irrigation in various ways: (a) public utilities are allowed to discharge water in the irrigation system (usually via a storage tank); (b) the Water Agency authorises the user (e.g., irrigator communities) to directly uptake the reclaimed water from the WWTP once Directive 91/271 requirements are fulfilled at the transference point; and (c) in certain cases (e.g., in the region of Murcia), there is a regional public company that assumes the management of tertiary treatment and disinfection plants, but the ownership of the resource is still controlled by the Water Agency that authorises the discharge of reclaimed water into the irrigation systems. In this latter case, the cost of tertiary treatment is financed with regional and municipality funds. The implementation of this last model of water allocation is demanded by Andalusian irrigators (and other Spanish regions) as a benchmark model, which is already operating in the Murcia region with optimal results.

Case studies and materials

The Andalusian Mediterranean Basins Demarcation (DHCMA, Spanish acronym), located in south-eastern Spain, is the union of approximately 16 hydrological subsystems with a partial connection between them. In the DHCMA, the reuse of treated water has increased from 21 Mm^3 in 2005 up to 27.4 Mm^3 in 2015, with 47 Mm^3 reached in 2023 (and 67 Mm^3 expected by the recent Drought Plan Decrees). Figure 3 shows the existing WWTPs with reclamation capacity (i.e., tertiary treatment and disinfection) and the facilities planned to be built between 2021 and 2027. Due to its climatic conditions, this area enjoys highly technical intensive agriculture characterised by high-value crops such as subtropical crops (e.g., avocado, mango), horticulture, and greenhouse cultivations. Currently, the area is suffering from a persistent drought episode with historically low precipitations, and the use of non-conventional water resources has become a strategic issue for the economic survival of most agricultural businesses.

This study employs the financial and costs information gathered from the main operating coastal WWTPs located in the DHCMA to analyse the operational costs of tertiary treatments and disinfection, to produce reclaimed water fulfilling the recently approved quality standards set by the EU for irrigation uses. The data refers to the operating costs of six WWTPs in the year 2022. The WWTPs are located in the provinces of Cadiz (1), Málaga (2), Granada (1), Almeria (1), and Cordoba (1). The information on the investment costs has been obtained from the public construction budgets approved by the regional government, and from the information gathered from our WWTP case studies.

All the WWTPs studied herein have four stages: (1) physical–chemical (e.g., lamellar decanters with the addition of coagulant–flocculants); (2) filters (sand filtration and microfiltration); (3) UV lamps (open channels for big WWTPs and closed reactors for the smallest WWTPs); and (4) final chlorination. Moreover, based on the different scales of these WWTPs, this study considers the existence of economies of scale, with the aim of providing an accurate cost estimation of reclaimed water production at different plant scales.

METHODS

Based upon the financial information of the analysed WWTPs in their reclamation processes, a simulation of the operational costs for alternative production scales, from 1 up to 10 Mm^3, has been obtained. The schema of the estimated production cost has two components:

Figure 3 | Location of WWTPs in the DHCMA. *Source*: DHCMA.

- Fixed-cost component, which considers the existence of economies of scale in the production. This is expressed in euros per year (EUR/year), and includes the costs associated with the installed energy power and the maintenance of the investment.
- Variable-cost component, which is expressed in euros per cubic metre (EUR/m^3) and includes the remaining operational costs: labour, energy consumption, and chemical and consumable materials.

Our cost analysis considers two alternative scenarios, minimum and maximum, to consider the variability of costs reported by the analysed WWTP. This cost variability is explained by the differences in input costs, such as energy, chemicals, and labour.

It is worth noting that the WWTPs analysed have implemented similar technologies in their tertiary treatment processes, with the use of UV lamps and final chlorination for disinfection. Subsequently, assumptions on the economies of scale present in the operating costs for different plant sizes and the cost parameters employed for our scenario estimation are explained in detail below.

Total investment of tertiary treatment

Total investment depends on the treatment capacity of the WWTP in its tertiary process. In order to estimate the economies of scale, we have analysed the public budgets allocated for all tertiary treatments at WWTPs in the DHCMA in the years 2022–2023. Based on this information provided by the Andalusian Regional Government and by applying a simple logarithmic estimation, the following equation has been obtained to represent the relationship between treatment capacity and total investment needed:

$$\text{Investment } (€/\text{m}^3) = 0.60 - 0.104 \ln X; \;\; X = \text{capacity Mm}^3/\text{year}$$

As expected, this equation represents the existence of economies of scale, as shown by the negative parameter (-0.104), and consequently investment unit cost decreases as treatment capacity increases. This equation is employed to estimate the investment unit cost for each treatment scale, from 1 to 10 Mm^3. Our analysis considers two types of investment: equipment and building. Based on the gathered data from our case studies (WWTPs) and the investment information provided by the Andalusian Regional Government, building (construction) and equipment investments have been assigned an equal weight of 50% of total investment. Similarly, equipment investment includes mechanical and electronic equipment, both being assigned a weight of 25% of total equipment cost. These assumptions are also in line with the parameters employed by the Spanish government (and other EU countries) to apply the cost-recovery principle in water services (Berbel *et al.* 2011). For the sake of simplicity, these weight parameters are considered constant in the two alternative cost scenarios.

As previously mentioned, our analysis considers the amortisation of investments. As commonly assumed in the existing literature, an amortisation period of 25 years and an annual interest rate of 4% have been considered. This cost is added to the operating costs in order to recover the investment costs. As previously commented, investment is usually subsidised by the public authorities in the specific case of Spain, and this cost should therefore not be considered in the design of the pricing scheme for irrigators. In this case, all water users would be assuming these investment costs, thereby subsidising potential users. This issue is further discussed in the Discussion section, although the final decision would ultimately be made by the policy-makers.

Fixed-cost component

Based on the production data gathered, it is assumed that installed energy power is 135 kW in the case of 10 Mm^3 and 50 kW in the case of 1 Mm^3. Economies of scale are considered between these two extremes. Based on the current costs applied by energy suppliers in the WWTPs studied, the unit cost of power capacity is assumed to be 50 and 40 EUR/kW/year in the maximum and minimum cost scenarios, respectively.

The maintenance cost is estimated as a percentage, with the building maintenance cost of 0.25% for each of the cost scenarios. The mechanical equipment takes 5% (maximum scenario) and 4% (minimum scenario), while the electrical equipment takes 4% (maximum scenario) and 3% (minimum scenario). This assumption on maintenance costs yields a total (as a percentage of total investment) of 2.4 and 1.9% in the maximum and minimum cost scenarios, respectively.

The fixed component also assumes 19% of indirect costs (as reported on average by the WWTP operators). This assumption is also applied in the variable component.

Variable-cost component

This type of cost depends on the operating hours of the WWTP tertiary treatment. For the sake of simplicity, these costs will be estimated on an annual basis with 100% of the plant capacity in use.

Regarding labour costs and based on the information gathered from our sample of WWTPs, a total of 2,000 working hours of operational personnel per year in the maximum cost scenario is assumed, and 900 working hours per year in the minimum cost scenario. It is worth noting that only marginal costs are considered, since the tertiary treatment and disinfection is working in fully operating mode, with personnel also working in previous treatment phases (primary and secondary). In the case of the smallest scale (1 Mm^3), working hours of operational personnel are assumed to lie between 800 and 1,000 h/year. Moreover, for the operational personnel, the technical personnel who manage said operational workers are also considered as a percentage (10%) of the working hours of operational personnel.

With regards to the filtering equipment in the tertiary plant, the change of 70 filter cloths per year is considered for the 10 Mm^3 capacity, at a unit cost of 750 EUR (information provided by the WWTPs studied). For the remaining plant sizes, the number of filter cloths is estimated proportionally. Similarly, 90 ultraviolet lamps for disinfection are considered for the 10 Mm^3 plant and are proportionally calculated for the smaller plant scales.

Chemical analysis and water sampling are assumed to amount to between 9,000 (minimum cost) and 18,000 EUR (maximum cost) per year to deliver reclaimed water of Class A quality in accordance with the new EU regulation 2020/741 for the 10 Mm^3 plant, and between 6,000 (minimum cost) and 9,000 EUR (maximum cost) per year for the 1 Mm^3 plant. The rest of the plant sizes are lineally calculated. Chemical input, such as sodium hypochlorite, is assumed to be constant at a proportion of 0.06 kg/m^3 at a cost of 0.30 EUR/kg.

Regarding electricity consumption based on the technical information gathered from our sample of WWTPs, this varies from 0.112 kWh/m^3 (10 Mm^3) to 0.200 kWh/m^3 (1 Mm^3). Electricity prices have remained highly unstable in recent months. In order to take this variability into consideration, a price of 0.12 EUR/kWh has been considered in the minimum cost scenario and a price of 0.15 EUR/kWh in the maximum cost scenario. Lastly, return wastewater flows and technical stops for filter cleaning are considered as 8% of the variable energy cost.

RESULTS

By applying the aforementioned assumptions and parameters, a cost estimation is offered for the production of reclaimed water under the new EU Regulation 2020/741. Tables 2 and 3 summarise the cost calculation for three plant scales, at 1, 5, and 10 Mm^3. Figures 4 and 5 show the evolution of total operational costs and their two components, fixed and variable, together with the full cost including investment depreciation (otherwise known as investment amortisation cost).

As previously mentioned, investments are financed by public agencies in the case of Spain, and amortisation costs are traditionally not considered in cost-recovery price settings. Nevertheless, private agents might enter the market to explore the financial viability of producing reclaimed water. With this in mind, our comprehensive cost estimation includes investment depreciation costs for a range of plant scales between 1 and 10 Mm^3 of treated water per year. As can be observed, total costs, including investment amortisation, vary between 0.09 (10 Mm^3) and 0.16 (1 Mm^3) EUR/m^3 in the minimum cost scenario, while costs are slightly higher in the maximum cost scenario, from 0.10 (10 Mm^3) up to 0.19 EUR/m^3 (1 Mm^3). These costs would be significantly lower if investment depreciation costs were excluded, and would represent between 3 and 4 additional cents depending on the plant scale (as shown in Tables 2 and 3). It is also worth bearing in mind that fixed costs represent between 14% (10 Mm^3) and 17% (1 Mm^3) of operational costs, depending on the plant scale.

Figures 4 and 5 present the cost evolution for the full range of treatment scales in our two cost scenarios, minimum and maximum, respectively. As expected, due to the existence of economies of scale in the production process, estimated unit costs significantly decrease as the treatment capacity increases.

DISCUSSION OF FINDINGS

Our results offer valuable information for public and private agents involved in the management of the water cycle. Specifically, the comprehensive cost analysis carried out in this study offers valuable information for all agents and decision-makers involved in the exploitation of reclaimed water. Costs information is crucial in the analysis of the financial viability of water reclamation plants, and also in the design of suitable cost-recovery price settings that guarantee the recovery of costs and payment affordability for potential users. In our opinion, the results provide sufficient information for the design of a pricing

Table 2 | Tertiary treatment and disinfection costs in the minimum cost scenario

			Treatment capacity (Mm^3)		
		EUR/unit	**1**	**5**	**10**
Investment unit cost (EUR/m^3)			0.60	0.43	0.36
Total investment (EUR)			601,100	2,168,592	3,616,312
Fixed costs					
Energy (power)	kW	40	50.0	87.8	135.0
Maintenance			11,421	41,203	68,710
Fixed-cost subtotal (EUR)			13,421	44,714	74,110
Indirect costs (EUR/m^3)			2,550	8,496	14,081
Fixed-cost Total (EUR)			15,971	53,210	88,191
Fixed-cost Total (EUR/m^3)			**0.0160**	**0.0106**	**0.0088**
Variable costs					
Operational personnel	Hours/year	35	800	844	900
Technical personnel (10%)	Hours/year	54	80	84	90
Filter cloths	unit	750	7	35	70
UV lamps	unit	830	9	45	90
Sampling and analyses	EUR/year		6,000	6,044	18,000
Variable-cost subtotal (EUR)			51,040	103,760	181,560
Variable-cost subtotal (EUR/m^3)			0.0510	0.0208	0.0182
Sodium hypochlorite	Kg/m^3	0.30	0.0600	0.0600	0.0600
Electricity consumption	KWh/m^3	0.12	0.2000	0.1609	0.1120
Return flows and stops			0.0019	0.0022	0.0011
Variable-cost subtotal (EUR/m^3)			0.0950	0.0603	0.0507
Indirect costs (EUR/m^3)			0.0180	0.0114	0.0096
Variable-cost Total (EUR/m^3)			**0.1130**	**0.0717**	**0.0603**
Total Operating Cost (EUR/m^3)			**0.1290**	**0.0823**	**0.0691**
Total Cost, incl. depreciation (EUR/m^3)			**0.1675**	**0.1101**	**0.0923**

Source: Authors' own.

Calculations consider four stages of treatment: 1) physical-chemical, 2) filters, 3) UV lamps, and 4) final chlorination.

Another issue that, in our opinion, decision-makers should bear in mind is whether the pricing scheme needs to consider the establishment of a transfer price for those periods in which no water is demanded by the users. Moreover, this price should strictly reflect fixed costs related to WWTP operation, and eventually, investment depreciation.

scheme with both fixed and variable components, which would depend on the irrigation needs in terms of water quality and treatment capacity of the WWTP. In our specific case, the requested water quality is that of Class A, in accordance with EU Regulation 2020/741 (Crop category: all food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw; irrigation method: all irrigation methods). Another issue that, in our opinion, decision-makers should bear in mind is whether the pricing scheme needs to consider the establishment of a transfer price for those periods in which no water is demanded by the users. Moreover, this price should strictly reflect fixed costs related to WWTP operation, and eventually, investment depreciation.

The ability of the end user to pay will directly depend on the economic productivity of irrigation water, based on the crop profitability. Furthermore, the analysis of payment affordability for irrigators requires an examination of the cost of alternative water sources. According to the latest official data available, the average cost of irrigation water in Spain amounts to 107 EUR/ha (0.02 EUR/m^3) for surface water and approximately 50 EUR/ha (0.09 EUR/m^3) for groundwater (MIMAM 2006; Berbel *et al.* 2019). Alternatively, water production costs for large seawater desalination plants are currently at approximately 0.4–0.6 EUR/m^3, with values that increase up to 0.8–1.2 EUR/m^3 if investment depreciation is included (Zarzo & Prats 2018). According to data from the Spanish Association for Desalination and Reuse (AEDyR 2020), the current average

Table 3 | Tertiary treatment and disinfection costs in the maximum cost scenario

			Treatment Capacity (Mm^3)		
		EUR/unit	**1**	**5**	**10**
Investment unit cost (EUR/m^3)			0.60	0.43	0.36
Total investment (EUR)			601,100	2,168,592	3,616,312
Fixed costs					
Energy (power)	kW	50	50.0	87.8	135.0
Maintenance			14,426	52,046	86,791
Fixed-cost subtotal (EUR)			16,926	56,435	93,541
Indirect costs (EUR/m^3)			3,216	10,723	17,773
Fixed-cost Total (EUR)			20,142	67,158	111,314
Fixed-cost Total (EUR/m^3)			**0.0201**	**0.0134**	**0.0111**
Variable costs					
Operational personnel	Hours/year	35	1,000	1,444	2,000
Technical personnel (10%)	Hours/year	54	100	144	200
Filter cloths	unit	750	7	35	70
UV lamps	unit	830	9	45	90
Sampling and analyses	EUR/year		9,000	9,444	18,000
Variable-cost subtotal (EUR)			62,120	131,400	226,000
Variable-cost subtotal (EUR/m^3)			0.0621	0.0263	0.0226
Sodium hypochlorite	Kg/m^3	0.30	0.0600	0.0600	0.0600
Electricity consumption	KWh/m^3	0.15	0.2000	0.1609	0.1120
Return flows and stops			0.0024	0.0022	0.0011
Variable-cost subtotal (EUR/m^3)			0.1125	0.0706	0.0585
Indirect costs (EUR/m^3)			0.0214	0.0134	0.0111
Variable-cost Total (EUR/m^3)			**0.1339**	**0.0840**	**0.0696**
Total Operating Cost (EUR/m3)			**0.1540**	**0.0975**	**0.0807**
Total Cost, incl. depreciation (EUR/m^3)			**0.1925**	**0.1252**	**0.1039**

Source: Authors' own.

Calculations consider four stages of treatment: 1) physical-chemical, 2) filters, 3) UV lamps, and 4) final chlorination.

seawater desalination prices in Spain lie in the range of 0.6–1.0 EUR/m^3. In brackish water, costs are much lower due to lower energy consumption, with highly variable values depending on salinity, at approximately 0.15–0.3 EUR/m^3. The only difference in costs between a brackish and a sea water plant is due to energy consumption, with all the remaining costs usually set at very similar values.

These costs make reclaimed water a very competitive source compared with alternative non-conventional sources, such as desalinated water, although reclaimed water remains significantly more expensive than conventional water resources. The problem arises when there is no alternative water source due to full exploitation (and often overexploitation) of the conventional resources available. This overexploitation seldom arises in the case of surface resources, as they are easier to control and the allocation is based on resources guaranteed through multi-year models. In contrast, groundwater resources are more uncertain and difficult to monitor, which usually leads to late responses from the administration when the aquifer has already been overexploited. Consequently, when the cheapest option runs out and there are no alternatives to increase supply (e.g., new reservoirs), reclaimed water should enter the system with the aim to augment supply or substitute conventional sources (i.e., water saving). To facilitate this substitution, information on reclamation costs should be provided to potential users.

Nevertheless, it can be assumed that a representative cost of the tertiary treatment plus disinfection, as shown in the previous section, would be approximately 0.10–0.15 EUR/m^3 (excluding investment depreciation cost), to which transport and

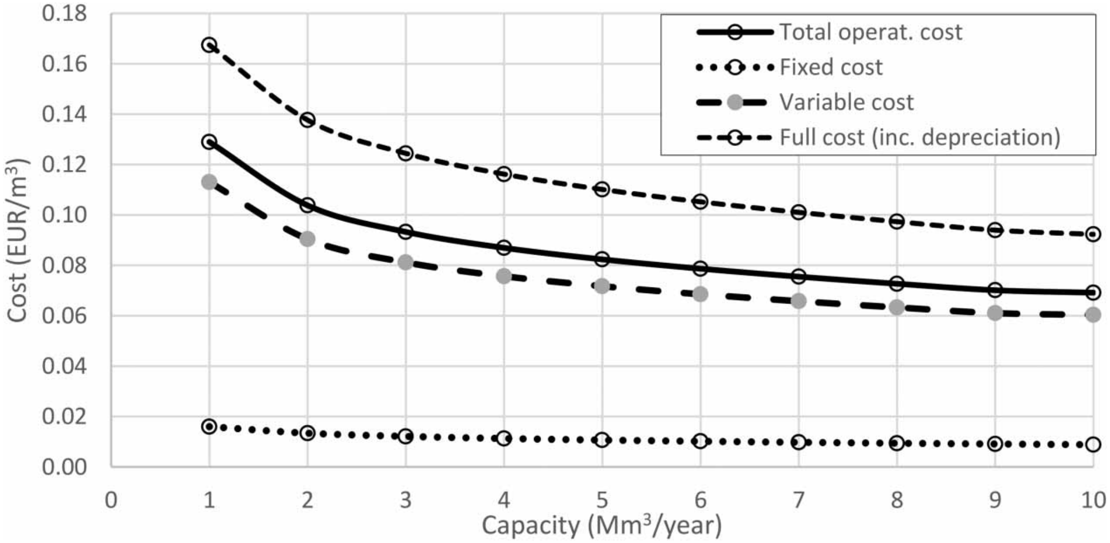


Figure 4 | Evolution of costs and WWTP capacity (minimum cost scenario).

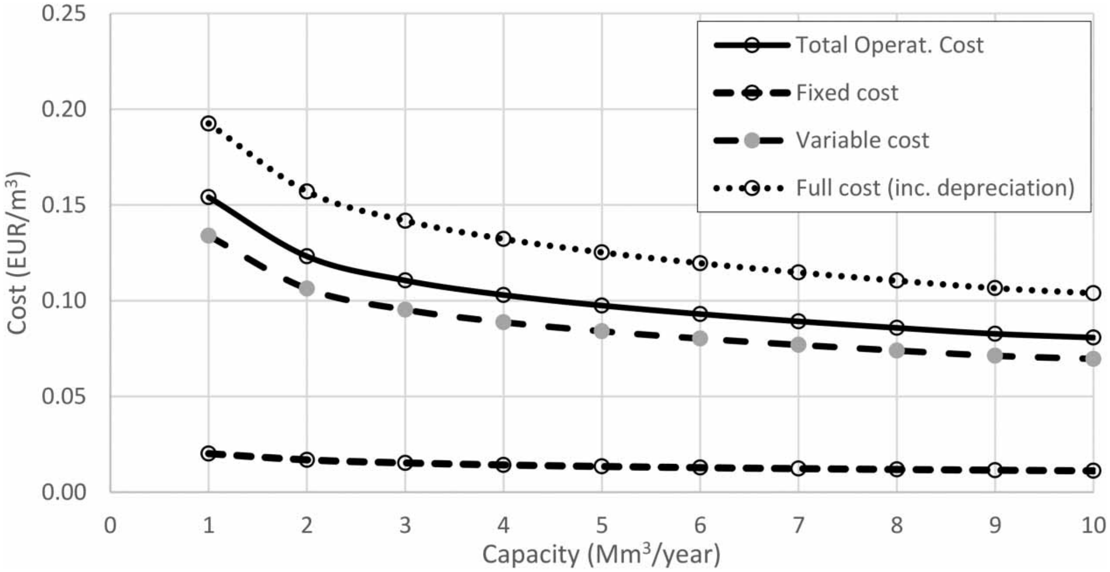


Figure 5 | Evolution of costs and WWTP capacity (maximum cost scenario).

storage must be added. Though transport and storage costs depend on a wide variety of factors, such as the user's location, certain studies have given a conservative reference at approximately 0.15 EUR/m^3 (Pistocchi *et al.* 2017). Consequently, to assume the costs of water reclamation for irrigation users, it would be necessary to cultivate crops whose marginal value of water (i.e., economic productivity of water) exceeds 0.25–0.30 EUR/m^3. It is again worth bearing in mind that, in our specific case study, the investment costs are fully financed by the regional government, and hence, the pricing scheme should not consider this type of cost: therefore, only operational costs (fixed and variable components) should be included.

Furthermore, it is worth noting that when reclaimed water is used, it enters as a component of a resource mix, with surface, groundwater, and other non-conventional sources (e.g., desalinated) in order to guarantee water supply and to achieve suitable water quality (depending on the crop). Consequently, the final cost of the irrigation water would be the weighted-average cost of the different sources. The higher cost of reclaimed water can then be moderated by the other water sources, as is the case in Almeria (Caparrós-Martínez *et al.* 2020).

Regarding payment affordability for irrigators in the DHCMA case study, most irrigated lands are dedicated to high-value horticultural crops (mostly in the form of greenhouse farming), as well as fruit (e.g., citrus), and subtropical crops (e.g., avocado, mango), with a significant recent growth in irrigated olive groves. Based on the information gathered from the DHCMA hydrological plan and the crop data from the Spanish Ministry of Agriculture, the payment capacity of these crops is usually very high, as shown by the estimated economic productivity of irrigation water. These productivities have been estimated at approximately 0.50 EUR/m^3 for irrigated olive groves, 0.60 EUR/m^3 for tropical crops (e.g., avocado and mangos), and 1.50 EUR/m^3 in the case of horticultural crops (e.g., tomatoes, cucumbers, lettuce) (Expósito & Berbel 2017; Martínez-Dalmau *et al.* 2023).

Lastly, it is worth bearing in mind that cascading water reuse constitutes one of the main constraints for the setting and practical implementation of water reuse targets at the basin level. In large river basins, return flows from upstream users (such as irrigation returns and treated urban wastewater) are commonly utilised by users downstream. Consequently, a river basin system often presents various levels of water-use efficiency in its different river sections (and sub-basins), and low efficiencies in upstream sections ensure water flows in downstream water bodies (Simons *et al.* 2015). In our opinion, it is critical that the use of reclaimed water should be treated as a component of the basin water balance so that the possibility of 'double counting' is avoided. This condition implies that reclaimed water resources in 'closed' (fully allocated) basins would only be feasible in coastal locations (or where return flows are not usable since they end in a saline sink), which is the case of the WWTPs analysed in this study.

CONCLUSIONS

This article offers a comprehensive cost analysis of reclaimed water for irrigation uses upon the financial and costs information gathered from various WWTPs located on the Mediterranean coast of Andalusia. We believe that our results offer valuable information for all agents involved in water cycle management for the design of suitable cost-recovery price settings and for the financial viability of future investments in water reclamation. Furthermore, this article contributes to the discussion on the financial affordability for irrigators to pay for this non-conventional water resource based on the water productivity of the crop mix in the region and on the cost of alternative water sources, such as desalination.

As the main conclusion of this study, once the tertiary treatment and disinfection costs have been comprehensively analysed, we believe that all efforts should be concentrated on helping public administrations and the water cycle operators place value on this non-conventional resource. This is especially valid in a context where irrigators (together with the rest of the economic sectors and general population) are suffering water cuts due to increasing water scarcity and to the unrelenting drought period currently affecting southern Spain. Due to climate change effects, these drought episodes are expected to be more persistent and occur more often, thereby compromising the future viability of strategic sectors such as irrigated agriculture. Furthermore, other non-conventional water sources, such as desalination, imply higher production costs and exert greater environmental impacts, which render the use of reclaimed water a more sustainable alternative to cope with water scarcity. Furthermore, the goals for the utilisation of reclaimed water should consider the location of WWTPs and prioritise coastal locations in order to minimise the volume of treated water discharged into the sea, and to increase the preservation of coastal water reservoirs.

Lastly, we would like to point out that our estimations have been obtained based on the information gathered from various WWTPs, since the direct extrapolation of these cost estimations to other locations is difficult due to significant differences in their major cost components, such as civil work, labour, energy, and chemicals. Though this represents a limitation of our study, we believe that our results significantly contribute to the existing gap in the literature regarding water reclamation costs. Moreover, further research should be directed towards testing management instruments of this non-conventional resource and towards analysing their impact on basin management, in order to incorporate this resource as a major source in the water mix at the basin level together with conventional surface water and groundwater.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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