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Operational drivers of water reuse efficiency in Portuguese wastewater service providers

António L. Amaral[a,b,c,d,*], Rita Martins[c], Luís C. Dias[c]

[a] Polytechnic Institute of Coimbra, Coimbra Institute of Engineering, Rua Pedro Nunes, 3030-199, Coimbra, Portugal
[b] CEB – Centre of Biological Engineering, University of Minho, Campus de Gualtar, 4710-057, Braga, Portugal
[c] University of Coimbra, CeBER – Centre for Business and Economics Research, Faculty of Economics, Av. Dias da Silva, 165, 3004-512, Coimbra, Portugal
[d] Instituto de Investigação Aplicada, Laboratório SiSus, Rua Pedro Nunes, Quinta da Nora, 3030-199, Coimbra, Portugal

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ABSTRACT

Identifying the service providers that perform best in key operational indicators is important for increasing the sustainability of the wastewater treatment sector. Wastewater reuse is increasingly considered as a relevant aspect in this context. The current study first identifies the Portuguese service providers in the efficiency frontier regarding wastewater reuse and proceeds to identify its main operational drivers. Reused wastewater was then successfully estimated using the selected drivers. The main policy recommendations, resulting from this study, towards wastewater reuse upsurge include fostering the aggregation of smaller SP to benefit from economies of scale, and strive for adequate infrastructure maintenance practices.

1. Introduction

Sustainability is, nowadays, a topic of the utmost significance for both decision-makers and the general public. The key pillars of sustainability include environmental preservation, as well as governance, technological, economic, and social progress. Wastewater treatment (WWT) systems must also adhere to the sustainability objectives (UN, 2005, 2022; Balkema et al., 2002; Davidson et al., 2007; van Leeuwen et al., 2012; Marques et al., 2015; Molinos-Senante et al., 2016).

Increasing freshwater demand, together with supply shortages, requires a responsible use of clean water sources (Balkema et al., 2002; Davidson et al., 2007), which can be met by a number of strategies including urban water reuse and desalination, among others (Marques et al., 2016; Cooper and Crane, 2016; Lee and Jepson, 2020). Additionally, increased seasonal demand (associated to climatic events), and the reduction of clean water sources in nature, claim for wastewater (WW) reuse, whether internally (within water sector utilities) or externally (i.e. through industrial and public networks or crops and landscape irrigation systems) (Gonzalez-Serrano et al., 2005; Hernández-Sancho and Sala-Garrido, 2009; Rodriguez-Garcia et al., 2011; Molinos-Senante and Donoso, 2016; Pinto et al., 2021; Amaral et al., 2022). One of the most advocated ways to do so, in a sustainable manner, relies on the reuse of treated WW, which motivated a number of governmental goals and directives for service providers (SP), such as the ones proposed by the Portuguese Government (Portuguese Secretary of State for the Environment, 2022).

The current study falls directly within the scope of the WW reuse goals, set both in the United Nations sustainable development goals report in 2022 (UN, 2022) and in the goals and directives for 2030 according to the Portuguese Strategic Plan for Water Supply and Wastewater and Stormwater Management – PENSAARP 2030. Therefore, and even though not being a required output of WW utilities, the potential reuse of wastewater should be timely addressed, which is the motivation behind the current research. Indeed, it seems likely that, although the reused WW does not usually appear among the mandatory operational indicators studied so far for WWT utilities, its growing importance will foster its study in the coming years.

The main inputs for WWT, in sustainability studies, include WW intake, expenditures, energy consumption and allocated personnel. As WWT utilities are unable to dictate the amount of WW they must treat, WW intake was employed as a non-discretionary input (Amaral et al., 2022, 2023). On the other hand, given that expenses are borne by customers through water tariffs, one of the most significant pillars of the WWT sector's sustainability pertains to its social and financial effects (Molinos-Senante et al., 2014; Castellet and Molinos-Senante, 2016; Moreno et al., 2017; Dong et al., 2017, 2018; Walker et al., 2021; Amaral

* Corresponding author. Polytechnic Institute of Coimbra, Coimbra Institute of Engineering, Rua Pedro Nunes, 3030-199, Coimbra, Portugal.
E-mail address: lpamaral@isec.pt (A.L. Amaral).

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et al., 2022, 2023). That being the case, total expenditures represent a valuable resource that needs to be carefully controlled by WWT utilities, either for decreasing the financial burden that WWT represent for the consumers, improve treatment quality or invest in sustainability goals (including WW reuse). Primary operating expenses are related to human resources and energy usage (Molinos-Senante et al., 2014; Castellet and Molinos-Senante, 2016; Moreno et al., 2017; Dong et al., 2017, 2018; Walker et al., 2021), which can largely surpass 50% of the total expenditures, counterbalanced by returns through revenue WW gains (Amaral et al., 2022, 2023). The revenue water volume was considered as a desirable output (such as in Amaral et al., 2022, 2023) taking into consideration that it represents a service provided by the utility, therefore being considered as a by-product of the SP activity, further valued in economic terms in Portugal through the water tariffs. Energy consumption is crucial from an environmental standpoint as well. The majority of the energy used by WWTPs originates from non-renewable sources releasing greenhouse emissions. However, energy consumption can be partially offset by the self-produced energy through the combustion of dried sludge and biogas, or by renewable energy generating systems (Molinos-Senante et al., 2014; Castellet and Molinos-Senante, 2016; Dong et al., 2017, 2018; Moreno et al., 2017; Walker et al., 2021; Molinos-Senante et al., 2016).

The main desirable output of a WWT utility is, of course, the treated WW, crucial form an environmental point of view, given that it allows the return of clean water to the environment. The generated sludge is often seen as an undesirable product that SP must deal with, in addition to the major (desired) output of WWT (treated WW), leading to additional costs in sludge treatment and/or deposition (Molinos-Senante et al., 2014; Castellet and Molinos-Senante, 2016; Dong et al., 2018; Henriques et al., 2020). Just a small portion of the WW sludge in Portugal is used for energy valorization, by anaerobic digestion or dehydrated sludge incineration. As a result, the sludge exiting a wastewater treatment plant (WWTP) is viewed as an undesirable output, adding to the WWT utilities expenditures since they must pay other parties for treatment and/or deposition (Amaral et al., 2022). In the current research, all of the above operational indicators were used to evaluate the Portuguese WWT SP sustainability.

Moreover, it is also crucial to understand the significance of potential drivers for the SP operational indicators (including WW reuse), concurrently with the use of benchmarking tools. A few authors have already addressed some of these factors in studying the sustainability of the water sector, namely: SP size (in terms of WW volumes, infrastructures and outreach) towards the determination of economies of scale (Byrnes et al., 2009; Romano and Guerrini, 2011; Martins et al., 2012; Carvalho and Marques, 2014, 2015, 2016; Pinto et al., 2017; Molinos-Senante and Guzman, 2018; Caldas et al., 2019; Henriques et al., 2020; Walker et al., 2021; Pereira and Marques, 2022); adequate infrastructure maintenance practices (Ferro and Mercadier, 2016; Palomero-González et al., 2021); high quality practices regarding perceived outputs and service and quality policies (Molinos-Senante et al., 2016; Pinto et al., 2017; Palomero-González et al., 2021; Walker et al., 2021); WW collecting network focusing on the need to avoid oversizing the overall length and connections (Güngör-Demirci et al., 2017; Molinos-Senante and Maziotis, 2021; Amaral et al., 2022, 2023); WWTP typology including urban, mostly urban and rural typologies towards economies of output density and urban typology (Marques et al., 2014; Carvalho and Marques, 2015, 2016; Henriques et al., 2020; Molinos-Senante and Maziotis, 2021; Sala-Garrido et al., 2021; Mergoni et al., 2022); governance model including, public, private and/or concession management (Byrnes et al., 2009; Pinto et al., 2017; Molinos-Senante and Guzman, 2018; Caldas et al., 2019; Marques and Simões, 2020; Henriques et al., 2020; Molinos-Senante and Maziotis, 2022) mainly favoring private and/or concession models, although other studies (Cruz et al., 2012; Sala-Garrido et al., 2019; Mocholi-Arce et al., 2022; Pereira and Marques, 2022) diverge from this conclusion; WWTP adequateness and usage (Lorenzo-Toja et al., 2015; Amaral et al., 2022, 2023); energy efficiency (Alves, 2016; Moreno et al., 2017; Sala-Garrido et al., 2019), and water scarcity (Molinos-Senante and Donoso, 2016; Pinto et al., 2021) towards water pricing modeling. Despite these efforts, detailed and state-of-the-art literature on potential sustainability drivers in the water sector is still scarce, with previous studies addressing solely a limited number of operational drivers at a time instead of a comprehensive analysis. The current study focuses on the extent to which a diverse range of operational descriptors may be recognized as WW reuse drivers, contributing to overcome this gap in the literature.

This research considers a country-wide scope, using data from Portugal. Being affected by seasonal droughts, water scarcity in Portugal is a pressing issue, with more than half of the country presenting a "medium" to "high" water scarcity level (GFDRR, 2020), Seven of the main hydrological basins (out of 20 in mainland Portugal) face a *Water Exploitation Index* + above 40%, signaling a high scarcity risk (APA – Agência Portuguesa do Ambiente, 2016). These facts further strengthen the usefulness of studying wastewater reuse within the Portuguese reality.

The key distinctions between the three governance models in the Portuguese case are: i) concessions, private companies that have been awarded municipal concession contracts to run water systems and are responsible for providing the service; ii) (public) delegations, municipal or inter-municipal enterprises and state-municipal partnerships; and iii) direct management, provided by municipalized and municipal services. Concessions and delegations are both independent services, run in an entrepreneurial manner and funded by private or public funds. Local governments approve contracts with for-profit organizations in concessions, establishing the relevant terms, whereas the public sector retains the exploitation right in delegations and direct management.

In Portugal, the Decree-Law 58/2005 or "Water Law" (Portuguese Republic Diary, 2005) establishes the bases and institutional framework for sustainable water management. The water uses encompassed in the Decree-Law 58/2005 are water abstraction and wastewater discharge. Water sector utilities that abstract or discharge water in Portugal must apply for a license (or permit). Cost and licensing of water abstracted and discharged are regulated by the Portuguese Environment Agency and by the Ministry of Environment and Climate Action. The licensing process includes an evaluation of the water source, volume of water to be abstracted, quality and quantity of the water to be discharged, potential impacts to the environment, and measures taken to reduce the impact. The licensing process also includes a fee, based on the volume of water to be abstracted, volume and quality of the discharged water, and potential environmental impacts. The fee is established by law and is subject to periodic revision. Currently it is divided into 6 different components, aiming to offset the benefit resulting from the private use of the public water domain, the environmental cost inherent to activities likely to cause a significant impact on water resources, and the administrative costs inherent to planning, management, inspection and guarantee of water quantity and quality.

However, comprehensive research on the operational factors influencing water reuse in the water sector is still lacking. In order to address the existing knowledge gap, in Portugal and elsewhere, the main goals of this study are: i) to identify the SP located on the WWT sector efficiency frontier (WW reuse wise), ii) to model the reused WW volumes and iii) to identify the most important operational drivers. As well as being, to the best of the authors' knowledge, the first study focusing on WWT utilities water reuse with such a broad scope and depth, in Portugal or elsewhere, the presented methodology has the potential to be used with data from any country, highlighting role model SP, associated WW reuse drivers and providing policy recommendations.

2. Literature review

In the literature, a growing number of sustainability studies of WWT systems also address WW reuse (Gonzalez-Serrano et al., 2005;

Hernández-Sancho and Sala-Garrido, 2009; Hernández-Sancho et al., 2011; Rodriguez-Garcia et al., 2011; Molinos-Senante and Donoso, 2016; Lee and Jepson, 2020; Pinto et al., 2021; Amaral et al., 2022, 2023). Gonzalez-Serrano et al. (2005) investigated the cost of WWT technologies in regions under seasonal stress based on several WW reuse possibilities (irrigation, aquifer replenishment through infiltration or direct injection). Based on the technical design and cost assessment of the unit processes and activities, these authors have established a set of cost functions for investment, operation, and maintenance. Hernández-Sancho and Sala-Garrido (2009) analyzed the efficiency of WWTPs to improve the potential for WW reuse. Data envelopment analysis (DEA), a benchmarking technique, was employed to calculate an efficiency index for the WWT processes, allowing to characterize the performance of each plant at the cost level. Hernández-Sancho et al. (2011) determined an extended cost function for a set of WWT technologies, based on cost structure, towards WW reuse and planning of new facilities. For that purpose, these authors developed a cost modelling methodology including the most representative variables in the process. Rodriguez-Garcia et al. (2011) were able to correlate the regulatory criteria set for WW reuse and discharge in sensitive and non-sensitive regions, with the employed treatment technology. The authors performed, alongside an environmental impact analysis, an economic evaluation of 24 WWTPs, emphasizing the importance of using pollutant removal metrics. Molinos-Senante and Donoso (2016) developed a water pricing model towards societal issues like fairness and affordability, while internalizing the value of water shortage. The suggested water rate structure corresponds to a rising block strategy emphasizing the variable component of the tariff. The empirical application to two Chilean regions demonstrated the envisioned water rate structure's effect towards a more sustainable and equitable water use.

Lee and Jepson (2020) performed a literature review on water reuse, encompassing wastewater reclamation, grey water and stormwater reuse, stating that reusing water has been suggested as a crucial adaptation measure for urban water systems experiencing shortfalls. These authors emphasize that, even though the recycled water volume has grown significantly since the 2000s, its integration into the municipal supply is poor. And, although external environmental shocks, like droughts, may operate as catalysts, a network of favorable economic, political, and regulatory conditions is more likely to promote a systemic change. Pinto et al. (2021) addressed the water resource scarcity problematic by examining the interaction between environmental phenomena and the management of water supply and demand to model tariffs. The authors concluded that water supply tariffs can be developed based on climatic and hydrologic data, utility costs, water demand, and appropriate and flexible tariff design, avoiding unneeded restrictions on SP. Amaral et al. (2022, 2023) studied the sustainability of the water sector utilities, using a DEA approach, determining improvement potentials, efficiency drivers and productivity changes. For this purpose, these authors employed, among others, the reused WW as a desirable output, given its increasing importance in establishing sustainability goals for the water sector. These authors have also found that, within the surveyed SP, solely 1.3% of the treated WW was reused. Indeed, a sharp increase in WW reuse by 2030 is one of the goals set by the Portuguese Secretary of State for the Environment for the water sector SP in Portugal (Portuguese Strategic Plan for Water Supply and Wastewater and Stormwater Management – PENSAARP, 2030).

Several studies seek to identify WWT efficiency drivers. Byrnes et al. (2009) employed DEA to analyze the economic performance of 56 non-metropolitan WWT utilities in the New South Wales and Victoria (Australia) regions from 2001 to 2004. These authors determined the main drivers and performed policy recommendations, advocating larger utilities governed by skills-based boards. Hernández-Sancho and Sala-Garrido (2009) used DEA to analyze the efficiency of 338 Spanish WWTPs to improve the potential for WW reuse, characterizing the WWTP performance at the cost level. These authors established maintenance and waste management costs as the most important drivers for efficiency, alongside WWTP size. In another study, Hernández-Sancho et al. (2011) determined an extended cost function for a set of 341 Spanish WWTPs of various treatment technologies, towards WW reuse and planning of new facilities. These authors established the importance of WWTP volume in the determination of the operating and maintenance costs, alongside plant age and pollutant removal efficiency. Romano and Guerrini (2011) studied the cost efficiency of 43 Italian water sector SP by DEA, based on cost structure, water volumes, and served population, to identify possible drivers. They concluded that ownership structure, location and SP size significantly impacted their efficiency, disclosing the existence of scale economies. Molinos-Senante et al. (2014) evaluated, using DEA, the efficiency of 192 Spanish WWTPs in terms of cost structure, and estimated the economic gains obtained by increasing WWTP efficiency. The main drivers behind cost reduction were identified as treated WW volume and energy costs. On the other hand, the work of Lorenzo-Toja et al. (2015) aimed to assess the operating efficiency of 113 Spanish WWTPs and identify inefficient WWTPs, by an environmentally based DEA benchmarking technique. These authors calculated the potential environmental gains and further identified the plant size and underuse, influent load, and climate as the main drivers. Later, Castellet & Molinos-Senante (2016) further employed DEA to study 49 Spanish WWTPs, from a technical, economic and environmental standpoint, allowing to quantify potential economic gains and savings in personnel and energy costs. Dong et al. (2017) studied the technical, economic, and eco-efficiency, by DEA, of 736 Chinese WWTPs. Trade-offs between costs, energy use, and environmental impacts were established, with the WWTP size, plant overuse, WW characteristics and climate as drivers for efficiency. Dong et al. (2018) further studied 157 municipalities in China by determining a single sustainability score from a DEA analysis. These authors established that, compared to water supply systems, the performance of WWTP has a larger influence on the sustainability score, being sensitive to sludge production and electricity consumption. On the other hand, the main sustainability drivers were found to be SP size and climate. Sala-Garrido et al. (2019) compared the productivity of 22 Chilean private and concessionary water SP from 2010 to 2016 using DEA. Technological gap regression was found to affect the private WWT utilities in that period.

More recently, Walker et al. (2021) undertook a holistic assessment to compare productivity and sustainability of 12 water sector utilities across a 6-year period in the United Kingdom, concluding that economies of scale and scope were drivers for productivity. In addition, Molinos-Senante and Maziotis (2021) assessed the productivity in the English and Welsh water sectors, between 2011 and 2019, identifying water source, treatment complexity, WWTP type, density and pumping capacity as the main drivers. Costs and operational performance were studied by Mocholi-Arce et al. (2022), employing a service quality based DEA model on 189 Chilean water sector utilities from 2010 to 2018, favoring public utilities with regard to private and concessionary SP. Considerable scale inefficiencies were found in 2160 municipal water and WWT utilities in Brazil, by Pereira and Marques (2022), through a two-stage DEA approach. Location, ownership, and water source were found to be important drivers.

With respect to the Portuguese context, Carvalho and Marques (2014) employed DEA to benchmark 74 water supply and WWT utilities in Portugal, showing scale and vertical integration economies in both sectors. Water supply and WWT utilities were also found to have economies of scope in subsequent studies (Carvalho and Marques, 2015, 2016). Based on investment effectiveness, service quality, costs and tariffs, Alves (2016) examined the performance and energy use of 13 WWTPs in Lisbon and Tagus valley with respect to the employed WWT processes. This allowed to identify the aerated processes as the major energy consumers, and WW volume and pollution load as the most significant drivers affecting energy use. Later, Moreno et al. (2017), still addressing energy and environmental performances, identified the population equivalent and plant size as drivers for performance.

Towards the determination of the ideal SP size, Caldas et al. (2019) employed DEA to analyze 308 Portuguese councils, determining scale economies and advocating a case-by-case approach for establishing government policies. Marques and Simões (2020) later examined the performance of the Portuguese private and public water sectors, from 2011 to 2015, showing increased performance for private SP. Henriques et al. (2020) employed composite indicators and DEA to assess 169 Portuguese WWT utilities, identifying the main drivers behind retail SP quality service as SP size, energy generation, investment incentives, concession model and urban typology.

More recently, Mergoni et al. (2022) studied the environmental performance of 149 Portuguese SP operating in the water supply, WW treatment and waste disposal sectors, concluding that small and very large utilities should improve in that regard. Amaral et al. (2022) benchmarked 120 Portuguese WWT utilities, from 2015 to 2019, using a DEA approach, for the determination of improvement potentials,

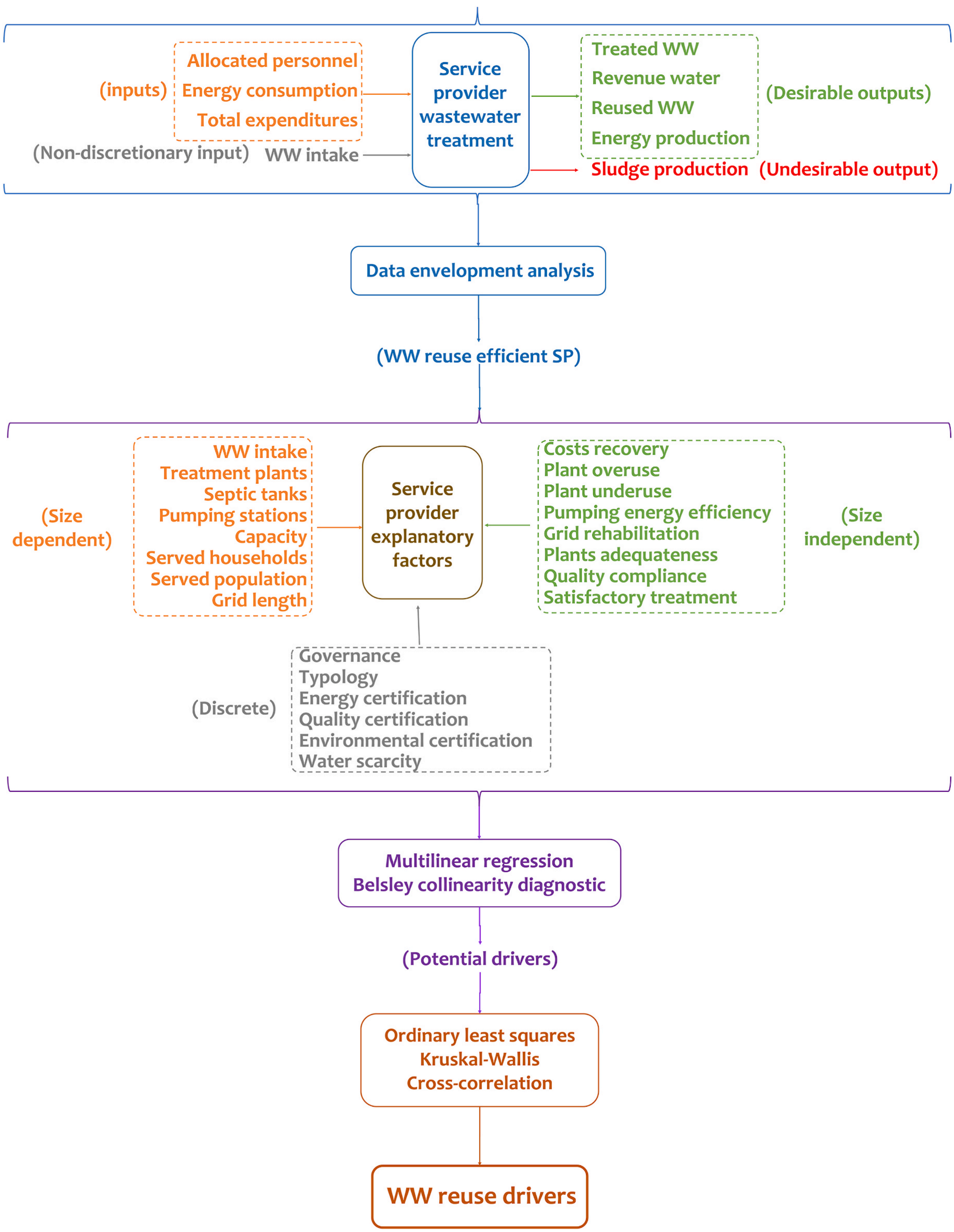

Fig. 1. Flowchart of the employed methodology.

efficiency drivers and productivity change. These authors found the SP size, WWTP underuse and quality, environmental and energy certification policies to be the main efficiency drivers, alongside the governance model and WWTP typology. Broadening the scope of the previous study to encompass water supply SP, Amaral et al. (2023) studied the main drivers associated to sustainability for over 150 utilities. Again, the SP size (suggesting the presence of economies of scale), certification policies, governance model and WWTP typology role in the SP sustainability were highlighted.

As presented, Portugal has been the focus of several studies concerning the water sector, which are of major importance due to its geographical, climate, and socioeconomic characteristics. However, water reuse has not been the main focus of sustainability studies from the SP standpoint. However, except for Amaral et al. (2022, 2023), none of the available literature thoroughly addressed the Portuguese WWT sector efficiency (including WW reuse) and respective drivers.

3. Materials and methods

The methodological approach used in this work is described next. After a data collection and validation process, DEA was used to determine the SP efficiencies in terms of selected indicators including reused WW (RWW). Solely the SP in the efficiency frontier, on an annual basis, were further considered for the RWW operational drivers' identification stage. The estimation of reused WW volumes and identification of potential drivers was performed by feeding the operational indicators to a Multilinear Regression (MLR) analysis, further subjected to a Belsley collinearity diagnostic. Next, a validation stage was carried out using a Kruskal-Wallis (KW) analysis for discrete drivers and an Ordinary Least Squares (OLS) analysis for continuous drivers. An additional Cross-Correlation (CC) study allowed identifying likely inter-relationships between potential drivers. Except for dimensionless or percentage-based drivers, which used solely absolute (raw) values, a second analysis employed normalized values (per WW intake), due to the diversity of the potential drivers' scale ranges. A flowchart of the employed methodology is presented in Fig. 1.

3.1. Data collection and validation

The *Water and Waste Services Regulation Authority's Annual Report on Water and Waste Services in Portugal* from 2015 to 2019 provided the data used in this study (Portuguese Water & Waste Services Regulation Authority, 2016, 2017, 2018, 2019, 2020), except for water scarcity (GFDRR, 2020). SP that did not operate WWTPs, nor submitted economic or energy data for the WWT, were excluded from the analysis. Missing economic data (from a small subsample of SP) was inferred, and likely outliers were identified and removed, according to the methodology employed by Amaral et al. (2022). The studied operational indicators were split into inputs, non-discretionary inputs, desired and undesired outputs for the DEA (Table 1).

Table 1
Studied operational indicators.

Operational indicators	Description
Inputs	Allocated personnel (p.e. year^{-1})
	Energy consumption (GW year^{-1})
	Total expenditure (M€ year^{-1})
Non-discretionary input	WW intake (m^3 year^{-1})
Desirable outputs	Energy production (GW year^{-1})
	Revenue water (m^3 year^{-1})
	Reused WW (m^3 year^{-1})
	Treated WW (m^3 year^{-1})
Undesirable output	Sludge generation (Kton year^{-1})

3.2. Data envelopment analysis

DEA has been successfully used in a wide variety of sustainability studies on WWT, as highlighted by the literature review. DEA is a non-parametric efficiency benchmarking method addressing multiple inputs and outputs without assuming a specific production function (Cooper et al., 2006). It computes an efficiency score for each decision-making unit for benchmarking purposes using linear programming. This score assesses the proficiency of the decision-making units to obtain a particular output production while minimizing input use (or maximizing output generation from a set of inputs). By definition, an efficient decision-making unit cannot further reduce input usage (or increase the generation of desirable output), in contrast to an inefficient one (Charnes et al., 1978; Cooper et al., 2007).

Decision-making units' efficiency determination by classical radial models (Charnes et al., 1978; Cooper et al., 2007) examines the largest permitted proportional input reduction (or output increase) considering the efficiency frontier set by its peers. On the other hand, a non-radial DEA model enables input minimization (or output maximization) in different proportions (Färe and Lovell, 1978), thus providing information on the efficiency of each studied input and output (Molinos-Senante et al., 2014). One of the most often used non-radial DEA models for setting efficiency benchmarks in WWT studies is the slacks-based model (SBM) (Lorenzo-Toja et al., 2015; Castellet and Molinos-Senante, 2016; Amaral et al., 2022, 2023), first developed by Tone (2001). SBM presents improved flexibility in the computation of decision-making units' inefficiencies (Thrall, 1996; Cooper et al., 2007) since it considers the non-radial features of inputs and outputs, making it more appropriate for monitoring inputs with elusive connections (Cooper et al., 2007). Therefore, in the current study, the use of the SBM model, in the DEA analysis carried out, aims to clearly differentiate the employed sustainability operational indicators, calculate the efficiency of each studied SP and identify the SP lying on the efficiency frontier.

According to Marques et al. (2011), over 70% of regulators in more than 50 countries employ benchmarking methods (including DEA) to evaluate service quality or support the economic regulation of the water sector. Non-radial DEA models are especially suited for WWT studies by enabling to isolate specific inputs on which to act to increase efficiency (Molinos-Senante et al., 2014). That being the case, the SBM model is one of the most suitable DEA methods for water sector sustainability studies, given its flexibility regarding the determination of inefficiencies, suitability to accommodate the non-radial characteristics of inputs and outputs, and provision of target values for inefficiency (slacks) calculation (Lorenzo-Toja et al., 2015). Indeed, Lorenzo-Toja et al. (2015) used an SBM approach to perform an environmental benchmark on a set of WWTPs. Also, Castellet and Molinos-Senante (2016) applied a DEA-WSBM (weighted slacks-based model), which allowed assigning weights to the set of pollutants removed from WW according to their environmental impact. More recently, Amaral et al. (2022, 2023) employed an DEA-SBM to benchmark the efficiency of WWT utilities and quantify improvement potentials.

In the current study, the SP in the RWW efficiency frontier were determined by an SBM–DEA model, using the operational indicators listed in Table 1. The aim was to maximize water reuse, alongside other desirable outputs (energy production, revenue water and treated WW), in order not to lose sight of the broader SP efficiency perspective, from a set of inputs of recognized importance (allocated personnel, energy consumption and total expenditures). Upon determining the SP in the efficiency frontier, solely these were used to model WW reuse and identify potential drivers, given that the use of SP falling outside the efficiency frontier (and, therefore, inefficient by definition) would only result in the introduction of noise into the predictive model and decrease its quality.

3.3. Identification of operational drivers for WW reuse

Potential operational drivers for WW reuse were determined by feeding the drivers reported in Table 2 to an MLR analysis. The studied drivers allowed for the coverage of a wide range of factors, including SP size, WWTP adequateness, governance model, quality of service, WWTP typology, length of sewers' grid, infrastructure maintenance, techno-economic factors, certification policy and water scarcity. All proposed drivers were also subjected to a Belsley collinearity diagnostic, prior to RWW modeling, and CC analysis to determine dependencies and observe inter-relationships. Individual OLS analyses (for continuous drivers) and Kruskal-Wallis (KW) tests (for discrete drivers) were used to further validate any potential RWW driver identified by the MLR study. Potential drivers determined as non-significant by the individual OLS or KW analysis, or inconsistent with the MLR analysis, were excluded as actual RWW drivers.

3.4. Employed statistical approach

MLR, Belsley collinearity diagnostic, OLS (for continuous drivers), KW (for discrete drivers) and CC analyses were among the statistical methods used in this work to identify the actual RWW operational drivers. All the above analyses were conducted using Matlab 8.3.0 (The MathWorks, Inc., Natick, USA), except for the CC analysis, which was conducted using Microsoft Excel (Microsoft Corporation, Redmond, USA). MLR analysis, a multilinear supervised learning technique, is commonly used to predict dependent (response) variables from a set of independent (predictor or explanatory) variables (Hill, 2006). The response variables coefficients in MLR are often determined using an OLS method, which is a least squares technique typically used in linear regression models to predict the dependent (Y) variable(s) from a set of independent variables. This is accomplished by minimizing the sum of the residuals (differences between actual and predicted Y values) squares (Einax et al., 1997). Alongside MLR, a Belsley collinearity diagnostic was performed with the potential drivers, determining single condition indices searching for dependencies between drivers in the found MLR model. Single condition indices below 10 are considered to infer weak dependencies, whereas moderate to high dependencies lead to values above 30. The determination of variance decomposition proportions above 0.5 allows for identifying possible collinear drivers in the model (Belsley et al., 1980).

Apart from MLR, used to model WW reuse and deduce the potential RWW drivers from the set of studied drivers, separate OLS analyses were conducted, between each potential continuous driver and the RWW, allowing for confirmation or rejection of the MLR results. On the other hand, KW was used to compare each possible pair within the discrete drivers, namely the governance model, WWTP typology, quality, environmental and energy certifications, and water scarcity (levels indicated in Table 2). The non-parametric KW test investigates statistically significant differences between the median values of two sets of variables. Given a statistical significance threshold (p-value) of 0.05, samples are deemed to differ from one another for larger p-values and otherwise for smaller p-values. Finding correlations between related variables in a given data collection is possible via CC analysis (Einax et al., 1997). CC was, therefore, used in this study to examine the entire drivers' dataset and to identify any inherent correlations and dependencies. In this study, drivers' pairings with a regression value (R) greater than 0.5 were deemed as being correlated (with stronger interrelationships presenting higher R values).

Table 2
Studied operational drivers for WW reuse.

		Drivers	Description
Size dependent factors	(Continuous variables)	Win	Wastewater intake (m^3 $year^{-1}$)
		#WWTP	Number of wastewater treatment plants (WWTP) (#)
		#ST	Number of septic tanks (#)
		Cap.	WWT capacity (m^3)
		#PS	Number of pumping stations (#)
		#HH	Number of served households (# $year^{-1}$)
		Pop.	Effectively served population (person-equivalent $year^{-1}$)
		GL	WWT sewers grid length (Km)
Size independent factors	(Continuous variables)	Adeq.	WWTP adequateness (served per dimensioned population) (%)
		Under.	WWTP underuse (% of total treated volume over the WWTP capacity) (%)
		Over.	WWTP overuse (% of total treated volume over the WWTP capacity) (%)
		Rec.	Cost recovery (%)
		Rehab.	Sewers grid rehabilitation (length of rehabilitated sewers per grid length) (%)
		EnE	Energy efficiency of the pumping system (kWh m^{-3} $100m^{-1}$)
		Comp.	Effluent quality parameters compliance (%)
		Satisf.	Satisfactory WWT (satisfied population per served population) (%)
	(Discrete variables)	Gover.	Governance model (1 – Direct management; 2 – Delegation; 3 – Concession)
		Typol.	WWTP typology (1 – Rural; 2 – Mostly urban; 3 – Urban)
		Qual. Cert.	Quality certification (0 – Absence; 1 – Existence)
		Env. Cert.	Environmental certification (0 – Absence; 1 – Existence)
		Ener. Cert.	Energy certification (0 – Absence; 1 – Existence)
		Water Scar.	Water scarcity (0 – Very low; 1 – Very low/Low; 2 – Low; 3 – Low/Medium; 4 – Medium; 5 – Medium/High; 6 – High)

4. Results

4.1. Service providers in the RWW efficiency frontier

The conducted DEA, fed with the operational indicators in Table 1, allowed to determine the WWT utilities efficiency, from 2015 to 2019, concerning WW reuse (Fig. 2). Due to possible efficiency changes (technical, operational, environmental, etc.) during the period under analysis, the DEA was carried on an annual basis. Utilities with an efficiency score of 1 represent the efficiency frontier. Given that most SP do not reuse WW, they present a null efficiency score (487 out of 601 studied SP, i.e. 81.0%, comprising the five-year period). This is mainly

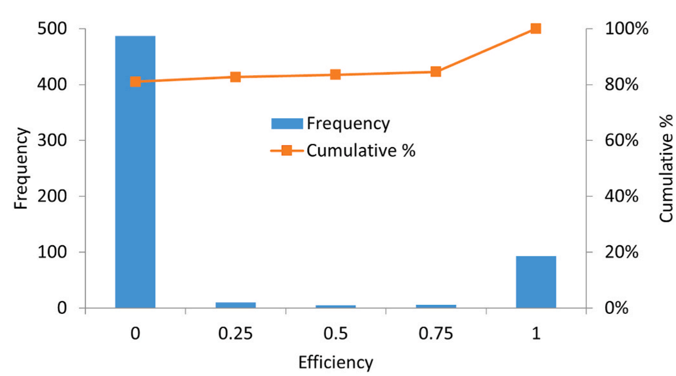

Fig. 2. Histogram of the DEA analysis results regarding the RWW efficiency score.

due to the fact that, currently, there is no significant reuse market in Portugal. Indeed, Portuguese SP currently reusing WW do so for addressing internal needs in water consumption. On the other hand, the large number of operational indicators taken into consideration for determining the RWW efficiency leads to a significative number of SP, within the ones reusing WW, lying in the efficiency frontier. These SP accounted for a total of 93 SP (comprising the five-year period), representing 15.5% of the total SP in the dataset. However, due to missing data, regarding the examined operational drivers, the number of SP employed in subsequent analyses was further cut off to a total of 49 SP (comprising the five-year period).

Furthermore, throughout the monitoring period, no significant evolution of the average SP efficiency towards WW reuse could be found (as established by a Malmquist-Luenberger analysis on the desirable products efficiency presented in Amaral et al., 2022). Thus, it is possible to conclude that no significant technological change affecting the SP efficiency occurred during the studied period, and that the differences found in RWW can be derived from the collected drivers' data.

4.2. Absolute RWW

The MLR (Table 3) revealed that the WWT capacity (Cap.) was the most important driver ($p = 4.95 \times 10^{-9}$) of the SP in the efficiency frontier (in terms of WW reuse). Indeed, the individual OLS analysis showed a substantial positive correlation ($p = 1.13 \times 10^{-27}$) between these two parameters, corroborating the WWT capacity contribution to increased RWW disclosed by MLR. This could be expected given that the WWT capacity is an SP size dependent driver, thus with the potential of influencing the absolute RWW values given that larger SP, as a rule, process larger WW volumes in WWTPs. Indeed, the CC analysis revealed an $R = 0.965$ between the WWT capacity and RWW (and $R > 0.9$ with the majority of the other SP size dependent drivers). Furthermore, no significant correlation ($R = 0.154$) was found between water scarcity and WW reuse by the SP, with all p-values above 0.05, for the studied water scarcity pairs.

The governance model was also found by MLR as a potential driver ($p = 3.46 \times 10^{-7}$ and $p = 2.39 \times 10^{-6}$, for delegation and concession, respectively), contributing to lower RWW. Upon the KW test regarding the three governance models (1 – direct, 2 – delegation and 3 – concession management), the delegation and concession governance models differed significantly from the direct management models ($p = 5.16 \times 10^{-4}$ and $p = 4.37 \times 10^{-4}$, respectively), but not from each other ($p = 0.484$). These results seem to point to a significant (and positive) effect of the direct management model towards WW reuse (regarding the retail level, as later discussed), comparing to the other two models, which was further confirmed by the normalized RWW analysis.

Table 3
Potential operational drivers, MLR and OLS/KW influence and p-values (absolute RWW values).

Drivers	MLR p-value	MLR Influence	OLS/KW p-value			OLS/KW Influence
Cap.	4.95×10^{-9}	+	1.13×10^{-27}			+
Gover.[a]	3.46×10^{-7}	–[b]	[1–2]: 5.16×10^{-4}	[1–3]: 4.37×10^{-4}	[2–3]: 0.484	
Ener. Cert.[a]	1.30×10^{-6}	–[c]	[0–1]: 6.05×10^{-3}			
Gover.[a]	2.39×10^{-6}	–[d]	[1–2]: 5.16×10^{-4}	[1–3]: 4.37×10^{-4}	[2–3]: 0.484	
Win	5.14×10^{-3}	–	5.39×10^{-22}			+
Adeq.	5.72×10^{-3}	+	0.528			+

[a] Discrete driver.
[b] Delegation.
[c] Without certification.
[d] Concession.

Concerning the certification policy, the MLR determined that the absence of energy certification (Ener. Cert.) resulted in lower RWW ($p = 1.90 \times 10^{-4}$). This was further supported by the KW test conducted on the two energy certification groups (0 – absence and 1 – existence), confirming the statistical difference between them ($p = 6.05 \times 10^{-3}$). However, it should be stressed that the subsequent analysis performed with the normalized data did not confirm the energy certification to be an actual driver for RWW given the high p-value obtained. That being the case, the positive correlation observed for the absolute values may be due, at least partially, to the correlation of the energy certification practices with the SP size. Indeed, energy certification was found to present correlation values around, or above, 0.6 with the majority of the SP size dependent drivers.

The MLR analysis also identified the WW intake (Win, $p = 5.14 \times 10^{-3}$) and WWTP adequateness (Adeq., $p = 5.72 \times 10^{-3}$) as potential RWW drivers. However, the fact that MLR and individual OLS analysis revealed conflicting influence directions for the WW intake, suggests that this parameter appears in the MLR analysis as a correction factor for the deviations between RWW and the WWT capacity. This is further confirmed by the high correlation ($R = 0.969$) found between these two parameters. With respect to the WWTP adequateness, this potential driver was not confirmed as an actual driver given the high (0.528) individual OLS p-value.

The Belsley collinearity diagnostic, performed with the potential operational drivers, resulted in a single condition index for the absolute RWW above 10 (10.8, slightly above what is considered a weak dependency), with the WWT capacity and WW intake presenting variance decomposition proportions above 0.5 (and being identified as the drivers explaining the found weak dependency). This is in accordance with the CC analysis between these two drivers, which yields $R = 0.969$. No condition indices above 30 (representing moderate to high dependencies) were found.

The potential drivers for WW reuse, represented in Table 3, were used to accurately estimate RWW (Fig. 3), resulting in a coefficient of determination (R^2) of 0.983. The obtained Root Mean Squared Error (RMSE) of 7.23×10^4, amounting solely for 2.00% of the overall range, further supports the viability of this strategy. Given that the majority of the data fell within a narrow range of the overall RWW span, a detailed look regarding the values up to 4×10^5 m^3 $year^{-1}$ (with an RMSE of 6.60×10^4, amounting for 19.8% of this range but solely 1.82% of the

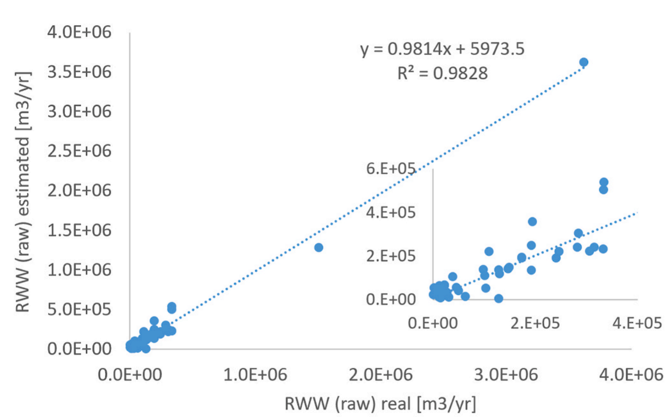

Fig. 3. Estimation of the absolute (raw) RWW. A detailed look regarding the small values range is also provided.

overall range) is also provided in Fig. 3.

4.3. Normalized RWW

Normalized values (per water intake) were also studied to bypass the effect of the SP size. The MLR analysis (Table 4) allowed determining the governance model as the most prominent driver ($p = 3.05 \times 10^{-12}$ and $p = 1.81 \times 10^{-11}$, for concession and delegation, respectively), regarding the normalized (per WW intake) RWW of the SP in the efficiency frontier. Indeed, upon a KW test regarding the three governance models, these two models were found to significantly differ from the direct management model ($p = 3.24 \times 10^{-3}$ and $p = 8.14 \times 10^{-4}$, respectively), but not from each other ($p = 0.910$). Again, these results seem to point to a more significant (and positive) effect of the direct management model towards the normalized WW reuse (regarding the retail level, as later discussed), for reasons that are detailed in the discussion section. Again, no significant correlation ($R = 0.096$) was found between water scarcity and WW reuse by the SP, with all p-values above 0.05, for the studied water scarcity pairs.

The sewers grid rehabilitation (Rehab.) was also found as a potential positive driver for the normalized RWW by the MLR analysis ($p = 8.38 \times 10^{-6}$), further confirmed by the individual OLS results ($p = 1.09 \times 10^{-9}$). It seems, thus, that the SP with the best practices regarding sewers grid rehabilitation also present an increased awareness for WW reuse. Another potential driver for the normalized WW reuse, found by the MLR analysis ($p = 4.46 \times 10^{-5}$), was the normalized (per WW intake) served population (Pop/Win), further endorsed by the individual OLS analysis ($p = 4.29 \times 10^{-7}$), corroborating the strong positive influence on RWW. Both these drivers also presented relatively high correlation values with the normalized RWW ($R = 0.661$ for the sewers grid rehabilitation and $R = 0.753$ for the normalized effectively served population), and between each other ($R = 0.574$). The correlation found between the normalized effectively served population and the sewers grid rehabilitation, alongside the correlation with the normalized treated WW ($R = 0.595$) and its positive influence on RWW, may also play a role in the emergence of these factors as potential drivers for RWW.

The MLR also pointed out the certification policies, such as the energy and environmental certifications, as potential drivers for the normalized WW reuse ($p = 4.52 \times 10^{-7}$ and $p = 2.95 \times 10^{-4}$, respectively). Yet, this assumption was not confirmed by the individual OLS analyses, that found no significant differences between the presence and absence of the two certifications ($p = 0.303$ and $p = 0.465$, respectively).

Both the mostly urban and urban WWTP typologies were identified, by the MLR analysis, as potential normalized RWW drivers ($p = 2.89 \times 10^{-2}$ and $p = 3.36 \times 10^{-2}$, respectively). However, no significant differences could be found between the three WWTP typologies studied ($p = 0.161$, $p = 0.507$ and $p = 0.196$). A number of other drivers could also be inferred as potential drivers by the MLR analysis, namely the normalized WWT capacity (Cap./Win), effluent quality parameters compliance (Comp.), normalized WWT sewers grid length (GL/Win) and energy efficiency of the pumping systems (EnE) ($p = 3.05 \times 10^{-6}$, $p = 1.73 \times 10^{-3}$, $p = 3.86 \times 10^{-3}$ and $p = 3.97 \times 10^{-3}$, respectively). Again, the individual OLS results did not confirm these assumptions given the p-values of 0.090 for the normalized WWT capacity, 0.676 for the effluent quality parameters compliance, and 0.618 for the energy efficiency of the pumping system. Although the p-value regarding the normalized grid length (0.018) was below 0.05, a conflicting influence between the MLR and individual OLS results was found. Given that this parameter was somewhat correlated with the sewers grid rehabilitation ($R = 0.502$) it may appear in the MLR analysis as a correction factor for this driver.

Again, a Belsley collinearity diagnostic was performed with the potential operational drivers, with two condition indices being found above 10 (14.5 and 21.5, slightly above what is considered a weak dependency). No pair of potential drivers was found presenting variance decomposition proportions above 0.5, for the 14.5 condition index. With regard to the 21.5 condition index, the energy efficiency of the pumping system, effluent quality parameters compliance and governance model presented values slightly above 0.5 (being identified as the drivers explaining the found weak dependency). No condition indices above 30 (representing moderate to high dependencies) were found.

The above potential drivers, represented in Table 4, were further used for estimating the normalized RWW (Fig. 4), resulting in a coefficient of determination (R^2) of 0.965, and an RMSE value of 2.34×10^{-3} representing 3.98% of the studied range. Again, the obtained results allowed for a successful estimation of the normalized RWW.

Table 4
Potential operational drivers, MLR and OLS/KW influence and p-values (normalized RWW values).

Drivers	MLR p-value	MLR Influence	OLS/KW p-value			OLS/KW Influence
Gover.[a]	3.05×10^{-12}	–[b]	[1–2]: 3.24×10^{-3}	[1–3]: 8.14×10^{-4}	[2–3]: 0.910	
Gover.[a]	1.81×10^{-11}	–[c]	[1–2]: 3.24×10^{-3}	[1–3]: 8.14×10^{-4}	[2–3]: 0.910	
Ener. Cert.[a]	4.52×10^{-7}	–[d]	[0–1]: 0.303			
Rehab.	8.38×10^{-6}	+	1.06×10^{-9}			+
Cap./Win	3.05×10^{-6}	+	0.090			+
Env. Cert.[a]	2.95×10^{-4}	+[d]	[0–1]: 0.465			
Comp.	1.73×10^{-3}	+	0.676			–
GL/Win	3.86×10^{-3}	–	0.018			+
EnE	3.97×10^{-3}	–	0.618			–
Pop./Win	4.46×10^{-3}	+	4.29×10^{-7}			+
Typol.[a]	2.89×10^{-2}	+[e]	[1–2]: 0.161	[1–3]: 0.507	[2–3]: 0.196	
Typol.[a]	3.36×10^{-2}	–[f]	[1–2]: 0.161	[1–3]: 0.507	[2–3]: 0.196	

[a] Discrete driver.
[b] Concession.
[c] Delegation.
[d] Absence.
[e] Mostly urban.
[f] Urban.

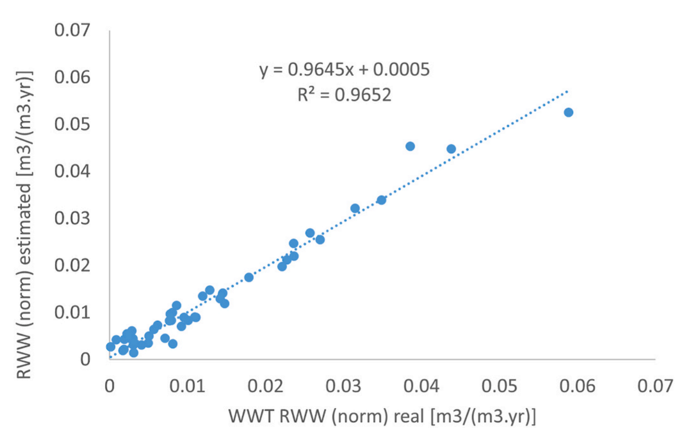

Fig. 4. Estimation of the normalized (per water intake volume) RWW.

5. Discussion

The obtained results suggest the SP size (and mainly WWT capacity) as the driving force behind WW reuse of the SP in the correspondent efficiency frontier, implying a scale effect in that regard. Economies of scale in the WWT treatment sector are recognized as one of the most important drivers for SP efficiency in a number of economic and sustainability studies. Such is the case of Byrnes et al. (2009) who advocated for larger utilities in New South Wales and Victoria, Romano and Guerrini (2011) stressing the SP size as significantly impacting the efficiency of Italian water sector SP, Walker et al. (2021) recognizing economies of scale as drivers for productivity in water sector utilities in the United Kingdom, and Pereira and Marques (2022) who found considerable scale inefficiencies in municipal WWT utilities in Brazil, among others. The same conclusions have already been obtained for the Portuguese reality, namely by Carvalho and Marques (2014, 2015, 2016) showing scale economies in the water sector utilities in Portugal, Caldas et al. (2019) determining scale economies in the water sector for Portuguese councils, Henriques et al. (2020) identifying the SP size as one of the main drivers behind retail SP quality service as in Portuguese WWT utilities, and Mergoni et al. (2022) who found small utilities to be environmentally outperformed in the water and waste sectors.

Although the presented studies did not, directly, targeted WW reuse, but rather the technical, economical or environmental SP efficiency, it seems licit to propose that more efficient SP may be better prepared to sustain, and align with, a policy of WW reuse. Indeed, this is in agreement with the recent works of Amaral et al. (2022, 2023), who studied the (eco)efficiency operational drivers in the Portuguese water sector, again highlighting the SP size as the main driver and suggesting the presence of economies of scale. Alongside a positive impact of the SP size on the reused WW of Portuguese WWT utilities inferred by Amaral et al. (2022), which the present findings corroborate, these authors also found a synergistic effect between WWT quality metrics such as WW quality, perceived satisfactory WWT, energy production and reused WW, exerting a positive influence over the inputs and desirable outputs efficiencies.

The results obtained in the present study seem to point towards a positive effect of direct governance models on the WW reuse of the SP in the efficiency frontier (at the retail level as further discussed). In that regard, the governance model relevance on SP efficiency has been thoroughly studied in recent years, with the literature presenting mixed results, depending on the studied country, period and efficiency metric. Whereas a positive influence of private and/or concessionary SP was found by Byrnes et al. (2009) in New South Wales and Victoria and Sala-Garrido et al. (2019) in Chile, for instance, higher performances for public SP and/or under direct management were reported by Romano and Guerrini (2011) in Italy, Mocholi-Arce et al. (2022) in Chile and Pereira and Marques (2022) in Brazil. Concerning the Portuguese utilities, Henriques et al. (2020) and Marques and Simões (2020) reported a positive influence of private and/or concessionary models on SP performance. Again, the aforementioned studies did not target WW reuse, on its own, but rather the technical, economical or environmental SP efficiency, On the other hand, the studies of Amaral et al. (2022, 2023) specifically encompassed the reused WW as one of the sustainability metrics. According to Amaral et al. (2022), SP within the concession model presented higher efficiency values, for both inputs and desirable outputs, and direct management lower efficiencies (though the SP size, WW quality and certification policy could be driving forces behind this relationship). Also, for the specific case of the WW reuse, direct management presented the lowest efficiency values and the concession model the highest. The reasons behind the apparent contradiction between this study results and the ones obtained by Amaral et al. (2022) are next described.

Roughly 240 different utilities comprise the Portuguese WWT sector, with around a dozen operating at the bulk level (4.6%) and the remaining at the retail level (95.4%). The State is responsible for bulk services (multimunicipal systems), and the municipalities for retail services (mostly municipal systems). The SP operating at the bulk level are, overwhelmingly, concessions, whereas the utilities operating at the retail level are comprised mostly by direct government (77.1%), followed by public delegations (12.8%) and by concessions (10.1%). The majority (83.0%) of the 49 WWT utilities used for the reused WW model development operated at the retail level, with the remaining SP (17.0%) operating at the bulk level. All of the SP operating at the bulk level were concessions (representing 28.6% of the overall concessions in the model), whereas different models of government were observed at the retail level, with the majority (51.3%) being concessions, 15.4% public owned delegations and 33.3% falling under direct management. These results are in line with the ones obtained by Amaral et al. (2022) concerning the SP in the efficiency frontier (in terms of WW reuse), given the percentage of concessions in the retail level SP (51.3%) that greatly outperform its weight (10.1%).

On the other hand, within the subset of the SP in the efficiency frontier, represented mostly by SP at the retail level, the results obtained in the present study inferred a positive effect of the direct management model towards WW reuse. An in-depth analysis of the SP under direct management, lying in the efficiency frontier, allowed to determine an average water intake around 16 million m^3 per year (with 70% of the data points above 10 million m^3 per year), considerably larger than the average 1 million m^3 per year for the overall SP under direct management. This is explained by the fact that solely the larger SP under direct management reused WW, whereas the overwhelmingly majority did not (in that sense the vast majority of SP under direct management can be considered as inefficient regarding WW reuse). As a result, the large size of the SP under direct management within this study, slightly lower than the average SP under the concession model (just above 19 million m^3 per year) but considerably larger than the SP under the delegation model (roughly 6.3 million m^3 per year), can be considered as a major influence regarding the government model results. On the other hand, it would also be understandable that municipalized and municipal services would find it easier to reuse WW (for instance for washing or irrigation of public areas under their jurisdiction) given the latitude of roles that they are responsible for. In those instances, the costs in the retail level run by direct management (municipalized and municipal services), when compared to the SP run by public delegations or concessions, would be largely dependent on the amount of RWW needing the expensive tertiary WW treatment, required for WW reuse, which is, by itself, dependent on the intended use (and, therefore, on the quality standards needed for the RWW). Given the above, the obtained result must be interpreted with caution, moreover, taking into consideration that the SP under direct management in Portugal are of little significance with respect to the overall RWW, with almost all WW being addressed by bulk water companies.

Sewers grid rehabilitation was found, in the current study, as one of the main operational drivers for WW reuse. The relevance of the sewer grid to WWT utilities performance has already been documented by Byrnes et al. (2009), emphasizing the advantages of a residential based, rather an industry based, sewer grid, and by Molinos-Senante and Maziotis (2021) describing how sewerage density negatively impacts WWT utilities productivity, among others. Considering the Portuguese case, Amaral et al. (2022) has found that larger sewers grid length negatively affects the SP efficiencies on energy consumption and expenditures. Later, these authors (Amaral et al., 2023) reported that the sewer grid length correlated directly with the SP's personnel and expenditures needs (and, hence, expenses) as well as revenue WW volumes. Indeed, the sewer grid length was found paramount for personnel allocation in the WW sector. Some degree of aggregation among sewers grid length, energy certification policy and WWTP typology was also reported by these authors. The current study shows that the SP with best practices regarding sewers grid rehabilitation, within the SP in the efficiency frontier, presented an increased awareness for WW reuse. Indeed, highly efficient SP may find it easier to invest on improved treatment technology, equipment and maintenance, including sewers grid rehabilitation. This, in turn, may positively affect the SP efficiency, including its economic counterpart, therefore making it easier to invest on WW reuse.

The normalized served population is also presented as a possible driver for WW reuse, in the current study. Amaral et al. (2022) reported that the normalized served population affected positively the SP efficiency, both in terms of inputs demand and desirable outputs production. This factor was also considered to be one of the main operational drivers behind the reused WW efficiency (as well as for the treated WW and energy production). Corroborating the previous study, Amaral et al. (2023) further found a positive correlation between the served population, supplied households and energy certification policy. The results obtained in the current study also point towards an increased awareness for WW reuse for the SP in the efficiency frontier presenting larger normalized served population values. The same principle applied in the sewers grid rehabilitation discussion may be used with respect to the normalized served population analysis. Large values of normalized served population implies lower volumes of produced WW per person. This, in turn, may represent increased revenues for the SP, given that a large percentage of the water tariffs (including the WWT charges) paid by the consumers, in Portugal, are fixed costs. Hence, and as previously discussed, making it easier to invest on WW reuse.

On the other hand, water scarcity was not proven to be a driving force towards WW reuse by the SP, at least for now, in the Portuguese water industry. There was neither for the absolute values ($R = 0.154$) nor for the normalized values ($R = 0.096$) a significant correlation with the WW reuse, and no significant differences were found by the Kruskal-Wallis analysis between the studied water scarcity levels, with the pair “Very low/Low” vs. “Medium” presenting the largest difference ($p = 0.178$) within the normalized reused WW analysis.

The present analysis focuses solely on the role of operational descriptors towards WW reuse practices, considering the governance and technology factors identified as key areas for water reuse studies by Lee and Jepson (2020). It should be stressed, nevertheless, that legal and regulatory drivers can also be a powerful driving force, through the definition of water tariffs, water abduction and wastewater discharge fees, for instance (Cooper and Crane, 2016; Marques et al., 2016; Molinos-Senante and Donoso, 2016; Lee and Jepson, 2020; Pinto et al., 2021). Such is the case of the impact on Portugal’s legislative and regulatory framework for water reuse of the European Union’s water reuse regulation (EC, 2023). Water reuse is anticipated to be encouraged, and made easier, by this regulation laying down standardized monitoring standards and requirements for the safe reuse of treated WW in agricultural irrigation, risk management provisions to address potential health and environmental risks, and the requirements for permits.

6. Conclusions

The operational drivers for the WW reuse of Portuguese service providers (SP) in the efficiency frontier of wastewater (WW) treatment were successfully identified. The reused WW of these SP was found to be mostly dependent on the WW treatment capacity. It should be noticed that this driver is related to the SP size, thus pointing towards a direct dependence of reused WW with SP size. This assumption is reinforced by the individual OLS results showing that all the potential drivers dependent of SP size were positively correlated with the absolute reused WW.

Considering the normalized (per water intake) reused WW values, the governance model was initially signaled as a potential driver, with the direct management governance model, within the SP in the efficiency frontier at the retail level, presenting a positive effect. However, an in-depth analysis revealed this result to be mostly due to the size of the SP under direct management in the current analysis subset. The sewers grid rehabilitation and normalized served population were also found as actual positive drivers for WW reuse, with the SP presenting the best practices regarding sewers grid rehabilitation, and larger normalized served population, also presenting an increased awareness for WW reuse. On the other hand, the correlation between sewers grid rehabilitation practices, normalized served population and treated WW, may relativize the actual influence of the former. No evidence of water scarcity being a driving force, for now, regarding WW reuse of Portuguese SP could be confirmed, though this is expected change in the future through the introduction of this metric in the definition of water tariffs.

Both the reused WW absolute and normalized values of the SP in the efficiency frontier were successfully estimated by the use of the potential drivers found by Multilinear Regression Analysis, with Root Mean Squared Errors not surpassing 2.0% and 4.0% of the overall range, respectively.

Summing up, the performed study highlighted: i) the SP size (and mainly wastewater treatment capacity) as the driving force behind WW reuse; ii) that the SP with best practices regarding infrastructure (sewers grid) maintenance and larger normalized served population present an increased awareness for WW reuse; and iii) that reused WW volumes for the SP in the efficiency frontier may be estimated through the use of the selected drivers. Given that the normalized served population is out of the SP control, the main policy implications that can be retrieved from the above findings imply fostering the aggregation of smaller SP to benefit from economies of scale, and strive for adequate infrastructure maintenance practices, rendering a more productive environment to sustain, and align with, a policy of WW reuse.

Further studies should, however, be performed to fully understand the underlying interrelationship between the governance model and reused WW. Also, the limited number of studied SP, regarding the determination of the reuse WW drivers, should be enlarged, though it is dependent on the Portuguese SP data available. To that effect, the introduction of data from other countries could help acquiring further insight on the importance of selected operational drivers (mainly drivers less dependent on a country’s particular characteristics). Indeed, the study of other countries’ contexts, using the methodology employed in the current study, would be advantageous on its own. Furthermore, the integration of non-operational WW reuse drivers, such as water tariffs, abduction and discharge fees data, alongside legal regulatory constraints metrics, should provide for a deeper understanding of water reuse interdependencies.

Credit author statement

A. Luís Amaral, Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Rita Martins, Conceptualization, Writing – review & editing, Supervision, Luís C. Dias, Conceptualization, Writing – review & editing, Supervision.

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

Data will be made available on request.

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