EFFICIENCY EVALUATION OF THE WASTEWATER TREATMENT PLANTS THROUGH INTERVAL DATA ENVELOPMENT ANALYSIS

(ATIKSU ARITMA TESİSLERİNİN ARALIKLI VERİ ZARFLAMA ANALİZİ İLE ETKİNLİKLERİNİN DEĞERLENDİRİLMESİ)

by

Selin AKSAÇ, B.S.

Thesis

Submitted in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

in

INDUSTRIAL ENGINEERING

in the

GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

of

GALATASARAY UNIVERSITY

March, 2022

This is to certify that the thesis entitled

EFFICIENCY EVALUATION OF THE WASTEWATER TREATMENT PLANTS THROUGH INTERVAL DATA ENVELOPMENT ANALYSIS

prepared by **Selin AKSAÇ** in partial fulfillment of the requirements for the degree of **Master of Science in Industrial Engineering** at the **Galatasaray University** is approved by the

Examining Committee:

Date:

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF SYMBOLS

AAT	:	Atıksu Arıtma Tesisi
AHP	:	Analytical Hierarchy Process
ANP	:	Analytic Network Process
BWM	:	The Best–Worst Method
CRS	:	Constant Returns to Scale
DEA	:	Data Envelopment Analysis
DWPTs	:	Drinking Water Treatment Plants
FARE	:	Factor Relationship
ISKI	:	Istanbul Water and Sewerage Administration
SBM	:	Slack-Based Model
SDGs	:	Sustainable Development Goals
SIR	:	Superiority and Inferiority Ranking
SWARA	:	Stepwise Weight Assessment Ratio Analysis
TUIK	:	Turkısh Statistical Institute
VRS	:	Variable Returns to Scale
VZA	:	Veri Zarflama Analizi
WWTPs	:	Wastewater Treatment Plants

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The biggest problem that we face to face in the current century is considered to be the climate crisis. In this context, one of the 17 "Sustainable Development Goals" (SDGs) determined by the United Nations to manage the climate crisis is "clean water and sanitation". Wastewater treatment plants (WWTPs) with the process of treatment, discharge under appropriate conditions, and recycling of the wastewater are strategic elements that directly serve the purpose of access to clean water and prevention of water pollution. WWTPs in the world increase in number with urbanization and industrialization and develop in parallel with technology. In addition, the issue of the effective, efficient and sustainable operation of WWTPs is also examined by researchers and experts, and studies and research that will guide public and private sector organizations are carried out.

Data envelopment analysis (DEA) is a method that allows the relative effectiveness of decision-making units (DMUs) to be measured and evaluated when there are multiple input and output variables. As will be examined in this study, there are valuable study and application examples in the international literature for the evaluation of the effectiveness of WWTPs using DEA. Nevertheless, there are a limited number of academic studies in this field in Turkey, and it is seen that the literature is open to development in terms of research and practice.

In this study, a three-stage methodology has been proposed to evaluate the effectiveness of WWTPs considering the uncertainties and some hesitations in the data. The case study has been carried out using the data of 88 WWTPs of the Istanbul Metropolitan Municipality. Firstly, expert opinions have been taken to determine the input and output variables for calculating efficiency values. These opinions have been evaluated with the extended

weight assessment ratio analysis (SWARA). Secondly, the data of the WWTPs have been converted into interval values to allow the evaluation of different year efficiencies at once and to eliminate the hesitations and uncertainties. Efficiency scores have been calculated using output-oriented DEA for the best-case, original, and worst-case scenarios that form the interval values. Finally, it has been examined whether there is a difference in the efficiency values of WWTPs based on age and type of facility.

This thesis study, with its proposed methodology, allows the evaluation of DMUs under uncertain situations and different time intervals, taking into account expert opinions. Beside this, it is an exemplary study for public and private institutions in the evaluation and development of the effectiveness of WWTPs in Turkey with its application.

ÖZET

İçinde bulunduğumuz yüzyılda karşı karşıya kaldığımız problemlerden en büyüğü iklim krizi olarak kabul edilmektedir. Bu kapsamda iklim krizini yönetmek için Birleşmiş Milletler tarafından belirlenmiş 17 adet sürdürülebilir kalkınma amaçlarından birisi de "temiz su ve sanitasyon"dur. Çevresel kirliliğin ana etmenlerinden olan atık suların; arıtılması, uygun şartlarda deşarj edilmesi ve yeniden kullanıma kazandırılması süreçleri ile atıksu arıtma tesisleri (AAT) temiz suya erişim ve kirliliğin önlenmesi amacına doğrudan hizmet eden stratejik öğelerdir. Dünyada atık su arıtma tesisleri kentleşme ve endüstrileşmeyle birlikte sayıca artmakta ve teknoloji paralelinde gelişim göstermektedir. Bununla birlikte AAT'lerin etkin, verimli ve sürdürülebilir biçimde faaliyet göstermeleri konusu da araştırmacılar ve uzmanlar tarafından irdelenmekte, kamu ve özel sektör kuruluşlara yön gösterecek çalışmalar ve araştırmalar yürütülmektedir.

Veri zarflama analizi (VZA), karar verme birimlerinin, birden çok girdi ve çıktı değişkeninin olduğu durumlarda göreceli etkinliklerinin ölçülüp değerlendirilmesine imkân sağlayan bir yöntemdir. Bu çalışmada inceleneceği üzere, uluslararası literatürde AAT'lerin etkinliklerinin VZA kullanılarak değerlendirilmesine yönelik değerli çalışma ve uygulama örnekleri mevcuttur. Ülkemizde bu alanda sınırlı sayıda akademik çalışmalar mevcut olup, literatürün araştırma ve uygulama bakımından gelişime açık olduğu görülmektedir.

Bu çalışmada AAT'lerin farklı yıllardaki faaliyetlerini ve verilerdeki belirsiz durumları, çekinceleri dikkate alarak etkinliğini ölçmek ve değerlendirmek üzere üş aşamalı bir metodoloji önerilmiştir. Önerilen metodolojiye ilişkin uygulama İstanbul Büyük Şehir Belediyesi 88 AAT'sine ilişkin veriler kullanılarak gerçekleştirilmiştir. İlk olarak etkinlik değerlerinin hesaplanmasına yönelik girdi ve çıktı değişkenlerinin belirlenmesi için uzman

görüşleri alınmış, bu görüşler çok kriterli bir karar verme yöntemi olan genişletilmiş SWARA ile değerlendirilmiştir. İkinci olarak AAT verileri farklı yıl etkinliklerinin tek seferde değerlendirilmesine olanak sağlamaya ve verilerdeki hata, belirsizlikleri gidermeye yönelik aralıklı değerlere dönüştürülmüştür. Bu aralıklı değerlerin farklı kombinasyonları için olası en iyi senaryo ve en kötü senaryolar için aralıklı bir biçimde etkinlik değerleri çıktı odaklı veri zarflama analizi kullanılarak hesaplanmıştır. Etkin ve etkin olmayan AAT'ler farklı senaryolardaki etkinlik değerleri dikkate alınarak sıralanmıştır. Son olarak ise AAT'lerin etkinlik değerleri için tesis yaşı ve türü bazında farklılık olup olmadığı irdelenmiştir.

Bu tez çalışması, önerilen metodolojisi ile uzman görüşlerinin dikkate alınarak belirsiz durumlar ve farklı zaman aralıkları için karar verme birimlerinin değerlendirilmesine olanak sağlamakla birlikte, uygulaması ile Türkiye'de AAT'lerin etkinliklerinin değerlendirilmesi ve geliştirilmesine yönelik kamu ve özel kuruluşlara örnek bir çalışma niteliğindedir.

1 INTRODUCTION

Water is essential for our ability to sustain our vital activities, our survival, and for the orderly functioning of the ecological cycle. But it is also a scarce resource. Approximately 3% of the water in the world excluded snow and ice masses, although 1% is known to be appropriate freshwater. Increasing industrialization and world population affect the water cycle by the way pollution and excessive consumption. This situation reveals the importance of accessing available clean fresh water and sustainable use of water resources.

In the United Nations SDGs, 17 main themes were determined concerning the problems that the world will face soon and that should be taken action to solve by 2030, one of which is “clean water and sanitation”. Under the theme of clean water and sanitation, sub-goals are defined for issues such as accessible drinking water, wastewater treatment, and sustainable management of water resources (United Nations Turkey, 2021).

Wastewater discharged to clean water sources uncontrolled and without adequate treatment is considered as one of the main causes of environmental and water resources pollution. In this context, the process of treating wastewater, discharging it under appropriate conditions, and reusing it with recycling serves the aim of accessing clean water, preventing water resources pollution, and their sustainable management.

Wastewater treatment plants (WWTPs) contribute to ecological sustainability by discharging or reusing wastewater without disturbing the ecological balance, without causing permanent and dangerous pollution in the air, water, and soil, that is, without harming the environment (ISKI, 2019).

When the public reports are examined (T.C. Çevre ve Şehircilik Bakanlığı 2010; T.C. Orman ve Su İşleri Bakanlığı 2013; Baştürk et al. (2017); Nas 2017; ISKI, 2019; ISKI 2020), the number of WWTPs in our country shows a parallel increase with industrialization and population growth over the years. With this increase, strategic decisions such as the positioning of WWTPs, their capacity and the choice of technologies to be used are shaped by regional terms and conditions, especially population density and the industrialization process.

Several analytical methods or methodologies are needed to evaluate the performance and efficiency of WWTPs that are established and continue to operate, to manage them economically, ecologically, and sustainably, and to take action for necessary situations.

In this study, it has been proposed that a three-stage methodology to measure and evaluate the effectiveness of WWTPs in different years, taking into account the uncertainties and some hesitations in the data. Firstly, it has described the general principles, information, and the importance of WWTPs in the context of environmental sustainability. Then it has presented a sectoral perspective and an assessment for WWTPs operating in Istanbul province in Turkey. Secondly, the studies in the literature have been scrutinized to have detailed information about the efficiencies of WWTPs. Third, the three-stage methodology of the study is detailed. Finally, the application has been made and reported with the data of Istanbul Metropolitan Municipality WWTPs regarding the proposed methodology.

2 WASTEWATER TREATMENT PLANTS MANAGEMENT

The differences in size, type, and processes of WWTPs affect the actions to be taken to manage WWTPs effectively and efficiently. Effective and efficient management of WWTPs is only possible with the end-to-end evaluation and development of all processes, from design to commissioning and putting into operation. Site selection, capacity, how it will meet its energy needs, the technology and processes it will use, etc. all issues are subjects of WWTP operation and management. Studies on the effectiveness of WWTPs in the world have been evaluated especially in terms of energy use (energy efficiency and clean energy). Although there are many research and development projects funded by ministries and local authorities (T.C. Çevre ve Şehircilik Bakanlığı, 2010; ÇTÜE, 2018) in this field in Turkey, interdisciplinary studies in this field are very limited.

2.1 Why We Recycle the Wastewater?

Wastewater is the output of the water, which is considered as a scarce resource that we use in all our humanitarian activities, and transformed by these activities. Wastewater has also started to be considered a resource in the context of environmental sustainability in recent years.

Recycled wastewaters, it is used for irrigation of parks and gardens, firefighting and toilets, as cooling and process water in industry, irrigation in agriculture, recreational use, and groundwater feeding. (T.C. Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2021)

With the proper discharge and reuse of wastewater by treating it in a harmless to the environment, it can contribute to the water cycle and the protection of existing water resources, saving the use of water resources.

The main point to be noted here is; the use of treated wastewater not only provides the recovery of current water resources but also reduces the environmental impacts of water use activities significantly (Hernández-Sancho and Sala-Garrido, 2009).

2.2 Wastewater Treatment Technologies

The differences in size, type, and processes of WWTPs affect the actions to be taken to manage WWTPs effectively and efficiently. Treatment of wastewater refers to the removal of pollutants by physical, chemical, and/or biological processes (Sala-Garrido et al., 2011).

While choosing proper technologies and processes to design WWTPs, the population of the settlement and receiving environment standards are evaluated.

These processes are generally defined as "*preliminary treatment*", "*primary treatment*", "*secondary treatment*" and "*tertiary treatment*". The following articles give general information about the treatment types in terms of their definitions.

- *Preliminary treatment* process is the physical operation treatment step where large solids, sand, gravel, or floating solids are removed from the wastewater (It includes grid, sand trap, flow rate balancing, and flow measurement units).
- *Primary treatment* process, sedimentation is the physical operation step where the solid materials suspended in the wastewater are removed from the raw wastewater or after the first treatment (pre-sedimentation unit is added in addition to the first treatment) (Nas, 2017).
- *Secondary treatment* process, including the activated sludge systems, lagoon systems, trickle filters, and rotary bio discs is the biological treatment method in which

microorganisms suspended or attached to the surface are used to bring the wastewater to the desired quality. After the wastewater is subjected to biological treatment, the microorganisms (biomass) that perform the purification function must be separated from the treated water by various methods.

- *Tertiary treatment* is an additional treatment step that provides more removal than primary and secondary treatment (micro sieve or filtration unit is added for further removal of suspended and organic materials that cannot be removed in secondary treatment). Tertiary treatment processes are applied in discharges to sensitive areas (T.C. Orman ve Su İşleri Bakanlığı, 2013).

2.3 Wastewater Treatment Plants Management in Turkey

Different legal regulations establish the required sanctions available and discharge standards in Turkey to conserve and sustain the water resources and prevent water pollution. It is possible to generalize the main objectives of these legal regulations under the following articles:

- Control of pollution sources
- Treatment of wastewater
- Reuse / safely use wastewater
- Ecosystem restoration

Design principles and criteria of the WWTPs in Turkey are determined and approval procedures for WWTPs are carried out by the Ministry of Environment and Urbanization and the Ministry of Agriculture and Forestry. In this context, all wastewater treatment plants managements must fulfill their obligations determined by lawmakers and be accountable to them.

This section has presented the general information about the WWTPs in Turkey to clearly understand the conceptual framework of this study.

According to data provided by the Turkısh Statistical Institute (TUIK); as of 2020, there is a total of 1,068 WWTPs in Turkey. 593 of the facilities are biological treatment, 223 are advanced treatment, 192 are natural treatment and 60 are physical treatment. These facilities serve 61,292,803 people. The capacity of WWTPs is 6,386,784,000 (m^3/year) in total (TUIK, 2022).

Besides these; as of 2020, there is a total of 88 WWTPs in Istanbul. 70 of the facilities are biological treatment, 10 are advanced treatment, 8 are physical treatment and 1 is a natural treatment. The total capacity of WWTPs is 1,396,180,805 (m^3/year) and approximately one-third of Turkey's (ISKI, 2020).

3 LITERATURE REVIEW

WWTPs efficiency evaluation has been handled by many researchers as a remarkable topic, especially with the growing and flourishing industrialization and urbanization problems. It has been seen that DEA and various techniques combined with DEA have been frequently used by researchers and experts in evaluating the efficiency of WWTPs. The development in the field of performance and efficiency evaluation of the WWTPs by using DEA started in the 2000s, and there have been significant developments in this field in 2010 and after with the increasing importance of resource sustainability, efficiently recycling practices, and re-usage. In the early stages of the literature, dimensions of the WWTPs' efficiency have been mostly considered the economic, productivity, and technological. However, in the subsequent literature studies and research, especially in 2014 and later, it has been seen that the dimensions of WWTPs' efficiency have taken into account sustainability, ecological and environmental effects, and undesirable outputs as well as economic, technical, and productivity dimensions.

Hernández-Sancho and Sala-Garrido (2009) evaluated the efficiencies of 338 WWTPs in Spain using DEA. In addition to this, they examined if there was a link between the size of WWTPs and their efficiency, and which variable was most influential on their efficiency.

Al-Assa'd and Sauer (2010) used a two-stage method as a combination DEA and Tobit Regression for 12 water and wastewater firms in Jordan during 2001-2006 to evaluate the water utilities' relative efficiencies and to examine the reasons for inefficiencies.

Hernandez-Sancho et al. (2011) used non-radial DEA to calculate the energy efficiency of the 177 WWTPs located in Spain according to their energy consumption. In addition to this, they examined how some variables such as plant size and age affect energy efficiency.

Sala-Garrido et al. (2011) used non-concave DEA calculating the techno-economic efficiencies of 99 Spanish WWTPs to select the most suitable technology among four alternatives.

Hernandez-Sancho et al. (2011b) analyzed the efficiency and productivity changes of 196 WWTPs over the five years in Spain by using DEA and Malmquist productivity index.

Sala-Garrido et al. (2012) evaluated the efficiencies of 45 Spanish WWTPs by using DEA with statistical tolerances in the context of uncertainty assessment.

Bian et al. (2014) proposed a network DEA approach to analyze the efficiencies of regional urban water use and wastewater decontamination systems in China decomposing the current systems into sub-systems. They defined the system efficiency as the average of the sub-systems' efficiencies.

Molinos-Senante et al. (2014) proposed three steps benchmarking methodology to analyze the efficiencies of 192 Spanish WWTPs in the context of cost-saving with non-radial DEA.

Molinos-Senante et al. (2014b) presented a study by integrating environmental impacts, both desirable and undesirable, to the assessment of the efficiency by using DEA for 60 WWTPs in Spain.

Lorenzo-Toja et al. (2015) analyzed the eco-efficiencies of the 113 WWTPs located in Spain, using a method that is a combination of life cycle assessment and DEA.

Guerrini et al. (2015) proposed a two-stage approach as a combination of DEA and regression analysis to measure the efficiency of 101 water and wastewater utilities in Denmark and to examine their efficiencies' relationships with independent variables like company size, population density, etc.

Fuentes et al. (2015) analyzed the efficiency of 158 WWTPs in Spain using the calculation of conditional order-m efficiency which allows continuous and discrete contextual variables to be directly involved in the analysis and enables the assessment of their statistical significance and effects.

Longo et al. (2016) evaluated the efficiencies of the 601 WWTPs according to their energy consumptions. For WWTP efficiency, they outlined the importance of the technology, layout, and country of location, besides energy consumption.

Castellet and Molinos-Senante (2016) used non-radial DEA to assess the techno-economic efficiency of 49 WWTPs in Spain. They assigned weights to inputs and outputs according to their importance.

Molinos-Senante et al. (2016) conducted a study to calculate the change of the total factor productivity (TFP) for 202 Spanish WWTPs between 2003 and 2008 by using the Hicks-Moorsteen productivity index that maintains total factor productivity properties under variable returns to scale (VRS) unlike Malmquist productivity index.

Molinos-Senante et al. (2016b) assessed the productivity changing for 175 WWTPs located in Spain for the first time considering undesirable outputs with statistical comparison of The Malmquist-Luenberger productivity index and Malmquist productivity index.

Dong et al. (2017) carried out a study to measure the eco-efficiencies and identify the best practices for 736 WWTPs in China. They overcame the uncertainty conditions by using the tolerance approach.

Zeng et al. (2017) assessed efficiencies of 1079 urban WWTPs in China by using distance function and considering greenhouse gas emissions. They evaluated the efficiency scores using statistical analysis according to plants scale, technology, and capacity of tertiary treatment.

Guerrini et al. (2017) proposed a two-stage approach (double bootstrap DEA) to identify the exogenous variables exerting an influence on the energy efficiency of wastewater treatment, observing 127 WWTPs located in Italy.

Gomez et al (2017) evaluated the bias-corrected efficiency and explored the factors that influenced the efficiency of the 30 WWTPs in Spain applying the double bootstrap DEA method.

Guerrini et al. (2017b) analyzed the efficiency of 139 WWTPs in Italy to underline the main efficiency factors besides these contextual variables (size, technology, etc.) by using a two-stage DEA methodology combined with ordinary least squares regression.

Fuentes et al. (2017) used the smoothed bootstrap Malmquist productivity index based on DEA methodology to analyze the changing efficiency of 199 WWTPs in Spain between 2018 and 2012.

Zhou et al. (2018) proposed a network structure extended with the SBM DEA model to assess integrated water use and wastewater treatment systems of 30 provinces in China during 2006-2015.

D'Inverno et al. (2018) assessed the environmental efficiency of 96 WWTPs in Italy by considering the undesirable outputs. They used a novel integrated DEA approach, using analytic hierarchy process and non-radial distance function to utilize the benefits of the two techniques' combination.

Wu et al. (2018) examined the construction efficiencies of urban wastewater transportation and treatment capacity in China's 70 megacities during 2006–2012 by applying an input-oriented non-radical DEA model.

Hernandez-Chover et al. (2018) analyzed the 217 WWTPs in Spain to understand the relationships between their efficiency and size by using radial and non-radial DEA. By using radial DEA analysis, they calculated economic and environmental efficiency and by using non-radial analysis they found the main topic to be considered on variables.

Gemar et al. (2018) proposed an approach calculating the eco-efficiency of WWTPs using the dynamic weighted Russell directional distance model to overcome the classical DEA's limitation of being static. They assessed the changes in eco-efficiency of 30 WWTPs in Spain by using this approach.

Lorenzo-Toja et al. (2018) applied a DEA window analysis model which considers dynamic input/output conditions in time to understand how to change environmental efficiencies of 47 WWTPs in Spain.

Dong et al. (2018) carried out a study by using DEA to measure the efficiencies regarding the economic, resource, and environmental aspects and identify the best practices for water infrastructure of 157 cities in China.

Gomez et al. (2018) applied the DEA tolerance approach to examine 30 WWTPs in Spain regarding uncertainty conditions.

Molinos-Senante and Guzman (2018) applied DEA to benchmark the energy efficiency of 42 drinking water treatment plants (DWPTs) in Chile. This study was the first application of DEA to DWPTs.

Torregrossa et al. (2018) proposed an approach that is a combination of environmental life cycle assessment, DEA, time series analysis, and statistical tests applying to randomly generated data by the online platform. Unlike many applications in the literature, they examined the daily performance of DMUs of a single WWTP for early detection of occurring inefficiencies.

Wang et al. (2018) applied the window method of DEA with combined Tobit regression to assess the dynamic efficiencies of four WWTPs in Canada, during 2007-2016.

Longo et al. (2018) proposed a guideline named Robust Energy Efficiency DEA methodology to systematize the energy efficiencies and benchmarking process of WWTPs. In this context, they carried out a case study by using 399 municipal WWTPs data collected with different methods from different countries.

Storto (2018) proposed a three-stage approach as a combination of conventional and network DEA considering sub-stage efficiencies and their statistical relationships to measure the efficiencies of 53 water and wastewater utilities in Italy.

An et al. (2018) analyzed the spatial pattern of urban wastewater discharge and the efficiencies of 31 WWTPs in China between 2011 and 2015 using a combined methodology which includes exploratory spatial data analysis, DEA, and Malmquist Productivity Index.

Hu et al. (2019) assessed the eco-efficiency of 281 WWTPs in 126 national-level industrial parks in China applying the SBM-DEA model.

Lombardi et al. (2019) assessed the efficiency of 68 Italian water companies using DEA between 2011-2013.

Zhang et al. (2019) investigated the industrial wastewater efficiency changing of 30 regions in China using dynamic SBM DEA during 2011-2015.

Wu et al. (2019) examined the discharge efficiencies and reduction potential of wastewater treatments in 68 Chinese cities megacities by applying a non-radial DEA model.

Ananda (2019) assessed the environmental efficiencies of 49 drinking water and wastewater utilities in Australia over 2006-2011 considering undesirable outputs and investigating their efficiencies according to explanatory variables.

Feng et al. (2020) calculated the efficiencies of 518 WWTPs in China considering undesirable outputs.

Jiang et al. (2020) used an SBM-DEA considering cluster benchmarking to evaluate the sustainability efficiency of 861 WWTPs in China.

Sarraf and Nejad (2020) evaluated the performance and ranking of 35 Iranian urban water and wastewater companies based on balanced scorecard criteria using DEA and gray relational analysis.

Pan et al. (2020) applied a three-step methodology to evaluate both the static and dynamic efficiencies of 113 urban WWTPs in China for 2008-2017 using bootstrap-DEA and Malmquist productivity index.

Fuentes et al. (2020) proposed an approach to evaluate the efficiency of 29 WWTPs in Spain, using a new variation of the weighted Russell directional distance model, taking into account the general description of desired outputs and the impossibility of extracting pollutant levels higher than those found in wastewater.

Fuentes et al. (2020b) proposed a new statistical model to analyze the existence of congestion in 47 Spanish WWTPs based on DEA considering undesirable outputs and multiple projections.

Cheng et al. (2020) assessed the 681 rural sewage facilities in China using a combining methodology including SBM-DEA and clustering analysis to evaluate the performance efficiencies and identify the impact of exogenous factors on these efficiencies.

Saghafi et al. (2020) assessed the 79 Iranian industrial WWTPs to calculate their energy efficiency using DEA and examined the effects of exogenous factors on their efficiencies.

Ayyildiz et al. (2020) proposed a two-step methodology combining extended stepwise weight ratio analysis (SWARA) which is a multi-criteria decision-making method to determine the criteria according to their importance and DEA to assess the performances of 30 metropolitan cities' WWTPs in Turkey.

Ananda (2020) proposed a framework including a double-bootstrap DEA model supplemented by an outlier detection to compute bias-corrected efficiency scores to evaluate the efficiencies of wastewater facilities in Australia considering service quality.

4 METHODOLOGY

In this study, it has been proposed a three-stage methodology for determining and evaluating the efficiency of WWTPs in Istanbul, Turkey. While determining the criteria to calculate the efficiency scores of WWTPs; literature studies, Istanbul Metropolitan Municipality WWTP performance reports, and TUIK statistics have been examined. Firstly, the extended SWARA method has been used to clarify the input and output variables by taking expert opinions. Secondly, efficiency scores have been calculated by applying interval DEA and WWTPs have been ranked according to their efficiency scores. Finally, the relationship between the calculated efficiency scores of WWTPs and external factors has been examined. The methodology of the study is summarized in Fig. 4-1 below:

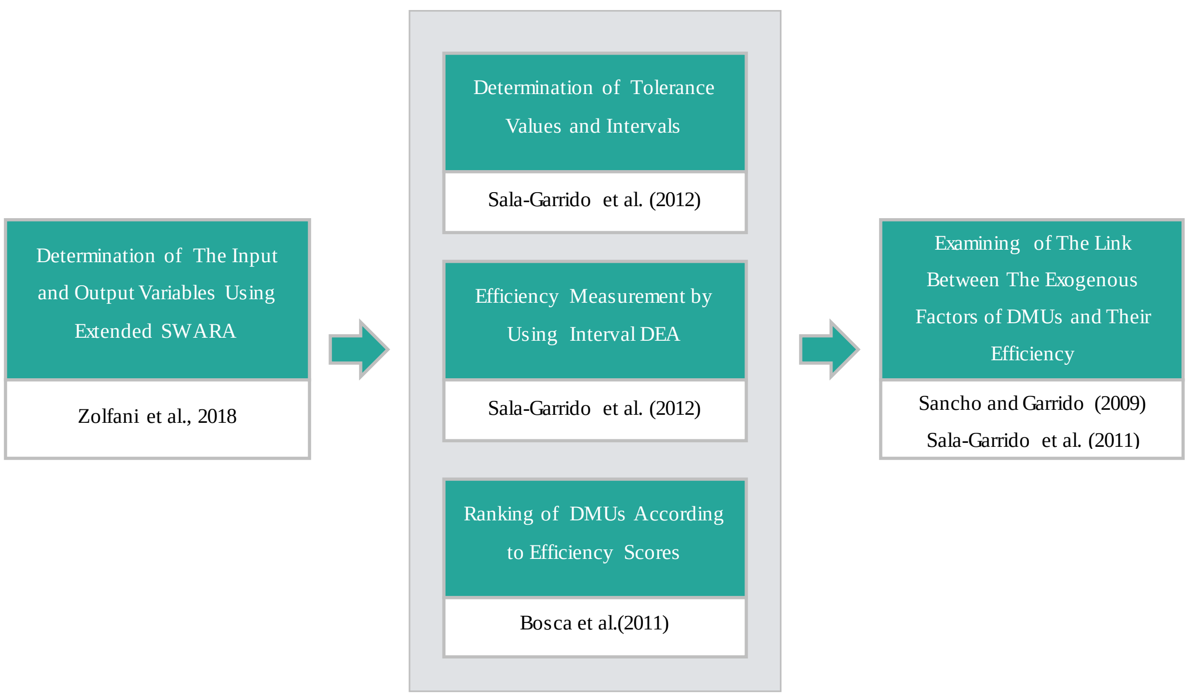

Figure 4.1 Proposed methodology of this study

In this section, the techniques and approaches used for the methodology of the study will be explained respectively.

4.1 Determination of The Input and Output Variables Using SWARA

Determining, prioritizing, and weighting the criteria is one of the most important stages of the multi-criteria decision-making process. There are many methods in the literature for determining, prioritizing, and weighting variables related to decision-making processes; entropy, analytical hierarchy process (AHP), analytic network process (ANP), superiority and inferiority ranking (SIR) method, stepwise weight assessment ratio analysis (SWARA), factor relationship (FARE), the best–worst method (BWM) that are examples of the most widely used methods and approaches (Zolfani et al., 2013; Zolfani et al., 2018).

Within the scope of this study, expert opinions will be taken to select the most appropriate input and output variables for the measurement of WWTPs' efficiency. Considering the difficulties in collecting and evaluating data, SWARA has been considered to be used to determine input and output variables due to its uncomplicated and user-friendly methodology.

SWARA was firstly proposed by Keršulienė (2010) and Zolfani et al (2018) extended SWARA to improve the quality of the MCDM process by incorporating the reliability evaluation of experts' opinions of the criteria (Keršulienė 2010, Zolfani et al., 2018)

In this study, experts' opinions will be evaluated with the extended SWARA method (Zolfani et al., 2018), and the variables that form the basis for the measurement of efficiency of WWTPs will be determined. This method is formulated as follows:

Step 1: Sorting the criteria according to the approach (most important is first) proposed by Kendall (1970)

Step 2: Calculating mean priority values ($\bar{t}_j$)

j, k, r are defined as variable, expert, and the number of experts respectively.

$$\bar{t}_j = \frac{\sum_{k=1}^{r} t_{jk}}{r} \tag{1}$$

Step 3: Calculating weights (q_j)

n describes the number of criteria and the sum of the weights of the criteria must be equal to one.

$$q_j = \frac{\bar{t}_j}{\sum_{j=1}^{n} \bar{t}_j} \tag{2}$$

Step 4: Calculating the dispersion of expert opinions (σ^2) and the variations (β_j)

$$\sigma^2 = \frac{1}{r-1} \sum_{k=1}^{r} (t_{jk} - \bar{t}_j)^2 \tag{3}$$

$$\beta_j = \frac{\sigma}{\bar{t}_j} \tag{4}$$

Step 5: Calculating the coefficient of concordance value (W)

$$W = \frac{12S}{r^2(n^3 - n) - r\sum_{k=1}^{r} T_k} \tag{5}$$

S, T_k describes the total square deviation of the rankings of each criterion and the index of reiterated ranks, respectively. S calculated as below:

$$S = \sum_{j=1}^{n}\left[\sum_{k=1}^{r} t_{jk} - \frac{1}{n}\sum_{j=1}^{n}\sum_{k=1}^{r} t_{kj}\right]^2 \tag{6}$$

Step 6: Calculating X^2 value

When $n > 7$ a distribution with the degrees of freedom is considered as $v = n - 1$.

$$X_{\alpha,v}^2 = W.r(n-1) = \frac{12S}{r.n(n+1) - \frac{1}{n-1}\sum_{k=1}^{r} T_k} \tag{7}$$

Step 7: Hypothesis testing using $X^2 > X_{tbl}^2$

If the value of $X_{\alpha,v}^2$ is larger than the critical tabular value of X_{tbl}^2 for the selected significance level ($\alpha = 0{,}05$)

$X_{\alpha,v}^2 > X_{tbl}^2$; H_0 is rejected;

- H_0: There is a consensus between independent expert opinions.
- H_1: There is no consensus between independent expert opinions.

Step 8: Calculating the comparative importance of the average value (s_j)

For each criterion (j), it is calculated of the importance levels relatively according to previous criteria (j-1), starting from the second.

Step 9: Calculating the coefficients (k_j)

$$k_j = \begin{cases} 1, & j = 1 \\ s_j + 1, & j > 1 \end{cases} \quad (8)$$

Step 10: Recalculating the weight (q_j)

$$q_j = \begin{cases} 1, & j = 1 \\ \dfrac{k_{j-1}}{k_j}, & j > 1 \end{cases} \quad (9)$$

Step 11: Calculating the relative weights of each criterion (w_j)

$$w_j = \frac{q_j}{\sum_{j=1}^{n} q_j} \quad (10)$$

4.2 Data Envelopment Analysis

Multiple inputs and outputs can be taken into account in calculating the performance and efficiency of decision-making units serving the same purpose. DEA methodology, which is based on the technical efficiency concept defined by Farell (1957), has been used by researchers and experts in many fields in the literature for such problems.

DEA is a basic linear programming methodology for evaluating the relative technical effectiveness of decision-making units using multiple inputs and outputs was developed by Charnes et al. (1978) and extended by Banker et al. (1984). DEA evaluates the efficiency of each DMU relative to an estimated production possibility frontier determined by all DMUs.

DEA models are divided into two types in principle; a constant returns-to-scale (CRS) developed by Charnes et al. (1978), and variable returns-to-scale (VRS) extended by Banker et al. (1984) (A. Hatami-Marbini et al., 2011). These models are accepted as basic general models of DEA methodology.

In addition, DEA models are divided into three as input-oriented, output-oriented, and non-oriented (additive model). With the input-oriented method; the output variables of the model cannot be controlled, so the outputs are kept constant and maximum efficiency is tried to be achieved with the change of the input variables. In the output-oriented method; the input variables of the model cannot be controlled, so maximum efficiency is tried to be achieved with the change in the output variables by keeping the inputs constant. Besides these, the additive model is a combination of input and output orientation (Cook and Seiford, 2009; Sala-Garrido et al., 2012).

Due to the assumptions of DEA, it provides some convenience to its users: (Guerrini et al., 2013; Gomez et al., 2017)

- It provides an evaluation that takes into account multiple input and output variables.
- It does not require specifying weighting coefficients for input and output variables.
- It does not require the assumption that there is a direct relationship between the input and output variables.

Gomez et al. (2017) explained the limitations of DEA as follows:

- It is a sensitive method against measurement errors.

- Since it is a deterministic method, no statistical inference can be made between DEA efficiency scores and the variables used in the model. Inferences can be made between DEA scores and external factors.

The mathematical interpretation of DEA is expressed as the ratio of weighted total outputs to weighted total inputs to calculate the relative efficiency of decision-making units (A. Hatami-Marbini et al., 2011). The efficiency ratio is calculated to provide the maximization goal for each DMU of the expressed mathematical model. The normalizing constraints of the model are to ensure that the relative efficiency ratio is less than or equal to unity for each DMU (Karsak and Dursun, 2014).

$$max E_{j_0} = \frac{\sum_r u_r y_{rj_0}}{\sum_r v_i x_{ij_0}} \tag{11}$$

$$\frac{\sum_r u_r y_{rj_0}}{\sum_r v_i x_{ij_0}} \leq 1; \quad j = 1, \dots, n$$

$$u_r, v_i \geq \varepsilon > 0; \quad r = 1, \dots, s; \quad i = 1, \dots, m$$

n defines the number of DMU, and with varying amounts; m defines the number of input variables required to produce s different outputs. E_{j_0} defines the efficiency score of DMU_j; x_{ij_0}, y_{rj_0} are the number of input i and output r for DMU_j respectively. v_i, u_r are the weights of input i and output r for DMU_j respectively. ε is assumed to be a fairly small positive number (i.e., 10^{-6}). The linear forms of DEA model are shown below: (Cook and Seiford, 2009)

Input Oriented CRS Model:

$$maxE_{j_0} = \sum_r u_r y_{rj_0} \tag{12}$$

s.t

$$\sum_r v_i x_{ij_0} = 1$$

$$\sum_r u_r y_{rj_0} - \sum_r v_i x_{ij_0} \leq 0; j = 1, \dots, n$$

$$u_r, v_i \geq \varepsilon > 0;\ r = 1, \dots, s;\ i = 1, \dots, m$$

Output Oriented CRS Model:

$$minE_{j_0} = \sum_r v_i x_{ij_0} \tag{13}$$

s.t

$$\sum_r u_r y_{rj_0} = 1$$

$$\sum_r u_r y_{rj_0} - \sum_r v_i x_{ij_0} \leq 0; j = 1, \dots, n$$

$$u_r, v_i \geq \varepsilon > 0;\ r = 1, \dots, s;\ i = 1, \dots, m$$

Input Oriented VRS Model:

$$maxE_{j_0} = \sum_r u_r y_{rj_0} - \mu_0 \tag{14}$$

s.t.

$$\sum_r v_i x_{ij_0} = 1$$

$$\sum_r u_r y_{rj_0} - \sum_r v_i x_{ij_0} - \mu_0 \leq 0; j = 1, \dots, n$$

$$u_r, v_i \geq \varepsilon > 0;\ r = 1, \dots, s;\ i = 1, \dots, m;\ \mu_0 = unrestricted$$

Output Oriented VRS Model:

$$minE_{j_0} = \sum_r v_i x_{ij_0} - \mu_0 \tag{15}$$

s.t

$$\sum_r u_r y_{rj_0} = 1$$

$$\sum_{r} u_r y_{rj_0} - \sum_{r} v_i x_{ij_0} + \mu_0 \leq 0; j = 1, \ldots, n$$

$$u_r, v_i \geq \varepsilon > 0;\ r = 1, \ldots, s;\ i = 1, \ldots, m;\ \mu_0 = unrestricted$$

Considering the operation of WWTPs and input-output variables for efficiency evaluation, it is considered that there is no or limited opportunity to intervene in the input variables. For this reason, output-oriented DEA models usage has been deemed appropriate in this study.

4.2.1 Efficiency Assessment with Interval DEA

In this study, while some data consist of precisely known and provided directly; some of them will be included in the calculations in an imprecise manner by inference from the available data. In addition to this, since the efficiency evaluation of 87 WWPTs in Istanbul will be carried out for two years between 2019 and 2020, no calculation will be made for each year, but a general efficiency evaluation will be made. For this reason, based on the criticisms brought to the classical DEA; interval DEA will be used in this study to eliminate the errors, uncertainties, and hesitations that may occur.

Calculation of tolerance intervals is an important element to eliminate subjectivities and hesitations in DEA models with uncertainty. Bonilla et al. (2004), Medal (2010), Bosca et al. (2011), Sala-Garrido et al. (2012), and Gomez et al. (2018) applied an approach using descriptive statistics to analytically determine interval values for inputs and outputs (Sala-Garrido et al., 2012 and Gomez et al., 2018). With this approach, appropriate levels of tolerance are calculated by taking into account the change in the input and output variables of the data within the period under consideration.

Sala-Garrido et al. (2012) handled the tolerance intervals as symmetrically as their distance from the mean. The approach to determining suitable tolerance ranges for input and output variables considering i periods, n DMUs in this study is explained in four steps below:

Step 1: Calculation of the mean, maximum and minimum values of input and output variables for each DMUs considering periods of data.

Step 2: Calculation of the (max-min) and (mean-min) differentiations for each DMUs as the percentage.

$$Difmax(i) = \frac{\max(i) - \min(i)}{mean(i)} \tag{16}$$

$$Difmin(i) = \frac{\text{mean}(i) - \min(i)}{mean(i)} \tag{17}$$

Step 3: Calculation of symmetric tolerance value for each DMUs.

$$Tol(i) = \frac{\text{Difmax}(i) - \text{Difmin}(i)}{2} \tag{18}$$

Step 4: Calculation of the global mean tolerance for each input and output and divided by two to show both positive and negative variations for each input and output.

$$Tol = meanTol(i) = \frac{\sum Tol(i)}{n} \tag{19}$$

Besides this symmetrical approach, Bonilla et al. (2004), calculated intervals as unsymmetrically, considering directly Difmax(i) and Difmin(i).

Efficiency scores have been calculated using Eq. 13 with intervals. Tolerance values have been considered according to the approach proposed by Sala-Garrido et al. (2012). Tolerance values are expressed as follows:

Tolerance values of input variables: $\alpha_{ij} = x_{ij}r_{ij}$ (20)

Tolerance values of output variables: $\beta_{kj} = y_{kj}s_{kj}$

r_{ij} and $s_{kj}$are the percentage of the deviation from the original values for the inputs and outputs So, considering the defined tolerance values, the input and output variables are defined as intervals (Gomez et al., 2018).

$$x_{ij} \in \left[x_{ij}\left(1 - r_{ij}\right), x_{ij}\left(1 + r_{ij}\right)\right] \quad (21)$$

$$y_{kj} \in \left[y_{kj}\left(1 - s_{kj}\right), y_{kj}\left(1 + s_{kj}\right)\right]$$

It is not possible to calculate all combinations of values in this interval. Therefore, only extreme values and real values in these intervals of each input, output variable are taken into account.

For input values: $x_{ij}(1-r_{ij}), x_{ij}, x_{ij}(1+r_{ij})$ (22)

For output values: $y_{kj}(1-s_{kj}), y_{kj}, y_{kj}(1+s_{kj})$

In this case, the calculation of efficiency scores using Eq.13 is evaluated 3^4(81) times for each DMU, with three different scenarios (best-case, worst-case, original) and four inputs-outputs (inputs for related DMU, outputs for related DMU, inputs for the remaining DMUs, outputs for the remaining DMUs).

The values for the best scenario and the worst scenario obtained with this calculation represent the maximum and minimum values of the interval where the efficiency score can be found for the relevant DMU.

4.2.2 Comparing and Ranking Interval Efficiencies of DMUs

These results obtained from the calculation of the efficiency scores similarly give interval values since the data on the input and output variables are interval. According to these results, R^1 and R^2 efficiency indicators suggested by Bosca et al (2011) are calculated to evaluate the efficiency of the DMUs and to interpret them comparably. These indicators are formulated and interpreted as follows (Bosca et al., 2011; Sala-Garrido et al., 2012; Gomez et al., 2018):

$$R^1_{j_0} = \frac{e_{j_0}}{\tau_{j_0}} \tag{23}$$

$$R^2_{j_0} = \begin{cases} \dfrac{S_{j_0} - e_{j_0}}{\tau_{j_0} - e_{j_0}}, & \tau_{j_0} \neq e_{j_0} \\ 0, & \tau_{j_0} = e_{j_0} \end{cases} \tag{24}$$

j_0 is defined as the order of DMU, $e_{j_0}$is defined as the number of times that efficiency score is equal to one, $\tau_{j_0}$is defined as the scenarios that analyzed (in this study it is equal to 81), $S_{j_0}$is defined as the sum of efficiency (Gomez et al., 2018).

The R^1 and R^2 efficiency indicators take values between 0 and 1. The R^1 value expresses the efficiency ratio of the relevant DMU in the scenarios examined. In the case of DMUs with the same R^1 value, comparisons are made according to R^2 values (Sala-Garrido et al., 2012).

5 A CASE STUDY: EVALUATION OF THE WWTPS EFFICIENCY IN ISTANBUL

Increasing urbanization and developing industrialization have brought along environmental problems and searches for efficient use of resources. With the increasing trends in the circular economy, especially in 2010 and later, the issue of evaluating WWTPs in terms of efficiency and studies on this have started to take place in the literature. In this topic, researchers from European countries (especially Spain), China, and the United States have made significant contributions to the literature.

Despite the limited number of academic studies on this subject in Turkey, there are informative sectoral reports and evaluations to fill the gap in this field. In order to fill this gap in the literature, a three-stage methodology has been proposed and implemented to evaluate the efficiency of wastewater treatment activities of a region.

In this section, the efficiency of 87 WWTPs operating under the Istanbul Metropolitan Municipality will be evaluated. For carrying out this assessment, the methodology is described in Section 4.

Firstly, the extended SWARA has been used to clarify the possible variables by taking expert opinions. Secondly, efficiency scores have been calculated by applying interval DEA and WWTPs have been ranked according to their efficiency scores. Finally, the relationship between the calculated efficiency scores of WWTPs and external factors has been examined.

This study, with its methodology for WWTPs' effectiveness evaluation; in addition to providing the opportunity to determine the variables by taking into account the expert opinions, is the first and unique study in Turkey in terms of evaluating the WWTPs' effectiveness with interval values to overcome uncertainty conditions.

5.1 Data Description

Data on WWTPs in Istanbul were obtained from the annual activity reports of the Istanbul Water and Sewerage Administration (ISKI), a subsidiary of Istanbul Metropolitan Municipality (ISKI, 2019 and ISKI, 2020).

General information on the 2019 and 2020 operating results of the WWTPs in Istanbul is available in the Table 5.1 below:

Table 5.1 General information for WWTPs in Istanbul (ISKI, 2019 and ISKI, 2020)

Information	**2019**	**2020**
Number of WWTPs	87	88
Biological+Advanced Biological WWTPs	79	80
Physical WWTPs	8	8
Wastewater Treatment Capacity (m^3/year)	2,121,255,900	2,121,347,150
Wastewater Treated (m^3/year)	1,381,290,767	1,396,180,804
Biological+Advanced Biologically Treated Wastewater (m^3/year)	524,813,959	560,462,665
Pre-Treated Wastewater (m^3/year)	856,476,808	835,718,138
Water Recycled (m^3/year)	25,376,863	24,869,460
Trash Held (kg/year)	6,090,161	6,327,055
Sand Retained (kg/year)	23,108,474	27,074,186
Foam Retained (kg/year)	413,435	533,330
Dried Sludge (kg/year)	458,038,675	519,081,969

Information	2019	2020
Electricity Consumption (kWh/year)	342,985,703	371,976,387
Natural Gas Consumption (Nm^3/year)	55,270,117	61,058,206

The data to be used in calculating the efficiency of Istanbul WWTPs in 2019 and 2020 are included in the Appendix A. Since the efficiency calculation will be made with two-years data in this study, a newly opened WWTP in 2020 and two WWTPs whose activity data are specified as 0 in the reports will be excluded. For this reason, 85 WWTPs will be evaluated within the scope of the study.

5.2 Determination of The Input and Output Variables

When the variables used in ISKI annual reports and literature research are examined, possible input variables have been determined as below:

Possible input variables;

- I_1: Total Wastewater Treatment Capacity
- I_2: Electricity Consumption
- I_3: Natural Gas Consumption

Possible output variables;

- O_1: Amount of Wastewater Treated
- O_2: Amount of Wastewater Recycled
- O_3: Capacity Utilization Rate
- O_4: Amount of Dried Sludge
- O_5: Amount of Trash Held

In this study, as the first step of the methodology, expert opinions have been taken for the variables (three inputs and five outputs) obtained as a result of the annual reports and literature reviews, and these opinions were evaluated with the extended-SWARA (Zolfani et al., 2018).

Firstly, eight experts working on the area of wastewater treatments and their technologies, efficiency & productivity evaluation, and multi-criteria decision making have been asked to rank the possible criteria according to their importance (the most important is 1 point) in accordance with the extended-SWARA methodology. These ranking suggestions are given in Table 5.2 below.

Table 5.2 Rankings by experts for possible variables

#	I_1	I_2	I_3	O_1	O_2	O_3	O_4	O_5
Expert 1	1	3	2	4	5	6	7	8
Expert 2	1	4	8	2	5	3	6	7
Expert 3	1	3	5	2	4	8	7	6
Expert 4	3	5	4	1	2	6	8	7
Expert 5	2	4	8	1	3	7	5	6
Expert 6	1	5	8	2	7	4	3	6
Expert 7	1	3	4	5	6	2	7	8
Expert 8	1	5	6	3	4	2	8	7

According to the extended-SWARA methodology, calculations of steps for assessing the consensus of expert opinions are available in Table 5.3 below.

Table 5.3 Calculation results of SWARA step 1 to step 7

	I_1	I_2	I_3	O_1	O_2	O_3	O_4	O_5
Sum of ranks	11	32	45	20	36	38	51	55
Average rank value ($\bar{t}_j$)	1.38	4.00	5.63	2.50	4.50	4.75	6.38	6.88
Attribute weight (q_j)	0.04	0.11	0.16	0.07	0.13	0.13	0.18	0.19
Dispersion (σ^2)	0.55	0.86	5.13	2.00	2.57	5.36	2.84	0.70
Variation (β_j)	0.54	0.23	0.40	0.57	0.36	0.49	0.26	0.12
Average of sum of ranks	36							
Total square ranging deviator	625	16	81	256	0	4	225	361
Concordance coefficient (W)	0.58							
Significance of concordance coefficient ($X^2_{\alpha,v}$)	32.67							
X^2_{tbl}	14.1							

According to Table 5.3, when it is tested whether there is a consensus among the expert opinions on the importance ranking values of the criteria with the hypotheses below;

- H_0: There is a consensus between independent expert opinions.
- H_1: There is no consensus between independent expert opinions.

Degrees of freedom (df) are v = 8 - 1 = 7, p=0.05 at the significance level, $X^2_{\alpha,v}$ > X^2_{tbl}(32.67>14.1); H_0 is rejected. There is no consensus between independent expert opinions. Expert opinions on the ranking are acceptable, so it is possible to move on to the next steps in the methodology. Table 5.4 expresses the importance weights of each variable after expert opinion evaluations.

Table 5.4 Final calculation results of SWARA step 8 to step 11

	Average rank value ($\bar{t}_j$)	Comparative importance of average value (s_j)	Coefficient (k_j)	Recalculated weight (q_j)	Weight (w_j)
I_1	1.38	-	1	1.00	0.41
O_1	2.50	0.55	1.55	0.65	0.26
I_2	4.00	0.63	1.63	0.40	0.16
O_2	4.50	0.89	1.89	0.21	0.09
O_3	4.75	0.95	1.95	0.11	0.04
I_3	5.63	0.84	1.84	0.06	0.02*
O_4	6.38	0.88	1.88	0.03	0.01*
O_5	6.88	0.93	1.93	0.02	0.01*

In this case, the most important variables regarding the efficiency evaluation of wastewater treatment plants are “total wastewater treatment capacity”, “amount of wastewater treated” “electricity consumption” “amount of wastewater recycled” and “capacity utilization rate”, which have a total weight of 96%. However, “natural gas consumption”, “amount of dried sludge” and “amount of trash held” have the lowest importance weights for the model. It has been decided not to include these three variables, which have a total significance of 4% (*), in the next steps in the efficiency calculation methodology.

5.3 Efficiency Assessment with Interval DEA

Considering the data of 2019 and 2020, tolerance values were found for each WWTP with the methodology applied by Sala-Garrido et al. (2012) and Gomez et al. (2018). By taking the average of these values, symmetric tolerance values were found to determine the tolerance intervals of the input and output variables. Tolerance values are in Table 5.5. To see all values of the Table 5.5, see Appendix B.

Since "total wastewater treatment capacity" does not change from year to year, a tolerance value could not be calculated to be used in the tolerance intervals for efficiency calculation. So, "total wastewater treatment capacity" variable will be considered in the interval calculation as maximum, minimum and actual values are equal to each other.

Table 5.5 Tolerance for inputs and outputs in (%)

	Inputs		**Outputs**		
	Total Wastewater Treatment Capacity (I_1)	**Electricity Consumption (I_2)**	**Amount of Wastewater Treated (O_1)**	**Amount of Wastewater Recycled (O_2)**	**Capacity Utilization Rate (O_3)**
WWTP 1	-	1.686	0.971	0.199	0.971
WWTP 2	-	7.199	0.799	0.026	0.799
WWTP 3	-	1.113	3.177	2.406	3.177
WWTP 4	-	4.329	6.222	5.460	6.222
WWTP 5	-	1.358	0.197	0.970	0.197
…	…			…	
WWTP 40	-	5.977	2.679	3.449	2.679
WWTP 41	-	0.621	1.889	2.660	1.889
WWTP 42	-	2.172	1.808	1.036	1.808
WWTP 43	-	0.965	6.034	6.795	6.034
WWTP 44	-	6.575	3.671	2.902	3.671
WWTP 45	-	0.846	7.527	6.770	7.527
…	…			…	
WWTP 80	-	0.958	16.237	16.925	16.237
WWTP 81	-	2.392	0.087	0.860	0.087
WWTP 82	-	1.867	1.029	0.256	1.029
WWTP 83	-	4.901	2.959	3.729	2.959
WWTP 84	-	2.613	3.131	2.360	3.131
WWTP 85	-	2.503	7.039	7.795	7.039
Mean	**-**	**3.867**	**4.571**	**4.620**	**4.571**

Input and output values with tolerance intervals prepared using the specified tolerance values are in Table 5.6. To see all values of the Table 5.6, see Appendix C.

Table 5.6 Tolerance intervals for inputs and outputs

	Total Wastewater Treatment Capacity			Electricity Consumption			Amount of Wastewater Treated			Amount of Wastewater Recycled			Capacity Utilization Rate		
	Lower	**Original**	**Upper**	**Lower**	**Original**	**Upper**	**Lower**	**Original**	**Upper**	**Lower**	**Original**	**Upper**	**Lower**	**Original**	**Upper**
WWTP 1	146,000,000	146,000,000	146,000,000	62,715,006	65,237,671	67,760,335	127,908,566	134,034,700	140,160,834	2,312,246	2,424,250	2,536,254	88%	92%	96%
WWTP 2	219,000,000	219,000,000	219,000,000	75,949,521	79,004,535	82,059,548	139,429,613	146,107,544	152,785,474	2,520,651	2,642,749	2,764,848	64%	67%	70%
WWTP 3	631,450	631,450	631,450	95,244	99,075	102,906	534,138	559,720	585,302	9,649	10,117	10,584	85%	89%	93%
WWTP 4	18,980,000	18,980,000	18,980,000	3,804,086	3,957,103	4,110,120	5,327,044	5,582,181	5,837,318	96,142	100,799	105,457	28%	29%	31%
WWTP 5	13,322,500	13,322,500	13,322,500	3,895,821	4,052,528	4,209,235	7,366,643	7,719,466	8,072,288	133,217	139,670	146,123	55%	58%	61%
…		…			…			…			…			…	
WWTP 40	365,000	365,000	365,000	113,967	118,552	123,136	372,147	389,971	407,794	6,735	7,061	7,387	102%	107%	112%
WWTP 41	182,500	182,500	182,500	97,686	101,615	105,544	71,188	74,598	78,008	1,288	1,350	1,413	39%	41%	43%
WWTP 42	182,500	182,500	182,500	153,784	159,970	166,156	187,475	196,455	205,434	3,388	3,552	3,716	103%	108%	113%
WWTP 43	182,500	182,500	182,500	100,905	104,964	109,022	51,428	53,891	56,354	932	977	1,022	28%	30%	31%
WWTP 44	182,500	182,500	182,500	124,598	129,610	134,622	167,450	175,470	183,489	3,025	3,171	3,318	92%	96%	101%
WWTP 45	182,500	182,500	182,500	229,587	238,822	248,057	312,073	327,020	341,967	5,630	5,903	6,175	171%	179%	187%
…		…			…			…			…			…	
WWTP 80	91,250	91,250	91,250	42,802	44,524	46,246	98,064	102,761	107,458	1,782	1,869	1,955	107%	113%	118%
WWTP 81	233,600,000	233,600,000	233,600,000	2,832,260	2,946,186	3,060,111	86,769,752	90,925,557	95,081,362	1,569,080	1,645,085	1,721,090	37%	39%	41%
WWTP 82	16,790,000	16,790,000	16,790,000	1,018,427	1,059,392	1,100,357	6,399,270	6,705,761	7,012,251	115,680	121,283	126,887	38%	40%	42%
WWTP 83	304,045,000	304,045,000	304,045,000	21,044,974	21,891,492	22,738,010	172,607,771	180,874,757	189,141,743	3,124,082	3,275,411	3,426,739	57%	59%	62%
WWTP 84	28,382,400	28,382,400	28,382,400	828,931	862,274	895,617	12,126,859	12,707,671	13,288,482	219,075	229,687	240,299	43%	45%	47%
WWTP 85	209,875,000	209,875,000	209,875,000	2,500,005	2,600,566	2,701,126	22,337,507	23,407,354	24,477,201	404,803	424,411	444,020	11%	11%	12%
Total	**2,119,795,900**	**2,119,795,900**	**2,119,795,900**	**317,100,936**	**329,856,086**	**342,611,236**	**1,324,915,671**	**1,388,372,020**	**1,451,828,368**	**23,956,256**	**25,116,682**	**26,277,107**	**-**	**-**	**-**
Average	**24,938,775**	**24,938,775**	**24,938,775**	**3,730,599**	**3,880,660**	**4,030,720**	**15,587,243**	**16,333,788**	**17,080,334**	**281,838**	**295,490**	**309,142**	**96%**	**101%**	**105%**

The basic general output-oriented DEA model in Eq. 13 has been considered in calculating the efficiency scores of the 85 WWTPs. In this context, the efficiency scores have been calculated as 81(3^4) times with three different scenarios (best-case, worst-case, original) and four inputs-outputs (inputs for related WWTPs, outputs for related WWTPs, inputs for the remaining WWTPs, outputs for the remaining WWTPs) for each WWTPs.

Calculations has been made using Excel VBA on a computer with an “11th Gen Intel(R) Core(TM) i7-1185G7 @ 3.00GHz 1.80 GHz” and the results were analyzed in about 3 hours. The efficiency values of 85 WWTPs analyzed for 81 scenarios considering interval values are given in Table 5.7. To see all values of the Table 5.7, see Appendix D.

Table 5.7 Efficiency scores of WWTPs using interval DEA for 81 scenarios

	Original	Mean	Max	Min	Amplitude (max-min) (%)	Amplitude (original-mean) (%)
WWTP 1	0.427	0.428	0.494	0.368	12.6%	-0.1%
WWTP 2	0.359	0.360	0.415	0.311	10.4%	-0.1%
WWTP 3	0.762	0.764	0.866	0.671	19.5%	-0.1%
WWTP 4	0.220	0.220	0.251	0.192	5.8%	0.0%
WWTP 5	0.348	0.349	0.401	0.302	9.8%	-0.1%
			…			
WWTP 41	0.163	0.163	0.190	0.140	5.0%	0.0%
WWTP 42	0.369	0.370	0.432	0.318	11.4%	-0.1%
WWTP 43	0.115	0.115	0.134	0.099	3.5%	0.0%
WWTP 44	0.315	0.317	0.368	0.274	9.5%	-0.1%
WWTP 45	1.000	1.000	1.000	1.000	0.0%	0.0%
			…			
WWTP 80	0.545	0.546	0.641	0.463	17.8%	-0.1%
WWTP 81	1.000	1.000	1.000	1.000	0.0%	0.0%
WWTP 82	0.474	0.475	0.530	0.424	10.6%	-0.1%
WWTP 83	0.683	0.684	0.765	0.609	15.6%	-0.1%
WWTP 84	0.780	0.781	0.892	0.681	21.0%	-0.1%
WWTP 85	1.000	0.761	1.000	0.256	74.4%	23.9%
Mean	**0.507**	**0.503**	**0.570**	**0.444**	**12.6%**	**0.4%**

5.4 Comparing and Ranking Interval Efficiencies of DMUs

In order to rank the interval efficiency values of 85 WWTPs, $\boldsymbol{R_{j0}^1}$ and $\boldsymbol{R_{j0}^2}$ values have been calculated by considering the efficiency values of each WWTP in 81 calculation scenarios. The $\boldsymbol{R_{j0}^1}$ value indicates how many times the relevant WWTP is ranked effectively in 81 scenarios. In this case, WWTPs 10, 45, 55, 71, 76, 79 and 81 have been found to be effective for all scenarios. In addition, it was seen that WWTPs 58, 68, 85, 52 and 51 have been ranked more effectively than the remaining WWTPs. $\boldsymbol{R_{j0}^2}$ values of the remaining WWTPs should be examined in order to rank their efficiencies. Considering the $\boldsymbol{R_{j0}^1}$ and $\boldsymbol{R_{j0}^2}$ values, the ranking of 85 WWTPs' efficiencies are listed in Table 5.8. To see all values of the Table 5.8, see Appendix E.

Table 5.8 Ranking of WWTPs according to efficiency scores for 81 scenarios

	$\boldsymbol{R_{j0}^1}$	$\boldsymbol{R_{j0}^2}$
WWTP 10	1.000	-
WWTP 45	1.000	-
WWTP 55	1.000	-
WWTP 71	1.000	-
WWTP 76	1.000	-
WWTP 79	1.000	-
WWTP 81	1.000	-
WWTP 58	0.691	0.966
WWTP 68	0.679	0.961
WWTP 85	0.667	0.284
WWTP 52	0.062	0.897
WWTP 51	0.012	0.329
WWTP 63	0.000	0.881
WWTP 54	0.000	0.875
WWTP 59	0.000	0.870
WWTP 53	0.000	0.820
WWTP 84	0.000	0.781
WWTP 77	0.000	0.772
WWTP 3	0.000	0.763
WWTP 72	0.000	0.705
	...	

	R_{j0}^1	R_{j0}^2
WWTP 25	0.000	0.283
WWTP 33	0.000	0.281
WWTP 69	0.000	0.278
WWTP 62	0.000	0.270
WWTP 29	0.000	0.267
WWTP 20	0.000	0.255
WWTP 21	0.000	0.255
WWTP 37	0.000	0.224
WWTP 4	0.000	0.220
WWTP 23	0.000	0.218
WWTP 28	0.000	0.209
WWTP 32	0.000	0.204
WWTP 9	0.000	0.186
WWTP 41	0.000	0.163
WWTP 43	0.000	0.115
WWTP 47	0.000	0.113

5.5 Investigation of Linking Between the Efficiencies and Exogenous Factors

Finally, it has been examined the difference of the average efficiency scores calculated interval for each WWTPs according to their service year and type. This examination has been carried out using Kruskal-Wallis is a non-parametric hypothesis test in SPSS 22 program. The data used in this study provide the necessary assumptions of the Kruskal-Wallis test. These assumptions are; the requirement that the population does not have a normal distribution and the dependent variable must be at least ordinal.

This test was proposed by Kruskal-Wallis in 1952, as a nonparametric method for testing whether samples are originated from the same distribution. It is an extension of the Mann-Whitney U test applicable for more than two groups.

The data used in this study provide the necessary assumptions of the Kruskal-Wallis test (the population does not have a normal distribution and the dependent variable must be at least ordinal).

The hypothesis of Kruskal-Wallis is below and p=0.05 at the significance level;
If Asymp. Sig. <0.05; H_0 is rejected.

- H_0: There is no significant difference between the medians of all groups.
- H_1: There is a significant difference between the medians of at least two groups.

If the age of the facility (year) is determined as a group variable, it is tested whether there is a significant difference between the median values of the efficiency scores;

Table 5.9 Kruskal-Wallis H test statistics (efficiency scores and years)

Test Statistics[a,b]

	Mean
Kruskal-Wallis H	25.417
df	18
Asymp. Sig.	.114

a. Kruskal Wallis Test

b. Grouping Variable: Year

p=0.05 at the significance level; since 0.114 > 0.05, the hypothesis H_0 is not rejected. There is no significant difference between the medians of efficiencies according to the age of the facility.

If the facility type is determined as a group variable, it is tested whether there is a significant difference between the median values of the efficiency scores;

Table 5.10 Kruskal-Wallis H test statistics (efficiency scores and type)

Test Statistics[a,b]

	Mean
Kruskal-Wallis H	11.378
df	2
Asymp. Sig.	.003

a. Kruskal Wallis Test

b. Grouping Variable: Type

p=0.05 at the significance level; since 0.003 < 0.05, the hypothesis (H_0) is rejected. There is a significant difference between the medians of at least two groups' efficiency scores according to the type of the facility. The median of at least one type of facility is different from the others.

To find out which groups' medians of rank values differ, the groups are compared in pairs and evaluated with hypothesis tests. If Asymp. Sig. < 0.05; H_0 is rejected;

- H_0: There is no significant difference between the medians of the two groups.
- H_1: There is a significant difference between the medians of the two groups.

If it is tested whether there is a significant difference between the median values of the efficiency scores at the significance level p=0.05 only physical WWTPs differ from the biological and advanced biological WWTPs:

Table 5.11 Kruskal-Wallis H test pairwise comparison

Pairwise Comparisons of Type

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
3-2	2.715	8.373	.324	.746	1.000
3-1	31.561	11.337	2.784	.005	.016
2-1	28.846	8.768	3.290	.001	.003

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .050.
a Significance values have been adjusted by the Bonferroni correction for multiple tests.

- Biological and advanced biological WWTPs; since 0.746 > 0.05, the hypothesis (H_0) is not rejected. There is no significant difference between the medians of biological and advanced biological WWTPs' efficiencies.
- Advanced biological and physical WWTPs; since 0.005<0.05, the hypothesis (H_0) is rejected. There is a significant difference between the medians of and physical and advanced biological WWTPs' efficiencies.

- Physical and biological WWTPs; since 0.001<0.05, the hypothesis (H_0) is rejected. There is a significant difference between the medians of and physical and biological WWTPs' efficiencies.

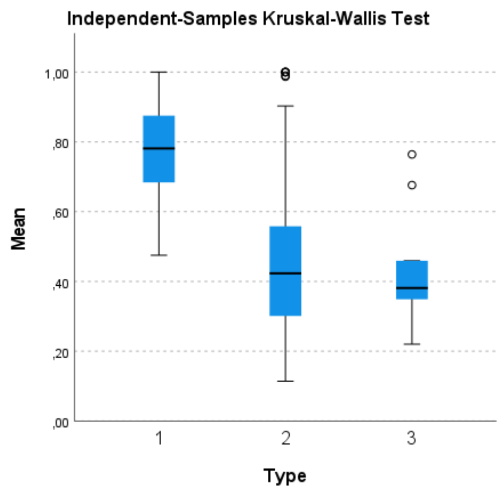

Figure 5.1 Median across the type of WWTPs

As can be seen in Figure 5.1, above, the median rank values of the efficiency values according to the WWTP plant type, physical WWTPs differ from the others.

6 CONCLUSIONS

The global climate crisis that we are facing in the current century requires taking action on certain issues. One of the themes determined for the realization of these actions is “clean water and sanitation”. Within the scope of these actions, WWTPs have strategic importance in the treatment, removal, and reuse of urban and industrial waters without harming nature after their use. Industrialization and the increase in domestic pollutants brought about the increase in the number of WWTPs, and the increase in WWTPs brought along the problems related to the effective evaluation and management of their activities. Therefore, studies on the evaluation of the effectiveness of WWTPs due to these problems have contributed to the development of the international literature. In this study, a three-stage methodology has been proposed for evaluating the effectiveness of WWTPs with uncertainties in the data. By the proposed methodology, the efficiency evaluation of 85 WWTPs in Istanbul was carried out. This is the first study carried out in Turkey in terms of the methodology used in this field.

In the first stage of the study, expert opinions have been used and the variables to be used in the efficiency calculation have been determined with the extended-SWARA. Firstly, it has been determined that the expert opinions were consistent and the weights of the variables have been calculated. As a result of the literature review and the examination of ISKI activity reports, from the eight possible variables (three inputs, five outputs) have been determined and three variables (one input, two outputs) with a weight of 4% in the total have been excluded with the evaluation of expert opinions.

In the second stage of the study, efficiency calculations have been made using the variables determined as a result of expert opinions' evaluations. It was desired to obtain a general, single evaluation result from the two-year data on the WWTPs. In addition to this, the data on "amount of wastewater recycled" is not precise; only the total amount is known. So, it has been calculated as the distribution of the total amount on the basis of WWTPs, using the percentages of the a "amount of wastewater treated" as the distribution key. For these two reasons, efficiency calculations have been made with interval data to overcome the uncertainty conditions in the data. Efficiency values have been calculated within 81 scenarios for each WWTP, taking into account tolerance intervals. When the averages of the calculated values of each WWTP for 81 scenarios are evaluated; in general, the original, mean, maximum and minimum efficiencies of 85 WWTPs have been found to be 50,7%, 50,3%, 57% and 44,4% effective, respectively. A ranking has been created as a result of the evaluation of the efficiency values of each of these WWTPs. According to this ranking, it has been calculated that seven WWTPs are effective in all scenarios, and five WWTPs are effective in some scenarios. It is recommended that the authorities take actions to increase the effectiveness of these five WWTPs in the short term and to make them effective continuously. In addition, it is recommended to evaluate the effectiveness of the remaining WWTPs one by one and analyze the mechanisms for the effective functioning of the WWTPs for all processes from the design of the WWTP to the commissioning. For example, for the WWTP to be established in a region, the facility should be constructed by making capacity assessments within certain projections, not instantaneous needs.

Finally, it has been examined the difference of the average efficiency scores that calculated interval for each WWTPs according to their service year and type. As a result of this examination, it has been that there is no significant difference in terms of the average efficiency scores of the WWTPs, considering the age of the facility. In addition, when the type of facility is considered, it has been observed that the average of the physical WWTPs differs in terms of average efficiency scores.

For future research, the use of fuzzy techniques can be recommended for the criterion evaluation phase of this study. In addition to this, undesirable outputs can be included in the model in determining the output variables, and the interval calculation methodology can be applied.

REFERENCES

Al-Assa'd, T., & Sauer, J. (2010). The performance of water utilities in Jordan. Water Science and Technology, 62(4), 803-808.

An, M., He, W., Degefu, D. M., Liao, Z., Zhang, Z., & Yuan, L. (2018). Spatial patterns of urban wastewater discharge and treatment plants efficiency in China. International journal of environmental research and public health, 15(9), 1892.

Ananda, J. (2019). Explaining the environmental efficiency of drinking water and wastewater utilities. Sustainable Production and Consumption, 17, 188-195.

Ananda, J. (2020). Assessing the operational efficiency of wastewater services whilst accounting for data uncertainty and service quality: a semi-parametric approach. Water International, 45(7-8), 921-944.

Ayyildiz, E., Yildiz, A., Taskin Gumus, A., & Ozkan, C. (2021). An integrated methodology using extended swara and dea for the performance analysis of wastewater treatment plants: Turkey case. Environmental Management, 67(3), 449-467.

Banker, R. D., Charnes, A., & Cooper, W. W. (1984). Some models for estimating technical and scale inefficiencies in data envelopment analysis. Management science, 30(9), 1078-1092.

Baştürk et al. (2017). Atıksu Mühendisliği. İstanbul, TURKEY: ISKI

Bian, Y., Yan, S., & Xu, H. (2014). Efficiency evaluation for regional urban water use and wastewater decontamination systems in China: A DEA approach. Resources, Conservation and Recycling, 83, 15-23.

Birleşmiş Milletler Türkiye. Sürdürülebilir Kalkınma Amaçları. (27.12.2021) Erişim Adresi: https://turkey.un.org/tr/sdgs

Bonilla, M., Casasus, T., Medal, A., Sala, R., 2004. An efficiency analysis with tolerance of the Spanish port system. International Journal of Transport Economics XXXI (3), 379–400.

Bosca, J. E., Liern, V., Sala, R., & Martinez, A. (2011). Ranking decision making units by means of soft computing DEA models. International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, 19(01), 115-134.

Castellet, L., & Molinos-Senante, M. (2016). Efficiency assessment of wastewater treatment plants: A data envelopment analysis approach integrating technical, economic, and environmental issues. Journal of environmental management, 167, 160-166.

Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. European journal of operational research, 2(6), 429-444.

Cheng, P., Jin, Q., Jiang, H., Hua, M., & Ye, Z. (2020). Efficiency assessment of rural domestic sewage treatment facilities by a slacked-based DEA model. Journal of Cleaner Production, 267, 122111.

Cook, W. D., & Seiford, L. M. (2009). Data envelopment analysis (DEA)–Thirty years on. European journal of operational research, 192(1), 1-17.

D'Inverno, G., Carosi, L., Romano, G., & Guerrini, A. (2018). Water pollution in wastewater treatment plants: An efficiency analysis with undesirable output. European Journal of Operational Research, 269(1), 24-34.

Dong, X., Du, X., Li, K., Zeng, S., & Bledsoe, B. P. (2018). Benchmarking sustainability of urban water infrastructure systems in China. Journal of cleaner production, 170, 330-338.

Dong, X., Zhang, X., & Zeng, S. (2017). Measuring and explaining eco-efficiencies of wastewater treatment plants in China: an uncertainty analysis perspective. Water Research, 112, 195-207.

Farrell, M. J. (1957). The measurement of productive efficiency. Journal of the Royal Statistical Society: Series A (General), 120(3), 253-281.

Feng, Y., Feng, J. K., Lee, J. H., Lu, C. C., & Chiu, Y. H. (2020). Undesirable Output in Efficiency: Evidence from Wastewater Treatment Plants in China. Applied Ecology and Environmental Research, 17(4), 9279-9290.

Fuentes, R., Bellver-Domingo, Á., Hernández-Chover, V., & Hernández-Sancho, F. (2020). Identification and correction of congestion in wastewater treatment plants in the Community of Valencia, Spain. Environmental Science & Pollution Research, 27(13).

Fuentes, R., Molinos-Senante, M., Hernández-Sancho, F., & Sala-Garrido, R. (2020). Analysing the efficiency of wastewater treatment plants: The problem of the definition of desirable outputs and its solution. Journal of Cleaner Production, 267, 121989.

Fuentes, R., Torregrosa, T., & Ballenilla, E. (2015). Conditional order-m efficiency of wastewater treatment plants: The role of environmental factors. Water, 7(10), 5503-5524.

Fuentes, R., Torregrosa-Martí, T., & Hernández-Sancho, F. (2017). Productivity of wastewater treatment plants in the Valencia Region of Spain. Utilities Policy, 46, 58-70.

Gémar, G., Gómez, T., Molinos-Senante, M., Caballero, R., & Sala-Garrido, R. (2018). Assessing changes in eco-productivity of wastewater treatment plants: The role of costs, pollutant removal efficiency, and greenhouse gas emissions. Environmental Impact Assessment Review, 69, 24-31.

Gómez, T., Gémar, G., Molinos-Senante, M., Sala-Garrido, R., & Caballero, R. (2017). Assessing the efficiency of wastewater treatment plants: A double-bootstrap approach. Journal of Cleaner Production, 164, 315-324.

Gómez, T., Gémar, G., Molinos-Senante, M., Sala-Garrido, R., & Caballero, R. (2018). Measuring the eco-efficiency of wastewater treatment plants under data uncertainty. Journal of environmental management, 226, 484-492.

Guerrini, A., Romano, G., & Campedelli, B. (2013). Economies of scale, scope, and density in the Italian water sector: a two-stage data envelopment analysis approach. Water resources management, 27(13), 4559-4578.

Guerrini, A., Romano, G., & Indipendenza, A. (2017). Energy efficiency drivers in wastewater treatment plants: a double bootstrap DEA analysis. Sustainability, 9(7), 1126.

Guerrini, A., Romano, G., Leardini, C., & Martini, M. (2015). The effects of operational and environmental variables on efficiency of Danish water and wastewater utilities. Water, 7(7), 3263-3282.

Hatami-Marbini, A., Emrouznejad, A., & Tavana, M. (2011). A taxonomy and review of the fuzzy data envelopment analysis literature: two decades in the making. European journal of operational research, 214(3), 457-472.

Hernández-Chover, V., Bellver-Domingo, Á., & Hernández-Sancho, F. (2018). Efficiency of wastewater treatment facilities: The influence of scale economies. Journal of environmental management, 228, 77-84.

Hernández-Sancho, F., & Sala-Garrido, R. (2009). Technical efficiency and cost analysis in wastewater treatment processes: A DEA approach. Desalination, 249(1), 230-234.

Hernández-Sancho, F., Molinos-Senante, M., & Sala-Garrido, R. (2011). Energy efficiency in Spanish wastewater treatment plants: A non-radial DEA approach. Science of the Total Environment, 409(14), 2693-2699.

Hernández-Sancho, F., Molinos-Senante, M., & Sala-Garrido, R. (2011). Techno-economical efficiency and productivity change of wastewater treatment plants: the role of internal and external factors. Journal of Environmental Monitoring, 13(12), 3448-3459.

Hu, W., Guo, Y., Tian, J., & Chen, L. (2019). Eco-efficiency of centralized wastewater treatment plants in industrial parks: A slack-based data envelopment analysis. Resources, Conservation and Recycling, 141, 176-186.

İstanbul Büyükşehir Belediyesi, ISKI (2019). Faaliyet Raporu 2019. Erişim Adresi: https://www.ISKI.gov.tr/web/assets/SayfalarDocs/faaliyetraporlari/faaliyetraporu/pdf/2019-FAAL%C4%B0YET-RAPORU.pdf

İstanbul Büyükşehir Belediyesi, ISKI (2020). Faaliyet Raporu 2020. Erişim Adresi: https://www.ISKI.gov.tr/web/assets/SayfalarDocs/faaliyetraporlari/faaliyetraporu/pdf/2020%20FAAL%C4%B0YET%20RAPORU.pdf

Jiang, H., Hua, M., Zhang, J., Cheng, P., Ye, Z., Huang, M., & Jin, Q. (2020). Sustainability efficiency assessment of wastewater treatment plants in China: A data envelopment analysis based on cluster benchmarking. Journal of Cleaner Production, 244, 118729.

Karsak, E. E., & Dursun, M. (2014). An integrated supplier selection methodology incorporating QFD and DEA with imprecise data. Expert Systems with Applications, 41(16), 6995-7004.

Kendall MG (1970) Rank correlation methods, 4th edn. Griffin, London

Keršuliene, V., Zavadskas, E. K., & Turskis, Z. (2010). Selection of rational dispute resolution method by applying new step-wise weight assessment ratio analysis (SWARA). Journal of business economics and management, 11(2), 243-258.

Lo Storto, C. (2018). Efficiency, conflicting goals and trade-offs: A nonparametric analysis of the water and wastewater service industry in Italy. Sustainability, 10(4), 919.

Lombardi, G. V., Stefani, G., Paci, A., Becagli, C., Miliacca, M., Gastaldi, M., ... & Almeida, C. M. V. B. (2019). The sustainability of the Italian water sector: An empirical analysis by DEA. Journal of Cleaner Production, 227, 1035-1043.

Longo, S., d'Antoni, B. M., Bongards, M., Chaparro, A., Cronrath, A., Fatone, F., ... & Hospido, A. (2016). Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement. Applied energy, 179, 1251-1268.

Longo, S., Hospido, A., Lema, J. M., & Mauricio-Iglesias, M. (2018). A systematic methodology for the robust quantification of energy efficiency at wastewater treatment plants featuring Data Envelopment Analysis. Water research, 141, 317-328.

Lorenzo-Toja, Y., Vázquez-Rowe, I., Chenel, S., Marín-Navarro, D., Moreira, M. T., & Feijoo, G. (2015). Eco-efficiency analysis of Spanish WWTPs using the LCA+ DEA method. Water research, 68, 651-666.

Lorenzo-Toja, Y., Vázquez-Rowe, I., Marín-Navarro, D., Crujeiras, R. M., Moreira, M. T., & Feijoo, G. (2018). Dynamic environmental efficiency assessment for wastewater treatment plants. The International Journal of Life Cycle Assessment, 23(2), 357-367.

Medal, A. (2010). Efficiency analysis of the Spanish port system: structure, evaluation and perspectives (Doctoral dissertation, Phd Thesis. University of Valencia, Spain).

Molinos-Senante, M., & Guzmán, C. (2018). Benchmarking energy efficiency in drinking water treatment plants: Quantification of potential savings. Journal of cleaner production, 176, 417-425.

Molinos-Senante, M., Hernandez-Sancho, F., & Sala-Garrido, R. (2014). Benchmarking in wastewater treatment plants: a tool to save operational costs. Clean Technologies and Environmental Policy, 16(1), 149-161.

Molinos-Senante, M., Hernández-Sancho, F., Mocholí-Arce, M., & Sala-Garrido, R. (2014). Economic and environmental performance of wastewater treatment plants: Potential reductions in greenhouse gases emissions. Resource and Energy Economics, 38, 125-140.

Molinos-Senante, M., Hernández-Sancho, F., Mocholí-Arce, M., & Sala-Garrido, R. (2016). Productivity growth of wastewater treatment plants–accounting for environmental impacts: a Malmquist-Luenberger index approach. Urban Water Journal, 13(5), 476-485.

Molinos-Senante, M., Sala-Garrido, R., & Hernández-Sancho, F. (2016). Development and application of the Hicks-Moorsteen productivity index for the total factor productivity assessment of wastewater treatment plants. Journal of Cleaner Production, 112, 3116-3123.

Nas, B., (2017). Atıksu Arıtma Tesislerinde İşletme Sorunları ve Çözümleri, Ankara

Pan, D., Hong, W., & Kong, F. (2020). Efficiency evaluation of urban wastewater treatment: Evidence from 113 cities in the Yangtze River Economic Belt of China. Journal of Environmental Management, 270, 110940.

Saghafi, S., Ebrahimi, A., Mehrdadi, N., & Nabi Bidhendy, G. (2020). Energy-Efficiency Index in Industrial Wastewater Treatment Plants Using Data-Envelopment Analysis. Journal of Environmental Engineering, 146(2), 04019112.

Sala-Garrido, R., Hernández-Sancho, F., & Molinos-Senante, M. (2012). Assessing the efficiency of wastewater treatment plants in an uncertain context: a DEA with tolerances approach. Environmental Science & Policy, 18, 34-44.

Sala-Garrido, R., Molinos-Senante, M., & Hernández-Sancho, F. (2011). Comparing the efficiency of wastewater treatment technologies through a DEA metafrontier model. Chemical Engineering Journal, 173(3), 766-772.

Sarraf, F., & Nejad, S. H. (2020). Improving performance evaluation based on balanced scorecard with grey relational analysis and data envelopment analysis approaches: Case study in water and wastewater companies. Evaluation and program planning, 79, 101762.

T.C. Çevre ve Şehircilik Bakanlığı (2010). Atıksu Arıtımında Enerji Verimliliği Rehberi. Erişim Adresi: https://webdosya.csb.gov.tr/db/cygm/editordosya/aaevrehberi.pdf, Ankara

T.C. Çevre, Şehircilik ve İklim Değişikliği Bakanlığı. Sık Sorulan Sorular, Su ve Toprak Yönetimi. (27.12.2021) Erişim Adresi: https://cygm.csb.gov.tr/sss/su-ve-toprak-yonetimi

T.C. Orman ve Su İşleri Bakanlığı (2013). Atıksu Arıtma Tesisleri Tasarım Rehberi. Erişim Adresi: https://www.tarimorman.gov.tr/SYGM/Belgeler/ar%C4%B1tma%20norm%20rehberi/AAT%20Tasar%C4%B1m%20Rehberi%20(1).pdf

TÜBİTAK, Marmara Araştırma Merkezi, Çevre ve Temiz Üretim Enstitüsü (2018). Enerji Verimli ve Enerji Pozitif Atıksu Arıtma Tesislerinin Geliştirilmesi Projesi Cilt 1 (5178602)

TÜBİTAK, Marmara Araştırma Merkezi, Çevre ve Temiz Üretim Enstitüsü (2018). Enerji Verimli ve Enerji Pozitif Atıksu Arıtma Tesislerinin Geliştirilmesi Projesi Cilt 2 (5178602)

Türkiye İstatistik Kurumu (TUİK) (2022). İstatistikler, Çevre ve Enerji, İstatistiksel Tablolar. (06.01.2022) Erişim Adresi: https://data.tuik.gov.tr/Kategori/GetKategori?p=cevre-ve-enerji-103&dil=1

Wang, S., Qiu, S., Ge, S., Liu, J., & Peng, Z. (2018). Benchmarking Toronto wastewater treatment plants using DEA window and Tobit regression analysis with a dynamic efficiency perspective. Environmental Science and Pollution Research, 25(32), 32649-32659.

Wu, G., Hong, J., Li, D., & Wu, Z. (2019). Efficiency assessment of pollutants discharged in urban wastewater treatment: evidence from 68 key cities in China. Journal of cleaner production, 233, 1437-1450.

Wu, G., Miao, Z., Shao, S., Jiang, K., Geng, Y., Li, D., & Liu, H. (2018). Evaluating the construction efficiencies of urban wastewater transportation and treatment capacity: evidence from 70 megacities in China. Resources, Conservation and Recycling, 128, 373-381.

Zeng, S., Chen, X., Dong, X., & Liu, Y. (2017). Efficiency assessment of urban wastewater treatment plants in China: Considering greenhouse gas emissions. Resources, Conservation and Recycling, 120, 157-165.

Zhang, R., Lu, C. C., Lee, J. H., Feng, Y., & Chiu, Y. H. (2019). Dynamic environmental efficiency assessment of industrial water pollution. Sustainability, 11(11), 3053.

Zhou, X., Luo, R., Yao, L., Cao, S., Wang, S., & Lev, B. (2018). Assessing integrated water use and wastewater treatment systems in China: A mixed network structure two-stage SBM DEA model. Journal of cleaner production, 185, 533-546.

Zolfani, S. H., Yazdani, M., & Zavadskas, E. K. (2018). An extended stepwise weight assessment ratio analysis (SWARA) method for improving criteria prioritization process. Soft Computing, 22(22), 7399-7405.

APPENDICES

Appendix A.

			Total Waste Water Treatment Capacity		Electricity Consumption		Amount of Wastewater Treated		Amount of Wastewater Recycled		Capacity Utilization Rate	
#	Type	Year	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
WWTP 1	Advanced	2012	146,000,000	146,000,000	63,038,411	67,436,930	131,430,406	136,638,994	2,414,619	2,433,881	90%	94%
WWTP 2	Advanced	2010	219,000,000	219,000,000	67,628,904	90,380,165	143,772,232	148,442,855	2,641,361	2,644,137	66%	68%
WWTP 3	Advanced	2000	631,450	631,450	101,280	96,870	524,160	595,280	9,630	10,603	83%	94%
WWTP 4	Advanced	2016	18,980,000	18,980,000	3,614,505	4,299,701	4,887,513	6,276,849	89,793	111,806	26%	33%
WWTP 5	Advanced	2016	13,322,500	13,322,500	3,942,457	4,162,599	7,749,895	7,689,036	142,380	136,961	58%	58%
WWTP 6	Advanced	2016	48,362,500	48,362,500	12,580,579	12,151,448	28,744,425	27,266,018	528,088	485,676	59%	56%
WWTP 7	Advanced	2016	25,550,000	25,550,000	5,613,785	5,736,177	13,553,975	12,914,343	249,012	230,037	53%	51%
WWTP 8	Biological	2007	1,204,500	1,204,500	252,270	249,326	1,148,648	1,105,881	21,103	19,698	95%	92%
WWTP 9	Biological	2008	146,000	146,000	113,650	105,706	87,976	77,409	1,616	1,379	60%	53%
WWTP 10	Biological	2008	43,800	43,800	16,539	20,983	34,268	29,818	630	531	78%	68%
WWTP 11	Biological	2010	182,500	182,500	147,424	140,534	213,069	178,789	3,914	3,185	117%	98%
WWTP 12	Biological	2010	91,250	91,250	91,158	86,149	71,574	87,892	1,315	1,566	78%	96%
WWTP 13	Biological	2012	91,250	91,250	102,020	136,566	105,254	94,452	1,934	1,682	115%	104%
WWTP 14	Biological	2012	182,500	182,500	84,041	101,978	321,688	244,529	5,910	4,356	176%	134%
WWTP 15	Biological	2010	182,500	182,500	166,763	190,857	223,017	212,204	4,097	3,780	122%	116%
WWTP 16	Biological	2010	182,500	182,500	98,911	109,390	177,098	281,980	3,254	5,023	97%	155%

			Total Waste Water Treatment Capacity		Electricity Consumption		Amount of Wastewater Treated		Amount of Wastewater Recycled		Capacity Utilization Rate	
#	Type	Year	2019	2020	2019	2020	2019	#	Type	Year	2019	2020
WWTP 17	Biological	2011	182,500	182,500	71,668	120,576	124,427	154,121	2,286	2,745	68%	84%
WWTP 18	Biological	2011	91,250	91,250	101,652	100,833	125,217	107,091	2,300	1,908	137%	117%
WWTP 19	Biological	2011	182,500	182,500	107,456	114,408	163,032	155,452	2,995	2,769	89%	85%
WWTP 20	Biological	2010	91,250	91,250	103,669	100,299	60,389	69,327	1,109	1,235	66%	76%
WWTP 21	Biological	2013	365,000	365,000	273,097	273,787	284,082	297,812	5,219	5,305	78%	82%
WWTP 22	Biological	2014	365,000	365,000	123,862	118,860	452,684	260,372	8,317	4,638	124%	71%
WWTP 23	Biological	2014	365,000	365,000	180,948	188,878	194,699	178,714	3,577	3,183	53%	49%
WWTP 24	Biological	2014	730,000	730,000	288,698	335,547	562,035	717,751	10,326	12,785	77%	98%
WWTP 25	Biological	2014	365,000	365,000	208,385	206,172	249,150	279,019	4,577	4,970	68%	76%
WWTP 26	Biological	2014	365,000	365,000	90,254	154,233	361,548	343,132	6,642	6,112	99%	94%
WWTP 27	Biological	2014	730,000	730,000	531,822	449,321	793,505	891,498	14,578	15,880	109%	122%
WWTP 28	Biological	2014	182,500	182,500	187,395	197,195	94,998	95,807	1,745	1,707	52%	52%
WWTP 29	Biological	2014	182,500	182,500	225,951	264,565	117,090	123,487	2,151	2,200	64%	68%
WWTP 30	Biological	2014	182,500	182,500	172,826	148,544	241,834	215,962	4,443	3,847	133%	118%
WWTP 31	Biological	2018	365,000	365,000	204,262	159,631	237,889	272,426	4,370	4,853	65%	75%
WWTP 32	Biological	2018	292,000	292,000	150,703	164,792	163,274	130,225	3,000	2,320	56%	45%
WWTP 33	Biological	2019	146,000	146,000	87,960	72,505	100,779	99,002	1,851	1,763	69%	68%
WWTP 34	Biological	2014	182,500	182,500	217,562	175,526	262,732	214,711	4,827	3,825	144%	118%
WWTP 35	Biological	2014	182,500	182,500	110,080	134,188	236,669	272,874	4,348	4,861	130%	150%
WWTP 36	Biological	2014	182,500	182,500	63,675	100,947	139,297	89,072	2,559	1,587	76%	49%
WWTP 37	Biological	2014	182,500	182,500	70,004	85,590	100,086	67,091	1,839	1,195	55%	37%
WWTP 38	Biological	2016	1,460,000	1,460,000	123,871	161,986	485,554	574,538	8,921	10,234	33%	39%
WWTP 39	Biological	2016	365,000	365,000	66,597	138,809	281,255	269,076	5,167	4,793	77%	74%
WWTP 40	Biological	2016	365,000	365,000	104,379	132,724	410,864	369,077	7,548	6,574	113%	101%
WWTP 41	Biological	2016	182,500	182,500	100,352	102,878	77,416	71,780	1,422	1,279	42%	39%
WWTP 42	Biological	2016	182,500	182,500	153,020	166,920	189,349	203,560	3,479	3,626	104%	112%
WWTP 43	Biological	2016	182,500	182,500	102,938	106,989	60,395	47,387	1,110	844	33%	26%
WWTP 44	Biological	2016	182,500	182,500	112,566	146,654	162,585	188,354	2,987	3,355	89%	103%
WWTP 45	Biological	2016	182,500	182,500	234,782	242,862	277,788	376,252	5,103	6,702	152%	206%
WWTP 46	Biological	2016	182,500	182,500	104,207	108,510	157,902	173,603	2,901	3,092	87%	95%

			Total Waste Water Treatment Capacity		Electricity Consumption		Amount of Wastewater Treated		Amount of Wastewater Recycled		Capacity Utilization Rate	
#	Type	Year	2019	2020	2019	2020	2019	#	Type	Year	2019	2020
WWTP 47	Biological	2016	182,500	182,500	90,191	65,201	45,300	39,579	832	705	25%	22%
WWTP 48	Biological	2018	91,250	91,250	48,201	54,163	76,181	73,519	1,400	1,310	83%	81%
WWTP 49	Biological	2018	91,250	91,250	69,832	94,406	84,965	149,968	1,561	2,671	93%	164%
WWTP 50	Biological	2016	182,500	182,500	124,966	154,039	291,689	231,025	5,359	4,115	160%	127%
WWTP 51	Biological	2018	2,190,000	2,190,000	200,744	103,644	1,112,310	115,679	20,435	2,061	51%	5%
WWTP 52	Biological	2018	91,250	91,250	50,657	49,041	117,172	262,232	2,153	4,671	128%	287%
WWTP 53	Physical	1988	315,360,000	315,360,000	23,484,813	20,586,233	238,220,411	208,087,995	4,376,549	3,706,566	76%	66%
WWTP 54	Physical	1997	228,125,000	228,125,000	24,626,570	28,701,219	187,846,059	220,974,791	3,451,079	3,936,112	82%	97%
WWTP 55	Physical	2003	129,210,000	129,210,000	6,850,707	6,593,671	102,564,752	105,258,740	1,884,304	1,874,921	79%	81%
WWTP 56	Advanced	1998	91,250,000	91,250,000	38,138,611	40,504,221	118,077,695	140,412,119	2,169,305	2,501,090	129%	154%
WWTP 57	Advanced	2000	73,000,000	73,000,000	26,937,905	25,863,341	60,303,297	64,237,086	1,107,883	1,144,223	83%	88%
WWTP 58	Biological	2016	91,250	91,250	66,424	50,946	192,299	279,483	3,533	4,978	211%	306%
WWTP 59	Biological	2013	91,250	91,250	109,890	63,163	249,007	191,805	4,575	3,417	273%	210%
WWTP 60	Biological	2013	91,250	91,250	58,792	61,681	106,350	107,404	1,954	1,913	117%	118%
WWTP 61	Biological	2013	91,250	91,250	72,055	80,271	126,809	103,074	2,330	1,836	139%	113%
WWTP 62	Biological	2013	182,500	182,500	120,378	136,017	151,251	144,996	2,779	2,583	83%	79%
WWTP 63	Biological	2013	91,250	91,250	69,101	60,638	206,790	216,618	3,799	3,859	227%	237%
WWTP 64	Biological	2013	182,500	182,500	149,937	151,329	173,235	192,679	3,183	3,432	95%	106%
WWTP 65	Biological	2013	91,250	91,250	77,565	64,642	162,945	168,937	2,994	3,009	179%	185%
WWTP 66	Biological	2013	182,500	182,500	96,840	93,293	148,706	160,299	2,732	2,855	81%	88%
WWTP 67	Biological	2013	91,250	91,250	73,774	58,171	76,764	71,662	1,410	1,276	84%	79%
WWTP 68	Biological	2013	91,250	91,250	41,572	64,513	174,601	270,765	3,208	4,823	191%	297%
WWTP 69	Biological	2008	182,500	182,500	96,646	108,950	133,883	122,816	2,460	2,188	73%	67%
WWTP 70	Advanced	2010	1,460,000	1,460,000	650,965	737,663	976,867	909,022	17,947	16,192	67%	62%
WWTP 71	Biological	2008	45,625	45,625	46,231	50,590	103,552	96,365	1,902	1,717	227%	211%
WWTP 72	Biological	2011	182,500	182,500	90,756	101,203	261,915	356,415	4,812	6,349	144%	195%
WWTP 73	Biological	2012	91,250	91,250	78,158	111,434	96,753	119,100	1,778	2,121	106%	131%
WWTP 74	Biological	2012	91,250	91,250	88,690	77,572	144,220	123,533	2,650	2,200	158%	135%
WWTP 75	Biological	2012	182,500	182,500	209,084	180,411	186,860	217,760	3,433	3,879	102%	119%
WWTP 76	Biological	2012	182,500	182,500	131,538	146,015	502,867	674,742	9,239	12,019	276%	370%

			Total Waste Water Treatment Capacity		**Electricity Consumption**		**Amount of Wastewater Treated**		**Amount of Wastewater Recycled**		**Capacity Utilization Rate**	
#	**Type**	**Year**	**2019**	**2020**	**2019**	**2020**	**2019**	**#**	**Type**	**Year**	**2019**	**2020**
WWTP 77	Biological	2008	73,000	73,000	22,303	25,617	66,441	77,320	1,221	1,377	91%	106%
WWTP 78	Biological	2010	73,000	73,000	22,823	22,182	52,041	35,501	956	632	71%	49%
WWTP 79	Natural	2009	45,625	45,625	22,009	21,652	61,340	59,339	1,127	1,057	134%	130%
WWTP 80	Biological	2017	91,250	91,250	45,377	43,671	136,132	69,390	2,501	1,236	149%	76%
WWTP 81	Physical	2004	233,600,000	233,600,000	2,805,262	3,087,109	91,083,394	90,767,720	1,673,370	1,616,799	39%	39%
WWTP 82	Physical	2008	16,790,000	16,790,000	1,019,835	1,098,949	6,567,727	6,843,794	120,661	121,905	39%	41%
WWTP 83	Physical	2003	304,045,000	304,045,000	24,037,234	19,745,750	191,579,888	170,169,626	3,519,676	3,031,145	63%	56%
WWTP 84	Physical	1992	28,382,400	28,382,400	817,208	907,340	11,911,912	13,503,429	218,844	240,530	42%	48%
WWTP 85	Physical	2009	209,875,000	209,875,000	2,730,734	2,470,397	26,702,666	20,112,042	490,577	358,246	13%	10%

Appendix B.

	Total Waste Water Treatment Capacity	Electricity Consumption	Amount of Wastewater Treated	Amount of Wastewater Recycled	Capacity Utilization Rate
WWTP 1	-	1.686	0.971	0.199	0.971
WWTP 2	-	7.199	0.799	0.026	0.799
WWTP 3	-	1.113	3.177	2.406	3.177
WWTP 4	-	4.329	6.222	5.460	6.222
WWTP 5	-	1.358	0.197	0.970	0.197
WWTP 6	-	0.868	1.320	2.092	1.320
WWTP 7	-	0.539	1.208	1.980	1.208
WWTP 8	-	0.293	0.948	1.721	0.948
WWTP 9	-	1.811	3.195	3.964	3.195
WWTP 10	-	5.922	3.472	4.240	3.472
WWTP 11	-	1.196	4.374	5.140	4.374
WWTP 12	-	1.413	5.116	4.350	5.116
WWTP 13	-	7.240	2.704	3.474	2.704
WWTP 14	-	4.821	6.814	7.571	6.814
WWTP 15	-	3.369	1.242	2.014	1.242
WWTP 16	-	2.515	11.423	10.688	11.423
WWTP 17	-	12.720	5.330	4.565	5.330
WWTP 18	-	0.202	3.901	4.669	3.901
WWTP 19	-	1.567	1.190	1.962	1.190
WWTP 20	-	0.826	3.445	2.675	3.445
WWTP 21	-	0.063	1.180	0.407	1.180
WWTP 22	-	1.030	13.485	14.199	13.485
WWTP 23	-	1.072	2.140	2.911	2.140
WWTP 24	-	3.752	6.084	5.321	6.084
WWTP 25	-	0.267	2.828	2.056	2.828
WWTP 26	-	13.084	1.307	2.079	1.307
WWTP 27	-	4.204	2.908	2.137	2.908
WWTP 28	-	1.274	0.212	0.561	0.212
WWTP 29	-	3.936	1.330	0.557	1.330
WWTP 30	-	3.778	2.826	3.595	2.826
WWTP 31	-	6.132	3.384	2.614	3.384
WWTP 32	-	2.233	5.630	6.392	5.630
WWTP 33	-	4.816	0.445	1.217	0.445
WWTP 34	-	5.347	5.029	5.793	5.029
WWTP 35	-	4.935	3.553	2.783	3.553
WWTP 36	-	11.320	10.996	11.730	10.996

	Total Waste Water Treatment Capacity	Electricity Consumption	Amount of Wastewater Treated	Amount of Wastewater Recycled	Capacity Utilization Rate
WWTP 37	-	5.009	9.868	10.609	9.868
WWTP 38	-	6.667	4.197	3.429	4.197
WWTP 39	-	17.578	1.107	1.879	1.107
WWTP 40	-	5.977	2.679	3.449	2.679
WWTP 41	-	0.621	1.889	2.660	1.889
WWTP 42	-	2.172	1.808	1.036	1.808
WWTP 43	-	0.965	6.034	6.795	6.034
WWTP 44	-	6.575	3.671	2.902	3.671
WWTP 45	-	0.846	7.527	6.770	7.527
WWTP 46	-	1.011	2.368	1.596	2.368
WWTP 47	-	8.041	3.370	4.139	3.370
WWTP 48	-	2.912	0.889	1.662	0.889
WWTP 49	-	7.481	13.834	13.118	13.834
WWTP 50	-	5.210	5.803	6.564	5.803
WWTP 51	-	15.950	40.580	40.840	40.580
WWTP 52	-	0.810	19.117	18.453	19.117
WWTP 53	-	3.289	3.376	4.144	3.376
WWTP 54	-	3.820	4.052	3.283	4.052
WWTP 55	-	0.956	0.648	0.125	0.648
WWTP 56	-	1.504	4.320	3.552	4.320
WWTP 57	-	1.018	1.579	0.807	1.579
WWTP 58	-	6.594	9.240	8.491	9.240
WWTP 59	-	13.501	6.488	7.247	6.488
WWTP 60	-	1.199	0.247	0.526	0.247
WWTP 61	-	2.697	5.162	5.926	5.162
WWTP 62	-	3.050	1.056	1.828	1.056
WWTP 63	-	3.262	1.161	0.388	1.161
WWTP 64	-	0.231	2.657	1.886	2.657
WWTP 65	-	4.544	0.903	0.130	0.903
WWTP 66	-	0.933	1.876	1.104	1.876
WWTP 67	-	5.913	1.719	2.490	1.719
WWTP 68	-	10.813	10.796	10.057	10.796
WWTP 69	-	2.992	2.156	2.927	2.156
WWTP 70	-	3.122	1.799	2.570	1.799
WWTP 71	-	2.251	1.797	2.569	1.797
WWTP 72	-	2.721	7.642	6.885	7.642
WWTP 73	-	8.776	5.176	4.411	5.176
WWTP 74	-	3.344	3.863	4.630	3.863
WWTP 75	-	3.681	3.818	3.049	3.818

	Total Waste Water Treatment Capacity	Electricity Consumption	Amount of Wastewater Treated	Amount of Wastewater Recycled	Capacity Utilization Rate
WWTP 76	-	2.608	7.298	6.539	7.298
WWTP 77	-	3.458	3.784	3.014	3.784
WWTP 78	-	0.712	9.447	10.190	9.447
WWTP 79	-	0.409	0.829	1.602	0.829
WWTP 80	-	0.958	16.237	16.925	16.237
WWTP 81	-	2.392	0.087	0.860	0.087
WWTP 82	-	1.867	1.029	0.256	1.029
WWTP 83	-	4.901	2.959	3.729	2.959
WWTP 84	-	2.613	3.131	2.360	3.131
WWTP 85	-	2.503	7.039	7.795	7.039
Mean	**-**	**3.867**	**4.571**	**4.620**	**4.571**

Appendix C.

	Total Waste Water Treatment Capacity			Electricity Consumption			Amount of Wastewater Treated			Amount of Wastewater Recycled			Capacity Utilization Rate		
	Lower	Original	Upper	Lower	Original	Upper	Lower	Original	Upper	Lower	Original	Upper	Lower	Original	Upper
WWTP 1	146,000,000	146,000,000	146,000,000	62,715,006	65,237,671	67,760,335	127,908,566	134,034,700	140,160,834	2,312,246	2,424,250	2,536,254	88%	92%	96%
WWTP 2	219,000,000	219,000,000	219,000,000	75,949,521	79,004,535	82,059,548	139,429,613	146,107,544	152,785,474	2,520,651	2,642,749	2,764,848	64%	67%	70%
WWTP 3	631,450	631,450	631,450	95,244	99,075	102,906	534,138	559,720	585,302	9,649	10,117	10,584	85%	89%	93%
WWTP 4	18,980,000	18,980,000	18,980,000	3,804,086	3,957,103	4,110,120	5,327,044	5,582,181	5,837,318	96,142	100,799	105,457	28%	29%	31%
WWTP 5	13,322,500	13,322,500	13,322,500	3,895,821	4,052,528	4,209,235	7,366,643	7,719,466	8,072,288	133,217	139,670	146,123	55%	58%	61%
WWTP 6	48,362,500	48,362,500	48,362,500	11,887,834	12,366,014	12,844,193	26,725,227	28,005,222	29,285,216	483,463	506,882	530,301	55%	58%	61%
WWTP 7	25,550,000	25,550,000	25,550,000	5,455,536	5,674,981	5,894,426	12,629,284	13,234,159	13,839,034	228,458	239,524	250,590	49%	52%	54%
WWTP 8	1,204,500	1,204,500	1,204,500	241,100	250,798	260,496	1,075,742	1,127,265	1,178,787	19,458	20,401	21,343	89%	94%	98%
WWTP 9	146,000	146,000	146,000	105,437	109,678	113,919	78,913	82,693	86,472	1,428	1,498	1,567	54%	57%	59%
WWTP 10	43,800	43,800	43,800	18,036	18,761	19,486	30,578	32,043	33,508	554	580	607	70%	73%	77%
WWTP 11	182,500	182,500	182,500	138,411	143,979	149,547	186,974	195,929	204,884	3,386	3,550	3,714	102%	107%	112%
WWTP 12	91,250	91,250	91,250	85,225	88,654	92,082	76,089	79,733	83,377	1,374	1,440	1,507	83%	87%	91%
WWTP 13	91,250	91,250	91,250	114,680	119,293	123,906	95,289	99,853	104,417	1,725	1,808	1,892	104%	109%	114%
WWTP 14	182,500	182,500	182,500	89,413	93,010	96,606	270,169	283,109	296,048	4,896	5,133	5,370	148%	155%	162%
WWTP 15	182,500	182,500	182,500	171,896	178,810	185,724	207,664	217,611	227,557	3,757	3,939	4,121	114%	119%	125%
WWTP 16	182,500	182,500	182,500	100,123	104,151	108,178	219,048	229,539	240,030	3,947	4,138	4,329	120%	126%	132%
WWTP 17	182,500	182,500	182,500	92,405	96,122	99,839	132,908	139,274	145,640	2,399	2,516	2,632	73%	76%	80%
WWTP 18	91,250	91,250	91,250	97,328	101,243	105,157	110,845	116,154	121,463	2,007	2,104	2,201	121%	127%	133%
WWTP 19	182,500	182,500	182,500	106,642	110,932	115,222	151,964	159,242	166,520	2,749	2,882	3,015	83%	87%	91%
WWTP 20	91,250	91,250	91,250	98,040	101,984	105,928	61,894	64,858	67,822	1,118	1,172	1,226	68%	71%	74%
WWTP 21	365,000	365,000	365,000	262,868	273,442	284,016	277,649	290,947	304,245	5,019	5,262	5,505	76%	80%	83%
WWTP 22	365,000	365,000	365,000	116,668	121,361	126,054	340,233	356,528	372,823	6,178	6,477	6,777	93%	98%	102%
WWTP 23	365,000	365,000	365,000	177,763	184,913	192,063	178,173	186,707	195,240	3,224	3,380	3,536	49%	51%	53%
WWTP 24	730,000	730,000	730,000	300,053	312,123	324,192	610,646	639,893	669,140	11,021	11,555	12,089	84%	88%	92%

	Total Waste Water Treatment Capacity			Electricity Consumption			Amount of Wastewater Treated			Amount of Wastewater Recycled			Capacity Utilization Rate		
	Lower	Original	Upper	Lower	Original	Upper	Lower	Original	Upper	Lower	Original	Upper	Lower	Original	Upper
WWTP 25	365,000	365,000	365,000	199,263	207,279	215,294	252,014	264,085	276,155	4,553	4,774	4,994	69%	72%	76%
WWTP 26	365,000	365,000	365,000	117,516	122,244	126,971	336,236	352,340	368,444	6,083	6,377	6,672	92%	97%	101%
WWTP 27	730,000	730,000	730,000	471,602	490,572	509,541	803,994	842,502	881,009	14,525	15,229	15,933	110%	115%	121%
WWTP 28	182,500	182,500	182,500	184,859	192,295	199,731	91,042	95,403	99,763	1,646	1,726	1,806	50%	52%	55%
WWTP 29	182,500	182,500	182,500	235,774	245,258	254,742	114,791	120,289	125,786	2,075	2,175	2,276	63%	66%	69%
WWTP 30	182,500	182,500	182,500	154,471	160,685	166,899	218,436	228,898	239,360	3,953	4,145	4,336	120%	125%	131%
WWTP 31	365,000	365,000	365,000	174,911	181,947	188,982	243,495	255,158	266,820	4,398	4,612	4,825	67%	70%	73%
WWTP 32	292,000	292,000	292,000	151,648	157,748	163,847	140,042	146,750	153,457	2,537	2,660	2,783	48%	50%	53%
WWTP 33	146,000	146,000	146,000	77,130	80,233	83,335	95,325	99,891	104,456	1,724	1,807	1,891	65%	68%	72%
WWTP 34	182,500	182,500	182,500	188,944	196,544	204,144	227,811	238,722	249,632	4,126	4,326	4,526	125%	131%	137%
WWTP 35	182,500	182,500	182,500	117,411	122,134	126,857	243,127	254,772	266,416	4,392	4,604	4,817	133%	140%	146%
WWTP 36	182,500	182,500	182,500	79,128	82,311	85,494	108,966	114,185	119,403	1,977	2,073	2,169	60%	63%	65%
WWTP 37	182,500	182,500	182,500	74,789	77,797	80,805	79,768	83,589	87,409	1,447	1,517	1,587	44%	46%	48%
WWTP 38	1,460,000	1,460,000	1,460,000	137,402	142,929	148,455	505,820	530,046	554,272	9,135	9,577	10,020	35%	36%	38%
WWTP 39	365,000	365,000	365,000	98,732	102,703	106,674	262,589	275,166	287,742	4,750	4,980	5,210	72%	75%	79%
WWTP 40	365,000	365,000	365,000	113,967	118,552	123,136	372,147	389,971	407,794	6,735	7,061	7,387	102%	107%	112%
WWTP 41	182,500	182,500	182,500	97,686	101,615	105,544	71,188	74,598	78,008	1,288	1,350	1,413	39%	41%	43%
WWTP 42	182,500	182,500	182,500	153,784	159,970	166,156	187,475	196,455	205,434	3,388	3,552	3,716	103%	108%	113%
WWTP 43	182,500	182,500	182,500	100,905	104,964	109,022	51,428	53,891	56,354	932	977	1,022	28%	30%	31%
WWTP 44	182,500	182,500	182,500	124,598	129,610	134,622	167,450	175,470	183,489	3,025	3,171	3,318	92%	96%	101%
WWTP 45	182,500	182,500	182,500	229,587	238,822	248,057	312,073	327,020	341,967	5,630	5,903	6,175	171%	179%	187%
WWTP 46	182,500	182,500	182,500	102,246	106,359	110,471	158,177	165,753	173,328	2,858	2,997	3,135	87%	91%	95%
WWTP 47	182,500	182,500	182,500	74,692	77,696	80,700	40,500	42,440	44,379	733	769	804	22%	23%	24%
WWTP 48	91,250	91,250	91,250	49,203	51,182	53,161	71,429	74,850	78,271	1,292	1,355	1,417	78%	82%	86%
WWTP 49	91,250	91,250	91,250	78,944	82,119	85,294	112,098	117,467	122,835	2,018	2,116	2,214	123%	129%	135%
WWTP 50	182,500	182,500	182,500	134,108	139,503	144,897	249,412	261,357	273,302	4,518	4,737	4,956	137%	143%	150%
WWTP 51	2,190,000	2,190,000	2,190,000	146,309	152,194	158,079	585,932	613,995	642,057	10,728	11,248	11,768	27%	28%	29%
WWTP 52	91,250	91,250	91,250	47,921	49,849	51,777	181,032	189,702	198,372	3,254	3,412	3,569	198%	208%	217%
WWTP 53	315,360,000	315,360,000	315,360,000	21,183,435	22,035,523	22,887,611	212,954,811	223,154,203	233,353,595	3,854,832	4,041,557	4,228,283	68%	71%	74%

	Total Waste Water Treatment Capacity			Electricity Consumption			Amount of Wastewater Treated			Amount of Wastewater Recycled			Capacity Utilization Rate		
	Lower	Original	Upper	Lower	Original	Upper	Lower	Original	Upper	Lower	Original	Upper	Lower	Original	Upper
WWTP 54	228,125,000	228,125,000	228,125,000	25,632,833	26,663,895	27,694,956	195,067,728	204,410,425	213,753,122	3,522,946	3,693,595	3,864,245	86%	90%	94%
WWTP 55	129,210,000	129,210,000	129,210,000	6,462,250	6,722,189	6,982,128	99,162,399	103,911,746	108,661,093	1,792,772	1,879,612	1,966,453	77%	80%	84%
WWTP 56	91,250,000	91,250,000	91,250,000	37,800,903	39,321,416	40,841,929	123,337,694	129,244,907	135,152,120	2,227,308	2,335,198	2,443,087	135%	142%	148%
WWTP 57	73,000,000	73,000,000	73,000,000	25,379,742	26,400,623	27,421,504	59,424,096	62,270,192	65,116,287	1,074,028	1,126,053	1,178,078	81%	85%	89%
WWTP 58	91,250	91,250	91,250	56,416	58,685	60,954	225,109	235,891	246,673	4,059	4,256	4,452	247%	259%	270%
WWTP 59	91,250	91,250	91,250	83,181	86,527	89,872	210,332	220,406	230,480	3,811	3,996	4,180	231%	242%	253%
WWTP 60	91,250	91,250	91,250	57,907	60,237	62,566	101,992	106,877	111,762	1,844	1,933	2,023	112%	117%	122%
WWTP 61	91,250	91,250	91,250	73,218	76,163	79,108	109,688	114,942	120,195	1,987	2,083	2,179	120%	126%	132%
WWTP 62	182,500	182,500	182,500	123,240	128,198	133,155	141,353	148,124	154,894	2,557	2,681	2,805	77%	81%	85%
WWTP 63	91,250	91,250	91,250	62,361	64,870	67,378	202,028	211,704	221,380	3,652	3,829	4,006	221%	232%	243%
WWTP 64	182,500	182,500	182,500	144,808	150,633	156,458	174,595	182,957	191,319	3,155	3,307	3,460	96%	100%	105%
WWTP 65	91,250	91,250	91,250	68,354	71,104	73,853	158,357	165,941	173,525	2,863	3,001	3,140	174%	182%	190%
WWTP 66	182,500	182,500	182,500	91,390	95,067	98,743	147,441	154,503	161,564	2,665	2,794	2,923	81%	85%	89%
WWTP 67	91,250	91,250	91,250	63,421	65,973	68,524	70,821	74,213	77,605	1,281	1,343	1,405	78%	81%	85%
WWTP 68	91,250	91,250	91,250	50,991	53,043	55,094	212,505	222,683	232,861	3,830	4,015	4,201	233%	244%	255%
WWTP 69	182,500	182,500	182,500	98,823	102,798	106,773	122,483	128,350	134,216	2,216	2,324	2,431	67%	70%	74%
WWTP 70	1,460,000	1,460,000	1,460,000	667,466	694,314	721,162	899,847	942,945	986,042	16,281	17,069	17,858	62%	65%	68%
WWTP 71	45,625	45,625	45,625	46,539	48,411	50,282	95,390	99,959	104,527	1,726	1,809	1,893	209%	219%	229%
WWTP 72	182,500	182,500	182,500	92,268	95,980	99,691	295,034	309,165	323,296	5,322	5,580	5,838	162%	169%	177%
WWTP 73	91,250	91,250	91,250	91,130	94,796	98,462	102,994	107,927	112,859	1,859	1,949	2,040	113%	118%	124%
WWTP 74	91,250	91,250	91,250	79,916	83,131	86,346	127,758	133,877	139,995	2,313	2,425	2,537	140%	147%	153%
WWTP 75	182,500	182,500	182,500	187,217	194,748	202,278	193,063	202,310	211,557	3,487	3,656	3,825	106%	111%	116%
WWTP 76	182,500	182,500	182,500	133,410	138,777	144,143	561,893	588,805	615,716	10,138	10,629	11,120	308%	323%	337%
WWTP 77	73,000	73,000	73,000	23,033	23,960	24,887	68,595	71,881	75,166	1,239	1,299	1,359	94%	98%	103%
WWTP 78	73,000	73,000	73,000	21,632	22,503	23,373	41,770	43,771	45,772	758	794	831	57%	60%	63%
WWTP 79	45,625	45,625	45,625	20,986	21,831	22,675	57,582	60,340	63,097	1,042	1,092	1,142	126%	132%	138%
WWTP 80	91,250	91,250	91,250	42,802	44,524	46,246	98,064	102,761	107,458	1,782	1,869	1,955	107%	113%	118%
WWTP 81	233,600,000	233,600,000	233,600,000	2,832,260	2,946,186	3,060,111	86,769,752	90,925,557	95,081,362	1,569,080	1,645,085	1,721,090	37%	39%	41%
WWTP 82	16,790,000	16,790,000	16,790,000	1,018,427	1,059,392	1,100,357	6,399,270	6,705,761	7,012,251	115,680	121,283	126,887	38%	40%	42%

	Total Waste Water Treatment Capacity			Electricity Consumption			Amount of Wastewater Treated			Amount of Wastewater Recycled			Capacity Utilization Rate		
	Lower	**Original**	**Upper**	**Lower**	**Original**	**Upper**	**Lower**	**Original**	**Upper**	**Lower**	**Original**	**Upper**	**Lower**	**Original**	**Upper**
WWTP 83	304,045,000	304,045,000	304,045,000	21,044,974	21,891,492	22,738,010	172,607,771	180,874,757	189,141,743	3,124,082	3,275,411	3,426,739	57%	59%	62%
WWTP 84	28,382,400	28,382,400	28,382,400	828,931	862,274	895,617	12,126,859	12,707,671	13,288,482	219,075	229,687	240,299	43%	45%	47%
WWTP 85	209,875,000	209,875,000	209,875,000	2,500,005	2,600,566	2,701,126	22,337,507	23,407,354	24,477,201	404,803	424,411	444,020	11%	11%	12%
Total	2,119,795,900	2,119,795,900	2,119,795,900	317,100,936	329,856,086	342,611,236	1,324,915,671	1,388,372,020	1,451,828,368	23,956,256	25,116,682	26,277,107	-	-	-
Average	24,938,775	24,938,775	24,938,775	3,730,599	3,880,660	4,030,720	15,587,243	16,333,788	17,080,334	281,838	295,490	309,142	96%	101%	105%

Appendix D.

	Original	Mean	Max	Min	Amplitude (max-min) (%)	Amplitude (original-mean) (%)
WWTP 1	0.427	0.428	0.494	0.368	12.6%	-0.1%
WWTP 2	0.359	0.360	0.415	0.311	10.4%	-0.1%
WWTP 3	0.762	0.764	0.866	0.671	19.5%	-0.1%
WWTP 4	0.220	0.220	0.251	0.192	5.8%	0.0%
WWTP 5	0.348	0.349	0.401	0.302	9.8%	-0.1%
WWTP 6	0.387	0.387	0.443	0.337	10.7%	-0.1%
WWTP 7	0.374	0.375	0.428	0.327	10.1%	-0.1%
WWTP 8	0.700	0.701	0.800	0.612	18.8%	-0.1%
WWTP 9	0.185	0.186	0.211	0.167	4.4%	-0.1%
WWTP 10	1.000	1.000	1.000	1.000	0.0%	0.0%
WWTP 11	0.342	0.345	0.396	0.305	9.1%	-0.3%
WWTP 12	0.313	0.314	0.344	0.286	5.8%	0.0%
WWTP 13	0.393	0.394	0.431	0.359	7.3%	-0.1%
WWTP 14	0.663	0.664	0.770	0.569	20.1%	-0.1%
WWTP 15	0.451	0.453	0.536	0.383	15.3%	-0.2%
WWTP 16	0.491	0.492	0.571	0.421	14.9%	-0.1%
WWTP 17	0.317	0.317	0.368	0.272	9.6%	-0.1%
WWTP 18	0.458	0.458	0.502	0.417	8.4%	-0.1%
WWTP 19	0.325	0.325	0.378	0.278	10.0%	-0.1%
WWTP 20	0.255	0.255	0.280	0.233	4.7%	0.0%
WWTP 21	0.251	0.255	0.292	0.228	6.4%	-0.5%
WWTP 22	0.557	0.558	0.642	0.483	15.9%	-0.1%
WWTP 23	0.217	0.218	0.252	0.187	6.5%	0.0%
WWTP 24	0.420	0.421	0.486	0.363	12.3%	-0.1%
WWTP 25	0.282	0.283	0.328	0.242	8.5%	-0.1%
WWTP 26	0.546	0.547	0.629	0.473	15.6%	-0.1%
WWTP 27	0.395	0.396	0.460	0.339	12.2%	-0.1%
WWTP 28	0.213	0.209	0.257	0.148	10.9%	0.4%
WWTP 29	0.044	0.267	0.396	0.187	20.9%	-22.3%
WWTP 30	0.432	0.434	0.506	0.372	13.4%	-0.2%
WWTP 31	0.300	0.301	0.348	0.259	9.0%	-0.1%
WWTP 32	0.204	0.204	0.237	0.175	6.1%	0.0%
WWTP 33	0.280	0.281	0.326	0.240	8.5%	-0.1%
WWTP 34	0.548	0.551	0.663	0.459	20.4%	-0.3%
WWTP 35	0.481	0.482	0.561	0.412	14.9%	-0.1%
WWTP 36	0.293	0.294	0.340	0.252	8.8%	-0.1%
WWTP 37	0.610	0.224	0.259	0.193	6.7%	38.6%

	Original	Mean	Max	Min	Amplitude (max-min) (%)	Amplitude (original-mean) (%)
WWTP 38	0.378	0.378	0.425	0.335	9.0%	-0.1%
WWTP 39	0.476	0.476	0.546	0.413	13.3%	-0.1%
WWTP 40	0.617	0.618	0.710	0.535	17.5%	-0.1%
WWTP 41	0.163	0.163	0.190	0.140	5.0%	0.0%
WWTP 42	0.369	0.370	0.432	0.318	11.4%	-0.1%
WWTP 43	0.115	0.115	0.134	0.099	3.5%	0.0%
WWTP 44	0.315	0.317	0.368	0.274	9.5%	-0.1%
WWTP 45	1.000	1.000	1.000	1.000	0.0%	0.0%
WWTP 46	0.349	0.350	0.406	0.299	10.7%	-0.1%
WWTP 47	0.113	0.114	0.131	0.098	3.4%	0.0%
WWTP 48	0.348	0.350	0.410	0.300	11.0%	-0.2%
WWTP 49	0.462	0.464	0.514	0.421	9.3%	-0.2%
WWTP 50	0.444	0.457	0.518	0.405	11.4%	-1.3%
WWTP 51	0.329	0.337	1.000	0.293	70.7%	-0.8%
WWTP 52	0.903	0.903	1.000	0.771	22.9%	-0.1%
WWTP 53	0.819	0.820	0.917	0.730	18.7%	-0.1%
WWTP 54	0.873	0.875	0.986	0.773	21.3%	-0.1%
WWTP 55	1.000	1.000	1.000	1.000	0.0%	0.0%
WWTP 56	0.675	0.676	0.781	0.583	19.8%	-0.1%
WWTP 57	0.458	0.459	0.529	0.397	13.2%	-0.1%
WWTP 58	1.000	0.990	1.000	0.918	8.2%	1.0%
WWTP 59	0.869	0.870	0.955	0.792	16.3%	-0.2%
WWTP 60	0.451	0.454	0.513	0.405	10.8%	-0.2%
WWTP 61	0.460	0.461	0.514	0.413	10.1%	-0.1%
WWTP 62	0.269	0.270	0.314	0.230	8.4%	-0.1%
WWTP 63	0.880	0.881	0.981	0.788	19.3%	-0.1%
WWTP 64	0.328	0.329	0.382	0.283	9.9%	-0.1%
WWTP 65	0.675	0.676	0.754	0.604	15.0%	-0.1%
WWTP 66	0.355	0.355	0.413	0.305	10.8%	-0.1%
WWTP 67	0.307	0.308	0.343	0.275	6.8%	0.0%
WWTP 68	1.000	0.987	1.000	0.880	12.0%	1.3%
WWTP 69	0.278	0.278	0.323	0.238	8.5%	-0.1%
WWTP 70	0.287	0.288	0.333	0.248	8.6%	-0.1%
WWTP 71	1.000	1.000	1.000	1.000	0.0%	0.0%
WWTP 72	0.704	0.705	0.818	0.605	21.3%	-0.1%
WWTP 73	0.424	0.425	0.465	0.387	7.8%	-0.1%
WWTP 74	0.527	0.529	0.586	0.481	10.5%	-0.2%
WWTP 75	0.458	0.460	0.554	0.384	16.9%	-0.2%
WWTP 76	1.000	1.000	1.000	1.000	0.0%	0.0%

	Original	Mean	Max	Min	Amplitude (max-min) (%)	Amplitude (original-mean) (%)
WWTP 77	0.771	0.773	0.904	0.657	24.8%	-0.2%
WWTP 78	0.497	0.498	0.583	0.423	15.9%	-0.1%
WWTP 79	1.000	1.000	1.000	1.000	0.0%	0.0%
WWTP 80	0.545	0.546	0.641	0.463	17.8%	-0.1%
WWTP 81	1.000	1.000	1.000	1.000	0.0%	0.0%
WWTP 82	0.474	0.475	0.530	0.424	10.6%	-0.1%
WWTP 83	0.683	0.684	0.765	0.609	15.6%	-0.1%
WWTP 84	0.780	0.781	0.892	0.681	21.0%	-0.1%
WWTP 85	1.000	0.761	1.000	0.256	74.4%	23.9%
Mean	**0.507**	**0.503**	**0.570**	**0.444**	**12.6%**	**0.4%**

Appendix E.

	R1	R2
WWTP 10	1.000	-
WWTP 45	1.000	-
WWTP 55	1.000	-
WWTP 71	1.000	-
WWTP 76	1.000	-
WWTP 79	1.000	-
WWTP 81	1.000	-
WWTP 58	0.691	0.966
WWTP 68	0.679	0.961
WWTP 85	0.667	0.284
WWTP 52	0.062	0.897
WWTP 51	0.012	0.329
WWTP 63	0.000	0.881
WWTP 54	0.000	0.875
WWTP 59	0.000	0.870
WWTP 53	0.000	0.820
WWTP 84	0.000	0.781
WWTP 77	0.000	0.772
WWTP 3	0.000	0.763
WWTP 72	0.000	0.705
WWTP 8	0.000	0.701
WWTP 83	0.000	0.684
WWTP 56	0.000	0.676
WWTP 65	0.000	0.676
WWTP 14	0.000	0.664
WWTP 40	0.000	0.618
WWTP 22	0.000	0.558
WWTP 34	0.000	0.551
WWTP 26	0.000	0.547
WWTP 80	0.000	0.546
WWTP 74	0.000	0.529
WWTP 78	0.000	0.498
WWTP 16	0.000	0.492
WWTP 35	0.000	0.482
WWTP 39	0.000	0.476
WWTP 82	0.000	0.475
WWTP 49	0.000	0.464
WWTP 61	0.000	0.461

	R1	R2
WWTP 75	0.000	0.460
WWTP 57	0.000	0.459
WWTP 18	0.000	0.458
WWTP 50	0.000	0.457
WWTP 60	0.000	0.454
WWTP 15	0.000	0.453
WWTP 30	0.000	0.434
WWTP 1	0.000	0.428
WWTP 73	0.000	0.425
WWTP 24	0.000	0.421
WWTP 27	0.000	0.396
WWTP 13	0.000	0.394
WWTP 6	0.000	0.387
WWTP 38	0.000	0.378
WWTP 7	0.000	0.375
WWTP 42	0.000	0.370
WWTP 2	0.000	0.360
WWTP 66	0.000	0.355
WWTP 46	0.000	0.350
WWTP 48	0.000	0.350
WWTP 5	0.000	0.349
WWTP 11	0.000	0.345
WWTP 64	0.000	0.329
WWTP 19	0.000	0.325
WWTP 17	0.000	0.317
WWTP 44	0.000	0.316
WWTP 12	0.000	0.314
WWTP 67	0.000	0.308
WWTP 31	0.000	0.301
WWTP 36	0.000	0.294
WWTP 70	0.000	0.288
WWTP 25	0.000	0.283
WWTP 33	0.000	0.281
WWTP 69	0.000	0.278
WWTP 62	0.000	0.270
WWTP 29	0.000	0.267
WWTP 20	0.000	0.255
WWTP 21	0.000	0.255
WWTP 37	0.000	0.224
WWTP 4	0.000	0.220
WWTP 23	0.000	0.218

	R1	R2
WWTP 28	0.000	0.209
WWTP 32	0.000	0.204
WWTP 9	0.000	0.186
WWTP 41	0.000	0.163
WWTP 43	0.000	0.115
WWTP 47	0.000	0.113

BIOGRAPHICAL SKETCH