Sectoral indices to evaluate the sustainability of wastewater utilities

CÉLIA M.P. GRANJA[1]; ANTÓNIO A.L.S. DUARTE[1]; PAULO J. RAMISIO[1]; RUI A.R. RAMOS[1]
[1]Department of Civil Engineering
University of Minho
Campus de Gualtar, 4710-057 Braga
PORTUGAL
pramisio@civil.uminho.pt http://www.civil.uminho.pt

ISABEL BENTES[2]
[2]Department of Engineering
University of Trás-os-Montes e Alto Douro
Quinta de Prados, 5001-801 Vila Real
PORTUGAL
ibentes@utad.pt

Abstract: - Wastewater systems are a structural part of public utilities and as such are vital to the general well-being, public health, economic activities and environment protection. These services, with the primary objective of protecting the interests of users, shall be governed by principles of universality of access, continuity and quality of service, efficiency, equity and sustainability of price.

The aim of this paper is to contribute for the improvement of the Portuguese performance assessment system, through the development and application of a complementary methodology to define sectoral and global indices of sanitation service performance in order to evaluate the sustainability of a given wastewater utility. This methodology allows a truly quantitative evaluation in which each performance indicator represents a criterion to be considered and judiciously weighted. The sectoral indices are calculated as a weighted linear combination of the normalized scores of each performance indicator, which is one of the most common aggregation procedures available in the context of multicriteria evaluation. The criteria normalization process essentially based on fuzzy sets defined for each indicator. A sensitivity analysis of indices values to different weighting methods was also performed.

Key-Words: - Wastewater utilities management; performance indicators; multicriteria analysis; weighting methods; sustainably indices.

1 Introduction

Environmental sustainability must be linked with an integrated water resources protection policy, in order to mitigate discharges impact effects in receiving waters. Excessive nutrients inputs can lead to the eutrophication of the aquatic ecosystems, which is widely recognized as a major worldwide threat [1]. So, utilization efficiency of energy resources, wastewater quality control, and compliance with parameters discharge standards and final disposal of produced sludge must also be considered in the sustainability analysis of wastewater utilities [2].

Being the sanitation service “market” a natural monopoly, regulation must, mainly, protect the interests of the user, based on a benchmarking strategy that promotes the quality of the sanitation utilities and assuring the balance of the ruling tariffs [3].

The regulatory action must incorporate the utilities' economic and service quality assessment based on a benchmarking strategy, and its public divulging, guaranteeing the equity, indispensability, feasibility, sustainability and cost-effectiveness principles. In Portugal, the regulation task is conducted by ERSAR (Portuguese Authority for the Regulation of Water and Waste), which has defined a specific set of performance indicators to enable the comparison of results between similar utilities (benchmarking). ERSAR’s regulatory strategy goes through two major action plans: the structural regulation of the wastewater sector and the regulation of the operators working in this sector (Fig. 1, [4]). The ERSAR’s assessment system of wastewater utilities performance comprises twenty performance indicators (Table 1), judiciously selected [5].

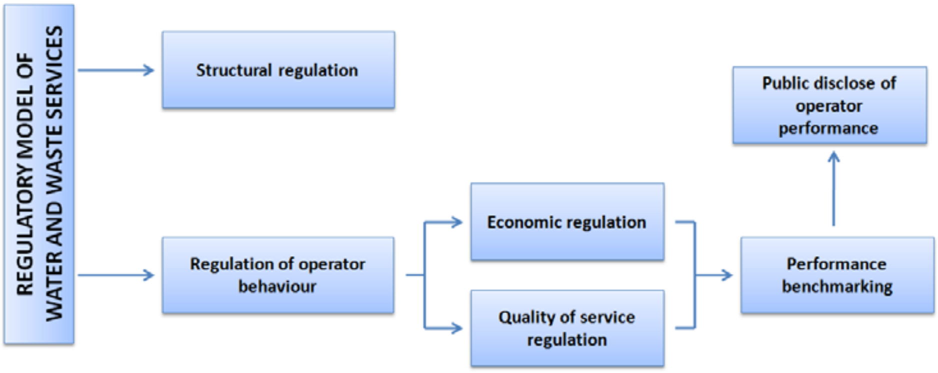


Fig. 1: The Portuguese regulatory model for the water and waste service [4]

Table 1: The ERSAR's Performance Indicators System for wastewater utility

PROTECTION OF THE USER INTERESTS (SI 1)
User service accessibility
AR 01 - Service coverage AR 02 - Average wastewater charges
Quality of service supplied to users
AR 03 – Occurrence of floods AR 04 - Answers to written complaints
SUSTAINABILITY OF THE UTILITY (SI 2)
Utility's economical and financial sustainability
AR 05 - Operating cost coverage ratio AR 06 - Unit running costs AR 07 - Solvency ratio
Utility's infrastructural sustainability
AR 08 - Treatment utilisation AR 09 - Treatment of wastewater collected AR 10 - Pumping of wastewater used in drainage mesh (*) AR 11 - Mains rehabilitation AR 12 - Service connection rehabilitation (*)
Utility's operational sustainability
AR 13 - Obstruction of collectors AR 14 - Failures in groups of electric AR 15 - Structural collapses in collectors
Utility's human resource sustainability
AR 16 – Employees
ENVIRONMENTAL SUSTAINABILITY (SI 3)
AR 17 - Analysis of wastewater held AR 18 - Compliance with the discharge parameters AR 19 - Utilization efficiency of energy resources (*) AR 20 - Final destination of sludge

(*) – Not applicable to the kind of wastewater systems analysed in this work.

The dissemination of all the formation produced (data collection, validation, and processing as well as results discussion for every utility) has been done, on a yearly basis, by the publication of a Performance Assessment Annual Report [6]. So, each wastewater facility knows the evolution over time of the different issues of its own management, which enable the setting up of new efficiency targets in a realistic way. Currently, ERSAR assesses the utility's performance for each indicator, but not an integrated evaluation that allows establishing an overall ranking of utilities.

This work aims to contribute to the improvement of the sustainability assessment of wastewater utilities, through the development of a complementary methodology based on a new application of multicriteria analysis for defining three sectoral indices (SI): (1) protection of user interests; (2) sustainability of the utility; and (3) environmental sustainability.

For a given wastewater utility, a *global index of sanitation service performance* (GISSeP) can then be calculated as a new weighted combination of the normalized scores of each SI. An innovative approach to weights definition [1] was applied, and a sensitivity analysis of different weighting methods on wastewater utilities' ranking positions was performed.

2 Methods

The methodology used in this work for evaluating quality of wastewater service was based upon the application of a multicriteria analysis model [in order to obtain service quality indices, sectoral and global.

These indices are used to quantitatively evaluate the performance of each wastewater service, enabling the possibility of establishing a general ranking order for different analytical scenarios

ISBN: 978-1-61804-088-6

defined as a function of year, indicator weighting method and universe of comparison.

A hierarchical structure was defined based precisely on the referred ERSAR's performance assessment system aiming to use the data sets published by ERSAR as the scores of the criteria (performance indicators) presented by each wastewater utility.

The twenty performance indicators of this assessment system were aggregated into three main sectoral indices: SI 1, considering the service accessibility (AR01 and AR02) and the service quality (AR03 to AR04); SI 2, taking into account economic (AR05 to AR07), infrastructural (AR09 to AR12), operational (AR13 to AR15) and human resources (AR16) performance indicators; and SI 3, assessing how the environmental aspects associated with the utility's activity is being considered.

The work presented herein only analyses the results obtained for a universe in which all utilities were compared considering all indicators, regardless of achieving a rating or not. This universe of comparison implies that a correction is made to the weights assigned when a given indicator (n.a.) is not applicable to an utility or when the utility has not provided data concerning a particular indicator (w.r.).

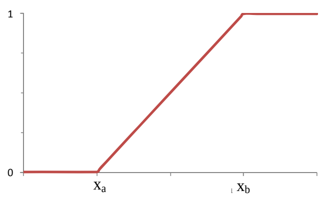
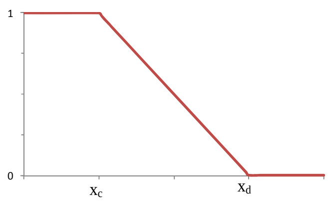
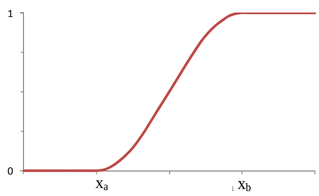
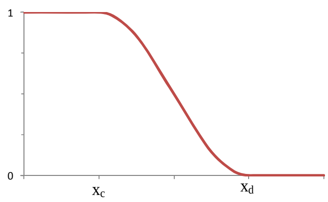
2.1 Criteria normalization and aggregation

In order to combine PI score which are expressed by distinct unities, the normalization was performed based on fuzzy sets functions [7], like sigmoidal (S-shaped), J-shaped [8], linear, and complex, defined for each indicator and based either on ERSAR criteria or legislation standards.

The normalization (or *fuzzification*) expresses a membership grade that ranges from 0.0 to 1.0, indicating a continuous variation from non-membership (null or very bad indicator result) to complete membership (indicator result is better than the overall reference values).

Table 2 shows some examples of used fuzzy sets membership functions and indicators normalization parameters implemented for sectoral indices calculation.

Table 2: Performance Indicators normalization procedure implemented for sectoral indices calculation

	Fuzzy Set Membership Functions		**Indicator - Normalisation parameters**	
Linear	**Increasing function**  $y = 0, x \leq x_a$ $y = \frac{x - x_a}{x_b - x_a}$, $x > x_a \; and \; x < x_b$ $y = 1, x \geq x_b$	**Decreasing function**  $y = 1, x \leq x_c$ $y = \frac{(x - x_d)}{x_c - x_d}$, $x > x_c \; and \; x < d_d$ $y = 0 \; and \; x \geq x_d$	AR01 AR08 AR09 AR14 AR15 AR17 AR18 AR20	Increasing: x_a = 85% and x_b = 100% Increasing: x_a = 50% and x_b = 70% Decreasing: x_c = 90% and x_d = 100% Increasing: x_a = 80% and x_b = 100% Decreasing: x_c = 48 and x_d = 55 Decreasing: x_c = 0 and x_d = 2 Increasing: x_a = 98% and x_b = 100% Increasing: x_a = 98% and x_b = 100% Increasing: x_a = 90% and x_b = 95%
Sigmoidal	**Increasing function**  $y = 0, x \leq xa$ $y = sen^2\left[\frac{x - x_a}{x_b - x_a} \times \frac{\pi}{2}\right]$, $x > x_a \; and \; x < x_b$ $y = 1, x \geq x_b$	**Decreasing function**  $y = 1, x \leq xc$ $y = sen^2\left[\frac{x - x_d}{x_c - x_d} \times \frac{\pi}{2}\right]$, $x > x_c \; and \; x < x_d$ $y = 0, x \geq x_d$	AR03 AR04 AR05 AR13 AR16 	Decreasing: x_c = 0 and x_d = 0.2 Increasing: x_a = 95% and x_b = 100% Increasing: x_a = 0,9 and x_b = 1,5 Decreasing: x_c = 15 and x_d = 20 Increasing: x_a = 2 and x_b = 3 Decreasing, x_c = 4 and x_d = 5

ISBN: 978-1-61804-088-6

The criteria aggregation process resulted, primarily, in three sectoral indices given by equation 1, and, after, the GISSeP value (Ig) has resulted of a similar weighted combination of those indices (equation 2).

$$SI_i = \sum (s_{i,j} \times w_{ARj}) \quad (1)$$

$$I_g = \sum (I_i \times w_{I_i}) \quad (2)$$

That method allows for a total trade-off among criteria. It means that a very poor attribute, translated as a low score obtained for one criterion, can be compensated by a number of good attributes, translated as higher scores obtained for some other.

A very important component of a multicriteria evaluation model concerns the priorities attached to the various criteria, i.e., the values of the weights in equations 1 and 2. The objective of developing weights is to quantify the relative importance of criteria to one another, in terms of their contribution to an overall index. This detail is highlighted by Cheng *et al*. [9], since evaluating decision alternatives in a new and complex problem setting often involves subjective evaluation by a group of decision makers with respect to a set of qualitative criteria.

2.2 Performance indicators weighting methods

Defining the relative importance of each indicator is a step in the multicriteria analysis methodology that requires a reliable and meticulous basis, namely through evaluations by analytical experts (academic, managers and advanced utility technicians). Accordingly, an on-line survey was implemented in which 22 participants were asked to rate, on a scale of 1 (insignificant) to 7 (extremely significant) the importance of several indicators in each group and of each of the three groups for performance and sustainability [10].

The performance indicator that was consensually considered to be the most important was AR18 (Compliance with the discharge parameters), whereas AR11 (Mains rehabilitation) was globally rated as the least important.

The results of this survey were used as a basis for setting up the two following performance indicator weighting methods: (A) *n-points scale modified* (complemented with a ranking); and (B) *pairwise comparison*. This was carried out in order to allow a sensitivity analysis of the GISSeP values and, consequently, of the changes in relative order of the several wastewater utilities in the established overall ranking. The *n-points scale method* consists in the assignment of weights as a function of the averages of the results obtained through the survey for each performance indicator.

The *method A* consists in assigning scores decreasing the weights given by the method initially used as a basis, thus creating a ranking [11]. Through the assignment of a rating by ranking those weights and applying the rank sum technique, the final weights of the criteria were calculated through equation 3. Therefore, the greatest rating corresponded to the highest weight ranking order and so forth, with rating decreasing with the ranking order.

$$w_j = \frac{n - r_j + 1}{\sum_k n - r_k + 1} \quad (3)$$

Where,

w_j is the normalized j criterion weight;

r_j is the order of the j criterion;

n is the number of criteria.

Naturally, the maximum rating depended on the total number of indicators in each one of the three groups under scrutiny.

The innovative *method B* is based on pairwise comparison of criteria, assigns a weight to an indicator as a consequence of its comparison with another indicator [11].

In applying this methodology, the information provided by each participant allowed the construction of an $n \times n$ symmetrical matrix for each group. In order to complete the matrix, the 7-point scale used in the survey was converted to the 9-point scale usually adopted in the context of a decision making process known as Analytical Hierarchy Process (AHP).

As showed by Silva *et al.* [12], the pairwise comparison strategy comprises seven stages: construction of a pairwise comparison matrix ($[a_{i,j}]$); calculation of the main eigenvector; calculation of the maximum eigenvalue; calculation of the Consistency Index (CI) and the Random Index (RI); calculation of the Consistency Ratio through CI/RI and, the possible repetition of the pairwise comparison matrix if the CR is greater than 0.1.

The eigenvector (w_i) results from the maximum matrix eigenvalue, translates the priority order of the factors and can be calculated by the equation 4.

$$W_i = \left(\prod_{j=1}^{n} a_{ij} \right)^{1/n} \Bigg/ \sum_{k=1}^{n} \left[\left(\prod_{j=1}^{n} a_{kj} \right)^{\frac{1}{n}} \right] \quad (4)$$

Table 3 highlights the differences introduced by the two weight assignment methods by synthesising the values of the weights obtained for each performance indicator and sectoral indices [10].

Table 3: Synthesis of the PI' weights calculation, applying two different methods

Indicator	Method A (%)	Method B (%)
AR 01	36,36	30.31
AR 02	27.27	26.15
AR 03	9.10	17.33
AR 04	27.27	26.21
Index 1	**50.00**	**43.17**
AR 05	10.71	11.50
AR 06	16.07	13.54
AR 07	3.57	6.11
AR 08	7.14	7.57
AR 09	17.86	15.14
AR 11	1.79	5.77
AR 13	7.14	6.90
AR 14	12.50	12.26
AR 15	14.29	12.50
AR 16	8.93	8.71
Index 2	**16.67**	**26.13**
AR 17	50.00	27.62
AR 18	16.67	36.12
AR 20	33.33	36.26
Index 3	**33.33**	**30.70**

Because it displays the least differences between weights, method B is the most conservative, leading to a lesser risk of influencing the final utility ranking results.

3 Results and discussion

The scenarios under analysis in this paper refer to the performance of regulated wastewater utilities achieved in two consecutive years (2007 and 2008), for the same analytical universe. The purpose is to evaluate the influence of the weighting method in the final rating and ranking order of each studied utility.

The results obtained for the sectoral indices (SI 1, SI 2, SI 3) considering these different weight assignment methods are synthesized in Table 4.

The developed model for GISSeP calculation further allows the analysis of the evolution of ranking orders from 2007 to 2008, thus identifying the utilities that have gone up, gone down or have maintained their ranking position. Figure 2 shows the observed annual evolution (2007 to 2008) of utility ranking order for each weight assignment method.

Table 4: Synthesis of the sectoral and global indices values for the weighting methods A and B (2008)

WW Utility	Index **SI 1**		Index **SI 2**		Index **SI 3**		**GISSeP**	
	A	B	A	B	A	B	A	B
A	**2.08**	**2.09**	**1.03**	**1.51**	**2.61**	**1.88**	**5.71**	**5.48**
B	**3.08**	**2.92**	**1.13**	**1.60**	**1.11**	**1.11**	**5.32**	**5.64**
C	**3.99**	**3.58**	**1.47**	**2.08**	**2.61**	**1.88**	**8.07**	**7.55**
D	**1.19**	**1.35**	**1.24**	**1.78**	**1.94**	**1.54**	**4.37**	**4.67**
E	**2.78**	**2.61**	**1.04**	**1.54**	**2.06**	**1.87**	**5.87**	**6.02**
F	**1.82**	**1.88**	**1.00**	**1.43**	**1.11**	**1.11**	**3.93**	**4.42**
G	**3.18**	**3.01**	**1.10**	**1.55**	**1.11**	**1.11**	**5.39**	**5.67**
H	**1.10**	**1.00**	**1.18**	**1.67**	**2.61**	**1.88**	**4.89**	**4.55**
I	**1.05**	**1.68**	**1.14**	**1.64**	**2.61**	**1.88**	**4.79**	**5.19**
J	**0.80**	**1.03**	**1.27**	**1.88**	**1.50**	**0.76**	**3.57**	**3.68**
K	**1.21**	**1.38**	**1.11**	**1.62**	**1.11**	**1.11**	**3.43**	**4.10**
L	**1.66**	**1.75**	**1.33**	**1.93**	**3.17**	**2.99**	**6.16**	**6.66**
M	**5.00**	**4.32**	**1.04**	**1.63**	**1.35**	**0.69**	**7.39**	**6.64**
N	**2.12**	**1.85**	**0.81**	**1.17**	**2.61**	**1.88**	**5.54**	**4.89**
O	**3.42**	**3.14**	**1.29**	**1.87**	**3.17**	**2.99**	**7.88**	**8.00**
P	**3.91**	**3.53**	**0.89**	**1.34**	**2.89**	**2.43**	**7.68**	**7.30**
Q	**3.12**	**2.96**	**0.76**	**1.24**	**2.61**	**1.88**	**6.49**	**6.07**
R	**4.61**	**4.03**	**0.87**	**1.20**	**2.06**	**1.87**	**7.53**	**7.11**

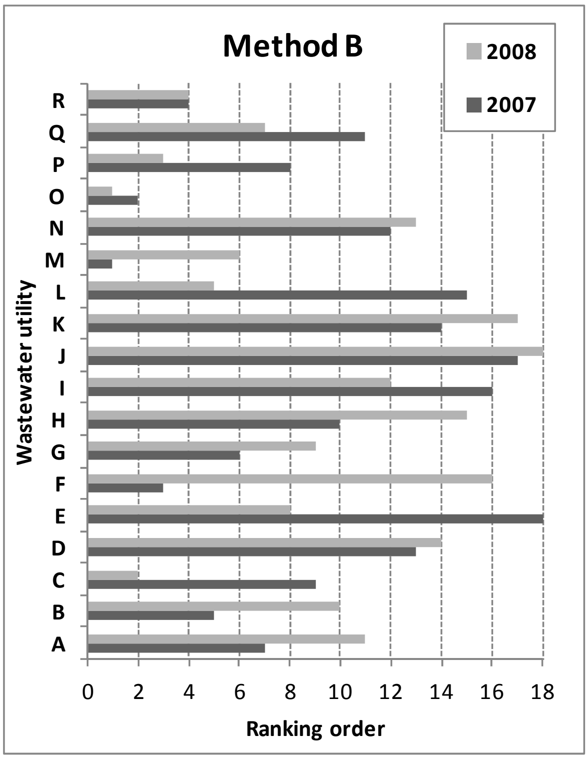


Fig. 2: Synthesis of the evolution of WW utility ranking orders from 2007 to 2008, for the weighting methods B

In this case, the change of weighting method only affects three of the eighteen wastewater utilities analysed. From the results obtained using method B, seven utilities improved their ranking order and only one maintained its position.

It is also verified that the influence imparted by the weighting methods in each utility's ranking is not only due to the change in values for each index but also to the relative order of the other utilities.

4 Conclusions

This research work is an important contribution for the improvement of the Portuguese performance assessment system of the sanitation services, through the development and application of a complementary methodology to define a global index of service quality (GISSeP).

In general, the wastewater utilities had worse performance in the environmental sustainability index (SI3), in 2008, but a better performance, in sustainability of the utility index (SI2), confirming the trend observed from the onset of the implementation of the performance evaluation system established by the regulatory entity.

The proposed methodology allows a truly quantitative service quality evaluation for a given wastewater utility in order to achieve accurate performance rates. With regards to the great importance imparted by the weights assigned to the performance indicators (criteria) in service quality indices values, a sensitivity analysis was carried out for the weighting method to use. Method A is the one that produces the greatest dispersion in GISSeP values; the results obtained in method B are slightly more conservative.

The developed model for the definition of the different indices allows the establishing of a global and sectoral ranking, evaluate the evolution of the performance of each wastewater utility in their different domains, and identify the corresponding weaknesses and potential, contributing to a continuous improvement of service quality in sanitation systems.

References:

[1] Duarte, A.A.L.S.; Rodrigues, G.M.C., Ramos, R.A.R.. A global service quality index to evaluate the performance and sustainability in water supply utilities. *WSEAS Transactions on Environment and Development*, **5** (12), 2009, pp. 759-769.

[2] Duarte, A.A.L.S.; Vieira, J.M.P., Estuarine hydrodynamic as a key-parameter to control eutrophication processes. *WSEAS Transactions on Fluid Mechanics*, **4** (4), 2009, pp. 137-147.

[3] Duarte, A.A.L.S.; Canais-Seco, T.; Peres, J.A.; Bentes, I.; Pinto, J.T., 2010. Sustainability indicators of subsurface flow constructed wetlands in Portuguese small communities. *WSEAS Transactions on Environment and Development*, **6** (9), pp. 625-634.

[4] Baptista, J.M, Pássaro, D.A., Santos, R.S., *The regulation of the water and waste sectors in Portugal*. In: www.ersar.pt

[5] ERSAR, *Guide for quality assessment of water and waste services provided to the users* (3*rd* edition), Portuguese Authority for the Regulation of Water and Waste, Lisbon, 2007. (in Portuguese).

[6] ERSAR, *Performance assessment annual report of the water and waste sectors in Portugal*, Portuguese Authority for the Regulation of Water and Waste, Lisbon, 2008. (in Portuguese)

[7] Jiang, H.; Eastman, J.R., Application of Fuzzy Measures in Multi-criteria Evaluation in GIS. *Int. Journal of Geographical Information Science*, **14** (2), 2000, pp. 173-184.

[8] Schmucker, K.J., *Fuzzy Sets, Natural Language Computations, and Risk Analysis*. Computer Science Press, USA, 1984.

[9] Cheng, J.; Lee, C.; Tang, C., An Application of Fuzzy Delphi and Fuzzy AHP on Evaluating Wafer Supplier in Semiconductor Industry, *WSEAS Transactions on Information Science and Applications*, **6** (5), 2009, pp. 756-767.

[10] Granja, C.M.P., *Development of service quality indices in wastewater facilities*. MSc Thesis, University of Minho, Braga, Portugal, 2010. (in Portuguese)

[11] •Duarte, A.A.L.S., Rodrigues, G.M.C., Ramos, R.A.R., Effect of criteria weighting methods on the ranking of water suppliers' performance. In: *Energy, Environment, Ecosystems and Sustainable Development*, WSEAS Press, Greece, 2009, pp. 350-355.

[12] Silva, A.N.R.; Ramos, R.A.R.; Souza, L.C.L.; Rodrigues, D.S.; Mendes, J.F.G., *GIS: A platform for the introduction of emerging techniques in urban, regional and transports planning: a 3-D tool for urban environmental analysis; multicriteria evaluation; artificial neural networks*. EDUFSCar Publishing House of Federal University of São Carlos, Brazil, 2008. (in Portuguese).