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Application of Data Envelopment Analysis to Assess and Improve Efficiencies of Activated Sludge Treatment Plants

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Abstract: The aim of the investigation was to apply data envelopment analysis to assess and improve the efficiencies of activated sludge treatment plants using a case study from Algeria. The treatment capacities of 35 plants were analyzed and then a determination was made if they operated at their optimal sizes. Based on the wastewater treatment plants (WWTPs) examined, the Data Envelopment Analysis (DEA) method showed that 94% of the plants did not operate at their optimal sizes (i.e., efficiency scores less than 1). This indicated they were inefficient from a treatment capacity point of view and may reflect poor management, due possibly to a deficiency in knowledge about the best operating conditions. The DEA analysis indicated that smaller WWTPs were more efficient (i.e., scores closer to 1) compared to larger ones. This should encourage decision-makers to choose for the construction of small or medium-sized WWTPs that are more manageable and can be operated at their optimal size.

Key words: Wastewater treatment plants · Activated sludge · Pollution load · Purification capacity · Data envelope analysis · Efficiency · Optimal size · Capacity

INTRODUCTION

It is crucial that wastewater treatment plants (WWTPs) be designed carefully not only to lessen pollution but also to diminish adverse impacts on human health and the environment [1, 2, 3]. Owing to chemical usage, energy consumption and emissions, WWTPs can generateecological impacts which can negativelyaffect society. To counteract this, Ramírez-Melgarejo *et al*. [4] performed eco-efficiency evaluation oftreatment plants by employinga data envelopment analysis-tolerance model. Their aim was to improve the environmental and economic efficiency of these processes and systems. In a related study Kim *et al*. [5] developed a model that could analyze and evaluate the efficiency of investment costs for the maintenance of water supply facilities, utilizing data envelopment analysis. They concluded that the results could be utilized to promote the economic efficiency of water services.

Stricterregulatory and environmental standards have resulted in the need for enhanced reliability and better control of discharges from WWTPs [6, 2, 7]. However, for many large plants, the operating costs are immense and depend, in part on the treatment capacity. Hence it is importantto review this parameter (i.e., optimum capacity for minimizing operating costs) after a period of operation and tomodifythe capacity if needed. A correction of this parameter would improve efficiency and allow for a reduction in operating costs.

Studies have been reported on the energy efficiency and economics of wastewater treatment plants (WWTPs) using Data Envelopment Analysis (DEA) [4, 8]. Although DEA has a strong link to production theory in economics, the tool is also used for benchmarking in operations management, where a set of measures is selected to benchmark the performance of manufacturing and service operations. In benchmarking, the efficient decision-making units (DMU), as defined by DEA, may

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not necessarily form a "production frontier", but rather lead to a "best-practice frontier" [9, 4, 8]. Studies have been reported by Hernández-Sancho *et al*. [10] and Yang *et al*. [11] on the efficiency of water economy and in particular wastewater in Spain and in China. A study byJiang *et al*. [12] dealt with WWTP's efficiency. A benefit and cost analysis wereconducted by Guerrini *et al*. [13] and Ghajarkhosravi *et al*. [14] in the measurement of sanitation services in Denmark and water consumption and domestic waste in Toronto, Canada, respectively. In the DEA method, there are two different models CRS and VRS; the CRS is the model under assumption of Constant Returns to Scale [15] and the VRS is the model under the assumption of Variable Returns to Scale [16, 17]. Makowska *et al*. [18] reported on the efficacy and reliability of wastewater treatment technology in small meat plants This study demonstrated that treatment of specific wastewater, such as meat industry wastewater, was effective. However, a complication may arise due to the apparent incomplete removal of nitrogen compounds. It can be argued that the data envelopment analysis technique might be a useful approach to try and solve this problem

In the semi-arid North African country of Algeria, research has dealt with the performance indicators of wastewater treatment plants (WWTP). Areportwas presented by Karef *et al*. [19], on the efficiency of the Médéa WWTP. However, studies which gather and compare the performance of numerous WWTPs by applying a mathematical model or benchmarking have barely been investigatedfor this region. It should be noted that decision-making or analytical tools as reported by Kellouche and Abdelbaki [20] have not focusedon the importance of readjusting physical parameters such as the theoretical capacity of these infrastructures. Thisresearchwas limited to comparing the measured values of the physico-chemical and biological parameters at the inlet and outlet of WWTPswith discharge or reuse standards [19, 21; 22]; and [23] without being able to develop real decision-making tools.

The aim of the current investigation was to apply data envelopment analysis to assess and improve the efficiencies of activated sludge treatment plants using a case study from Algeria. The theoretical treatment capacities of 35 plants which depended on factors such as the pollution load at the inlets, were analyzed and then a determination was made if they operated at their optimal sizes.

MATERIALS AND METHODS

The Data Envelopment Analysis Approach: Data Envelopment Analysis (DEA) is a non-parametric approach to operations research for assessing the relative efficiencies of a set of peer units, called Decision Making Units (DMUs), with multiple inputs and multiple outputs. The DEA method calculates efficiency scores and shows whether a wastewater treatment plant (WWTP) is technically efficient and operating at its optimum size [17]. This technique is built on a non-parameterized mathematical model whose configuration is based on inputs, outputs and orientation, either by maximizing outputs, or by minimization of entries [24]. The approach relies on nonparametric linear programming to measure the relative efficiency of a homogeneous set of decision-making units (DMU) with multiple inputs and outputs. A DEA study of DMU estimates an efficiency frontier based on empirical observations and thus distinguishes between efficient and inefficient units [9]. Such a frontier 'envelops' the inefficient units within it and clearly shows the relative efficiency of each branch. Branches which are located on the frontier are performing better than those below the frontier.

The DEA method seeks to define a production frontier determined by all the technically efficient DMUs (WWTPs) among the n DMUs of the sample. Each DMU_j (j = 1,...n), uses quantities x_{ij} of inputs (i = 1,...m), to produce quantities y_{rj} of outputs (r = 1,...,s).

By following the constant returns to scale (CCR) model of Charnes *et al*. [15], it is possible to estimate the technical efficiency θ_k with which the DMU of the reference k will use its inputs x_{ik} to produce the outputs y_{rk}, each n DMUs serving as a reference k in turn. Using linear programming, the following model will be solved n times (Equation 1):

$$Min_{\theta,\lambda,s^-,s^+} e_k = \theta - \varepsilon\left(\sum_{i=1}^{m} S_i^- + \sum_{r=1}^{s} S_r^+\right) \quad (1)$$

Under constraints

$$\sum_{j=1}^{n} \lambda_i x_{ij} + s_i^- = \theta x_{ik} \quad \text{for } i = 1,....,m$$

$$\sum_{j=1}^{n} \lambda_i y_{rj} + s_r^+ = y_{rk} \quad \text{for } r = 1,...,s$$

With:

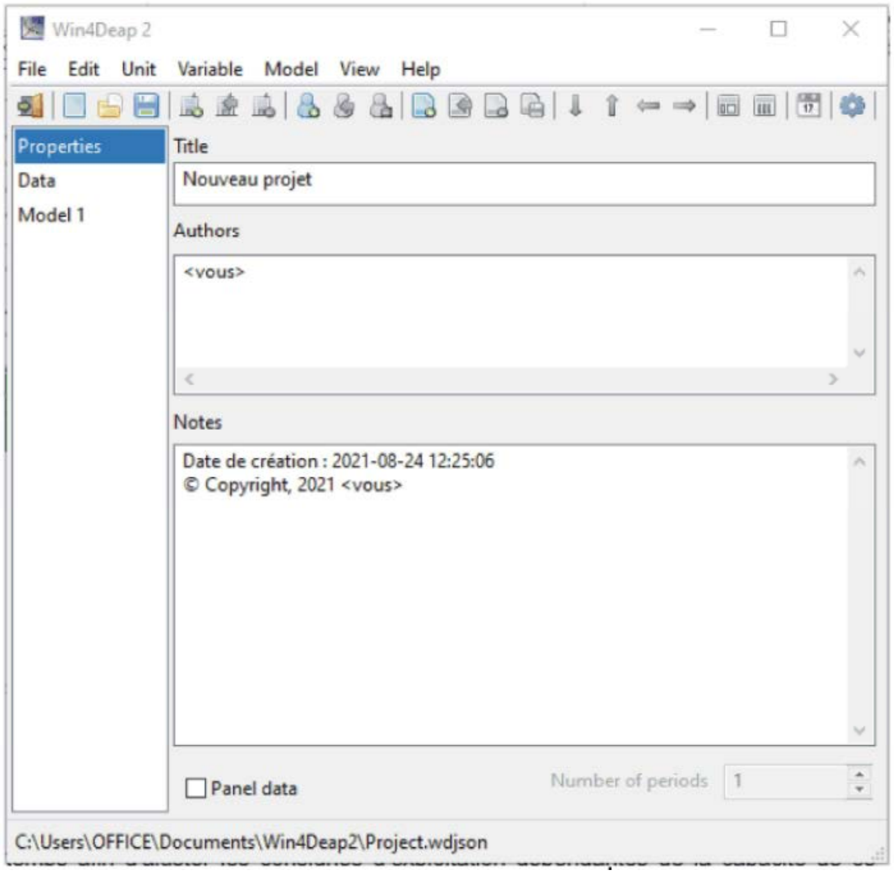

Fig. 1: Win4DEAP Software Interface

s_r^+ the vector associated with the outputs

s_r^- the vector associated with the inputs

ε_a a quantity small enough that maximizing the deviation variables remains a secondary objective compared to minimizing the coefficient θ

λ is the weighting coefficient of the inputs and outputs, which makes it possible to determine the production frontier, made up of efficient DMUs.

The efficiency frontier is reached when $\theta = 1$ and all the difference variables are zero. For any $\theta < 1$, the DMU will be declared inefficient.

Banker *et al*. [15, 25] extended the measure of efficiency to variable returns to scale by introducing an additional constraint in the model, $\sum_{j=1}^{n} \lambda_j = 1$ (model BCC). This made it possible to decompose the overall Technical Efficiency (*TE*) obtained from the CCR model, into Pure Technical Efficiency (PTE), determined by the BCC model, into Scale Efficiency (SE), ratio of the two previous efficiencies (Equation 2):

$$SE = \frac{TE(CRS)}{PTE(VRS)} \quad (2)$$

SE checks whether the size of a DMU is optimal or whether it can benefit from an economy of scale. Pure technical efficiency reflects the organizational efficiency of a DMU or the quality of its management. It is these different efficiency measures that are calculated for the WWTPs.

Application of DEA Approach in Calculating WWTP Efficiency: The theoretical treatment capacity of a wastewater treatment plant (WWTP) was determined from the pollution load as a function of the concentration of one of three pollution parameters:Biochemical Oxygen Demand measured after 5 days (BOD_5), Chemical Oxygen Demand (COD) and Total Suspended Solids (TSS), in addition to the flow entering the station. This capacity was expressed in population equivalents (PE). However, the manager of a WWTP applies operating instructions

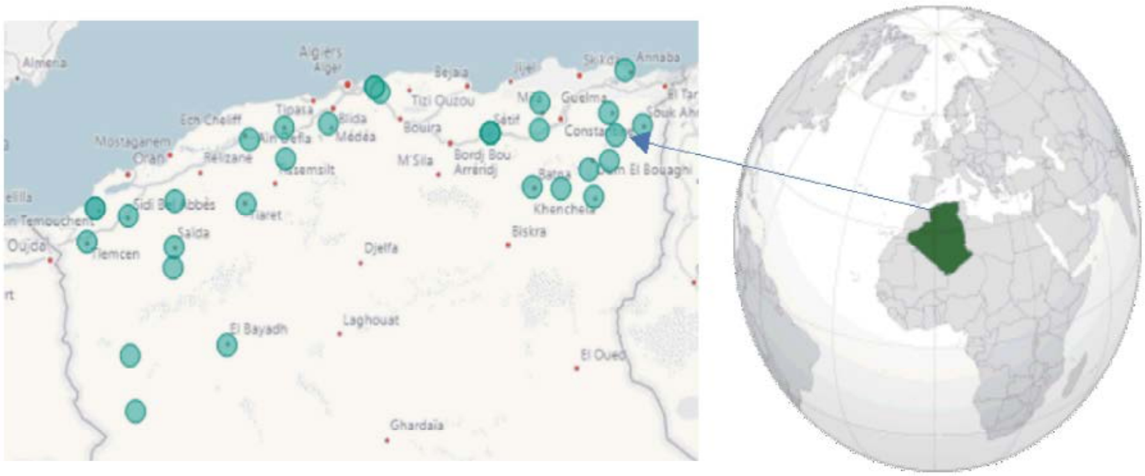

Fig. 2: Location of the 35 Wastewater Treatment Plants (WWTPs) investigated

Table 1: Theoretical capacities of the 35 WWTPs investigated [28]

#	WWTP	Capacity (PE)	#	WWTP	Capacity (PE)
01	Annaba	580 700	20	Sedrata	100 000
02	Tiaret	390 000	21	Mascara	100 000
03	Ain Sfiha	330 000	22	Ain Sefra	98 000
04	Bazer Sakhra	230 000	23	Mechria	92 000
05	Chlef	227 500	24	Boumerdes	75 000
06	Sidi Bel Abbés	220 000	25	Bougaa et H/Guergour	75 000
07	Batna	200 000	26	Ain Témouchent	72 800
08	Guelma	200 000	27	Touggourt	62 500
09	Khenchela	192 000	28	Ain Defla	50 000
10	Médéa	162 500	29	Chelghoum Laid	45 000
11	Souk-Ahras	150 000	30	Theniet El Had	33 000
12	Tlemcen	150 000	31	Thénia	30 000
13	Saida	150 000	32	Ain El Hadjar	30 000
14	Ain Oulméne	150 000	33	Zemmouri	25 000
15	Tissemssilt	150 000	34	Bouzedjar	19 000
16	Ain Beida	140 000	35	Timgad	13 800
17	Sidi Merouane	137 700			
18	El Bayadh	123 109			
19	El Milia	120 000			

which depend on the operating ability of his capacity, hence the need to review the actual treatment capacity and readjust this parameter to use the best operating conditions and thereby save on running costs.Thus, for each of the WWTPs, the DEA method calculated the efficiency scores and consequently generated a list called: "the best practices". These scores or measures were part of a benchmarking framework[26] which can be very useful for decision-making. The desired results can be considered as key performance indicators (KPI) to readjust processing capacities according to actual data from operating reports [20].

Tools Employed for Calculating Efficiency: To calculate efficiency by the DEA method, Win4DEAP [27] software was used (Figure 1). It is a free graphical application that provides simulation results in a text file. The input parameters were influent flow, BOD_5, COD and TTS. Capacity was the only output parameter. The data was imported and then the model (Constant Returns to Scale and Variable Returns to Scale) and orientation (maximize inputs or minimize outputs) were chosen.

Samples and Variables: The two DEA models were used to examine the theoretical capacities of 35 activated sludge treatment plants (Figure 2) and to adjust the operating instructions depending on the capacities of these WWTPs.According to the National Sanitation Office, the capacities of the WWTPs considered are indicated in Table 1. The DEA method was applied with the input parameters: BOD5, COD, MES and inlet flow which were available in the form of monthly average values for the year 2017 [28]. The output parameter was the actual processing capacity in population equivalents.

RESULTS AND DISCUSSION

Calculated Efficiency Scores: The application of the VRS model yielded the results indicated in Table 2. This model gives three types of efficiencies (Table 2): CRSTE: technical efficiency according to the model CRS; VRSTE: technical efficiency according to the model VRS; and SCALE: scale efficiency (CRSTE/VRSTE).

For example, for the WWTP of Annaba, values of CRESTE, VRSTE and SCALE are worth 0.106, 0.226 and 0.470 respectively.The margin for improvement for the three types of efficiency CRSTE, VRSTE and SCALE was very important. Remarkably, 33 out of 35 wastewater treatment plants had a score below 1 which indicated that they were not operating at their optimal size.

CRSTE gave an average of 44.2% for technical efficiency according to the CRS model (variation from 7.4% to 100%). A total of 31 out of 35 WWTPs operated with less than 80% of their processing capacity while keeping the same values of the input parameters (flow, BOD_5, DCO and MES). These WWTPs can lower their processing capacity because they receive hydraulic loads and pollutant loads lower than their operating capacities. In contrast, VRSTE resulted in an average of 66.3% in technical efficiency according to the VRS model (variation from 9.9% to 100%). The results were a better compared to the previous one, where almost half of the WWTPs operate with more than 80% of their processing capacity (where the values of the VRSTE are between 0.823 and 1). It can be argued that with better management of these WWTPs, the theoretical capacity could be reduced by 33.70% (100 – 66.3, where 66.3 is the average of the VRSTE values). Finally, SCALE produced an average score of 68.4% for efficiency (variation from 32.2% to 100%). In 21 out of 35 cases the WWTPs operated with less than 80% of their processing capacity (i.e., less than 0.80 in Table 2). This meant that by adjusting their size and keeping the same input parameter values (i.e., flow, BOD_5, COD and TSS), the WWTPs could reduce their processing capacity by an average of 31.6% (100-68.4) while keeping their output constant. With the three types of efficiency global, technical and scale, it should be noted that there was no WWTP with all three types of efficiency at 100% (i.e., score of 1.000). This means that each of the WWTPs suffers from at least one problem; management or size.

Table 2: Efficiency Scores for Wastewater Treatment Plants (WWTPs) Calculated from VRS and CRS Models

N°	WWTP	CRSTE	VRSTE	SCALE
1	Ain Oulmene	0.322	1.000	0.322
2	Sedrata	0.281	0.863	0.325
3	Ain Sfiha	0.112	0.343	0.327
4	Tiaret	0.349	1.000	0.349
5	Sidi Bel Abbes	0.369	0.899	0.411
6	Ain Beida	0.309	0.736	0.419
7	El Bayadh	0.413	0.913	0.452
8	Annaba	0.106	0.226	0.470
9	Tissemssilt	0.492	1.000	0.492
10	Batna	0.421	0.823	0.511
11	BazerSakhra	0.220	0.394	0.559
12	Mascara	0.573	1.000	0.573
13	Bouzedjarr	0.423	0.726	0.582
14	Khenchellaa	0.411	0.704	0.584
15	Bougaa et H/Guergour	0.335	0.560	0.599
16	Sidi Merouane	0.209	0.346	0.605
17	Touggourt	0.623	1.000	0.623
18	Mechria	0.387	0.560	0.692
19	Theniet El Had	0.700	1.000	0.700
20	Souk Ahras	0.074	0.099	0.749
21	Medea	0.211	0.272	0.776
22	Chlef	0.123	0.153	0.804
23	Saida	0.305	0.365	0.835
24	Ain ElHadjar	0.841	1.000	0.841
25	Guelma	0.359	0.418	0.858
26	Chelghoum Laid	0.435	0.483	0.900
27	Ain Sefra	0.212	0.228	0.930
28	Boumerdes	0.933	1.000	0.933
29	Tlemcen	0.444	0.475	0.935
30	Ain Tmouchent	0.832	0.887	0.938
31	El Milia	0.175	0.186	0.941
32	Ain Defla	0.815	0.850	0.959
33	Thnia	0.657	0.683	0.962
34	Zemmouri	1.000	1.000	1.000
35	Timgad	1.000	1.000	1.000
	Average	0.442	0.663	0.684

The results of the investigation on the energy efficiency and economics of the 35 wastewater treatment plants (WWTPs) using Data Envelopment Analysis (DEA) are presented in Figures 3 and 4. Since the CRS model brings out technical efficiency, it should be noted that 33 out of the 35 (i.e., 94%) of the WWTPs in service were technically inefficient (i.e., efficiency scores less than 1) (Figure 3). The VRS results presented in Figure 4

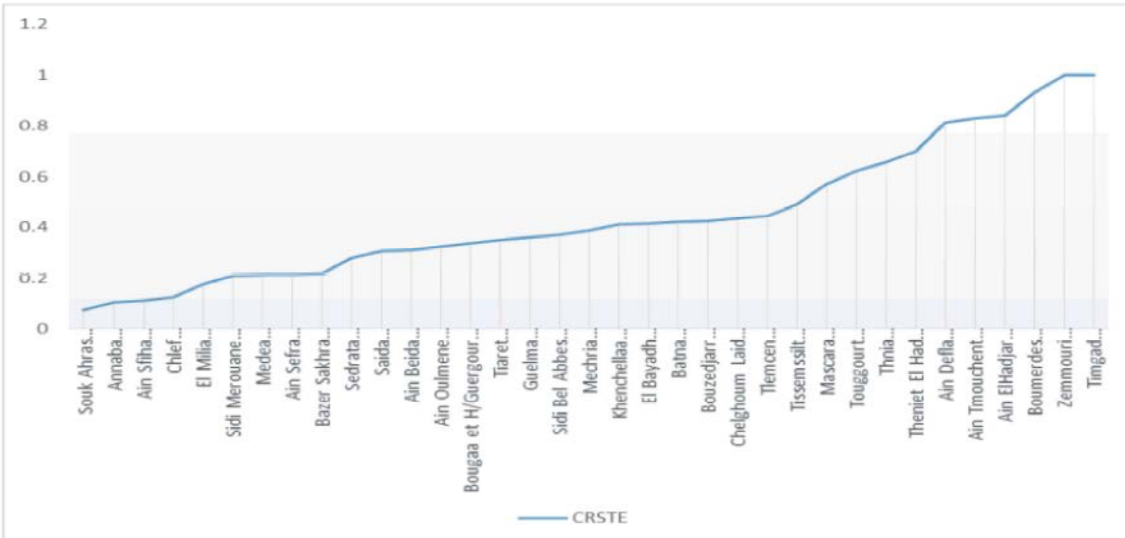

Fig. 3: Results of the plant technical efficiency based on the CRS model. The closer the value is to 1 the more efficient the plant

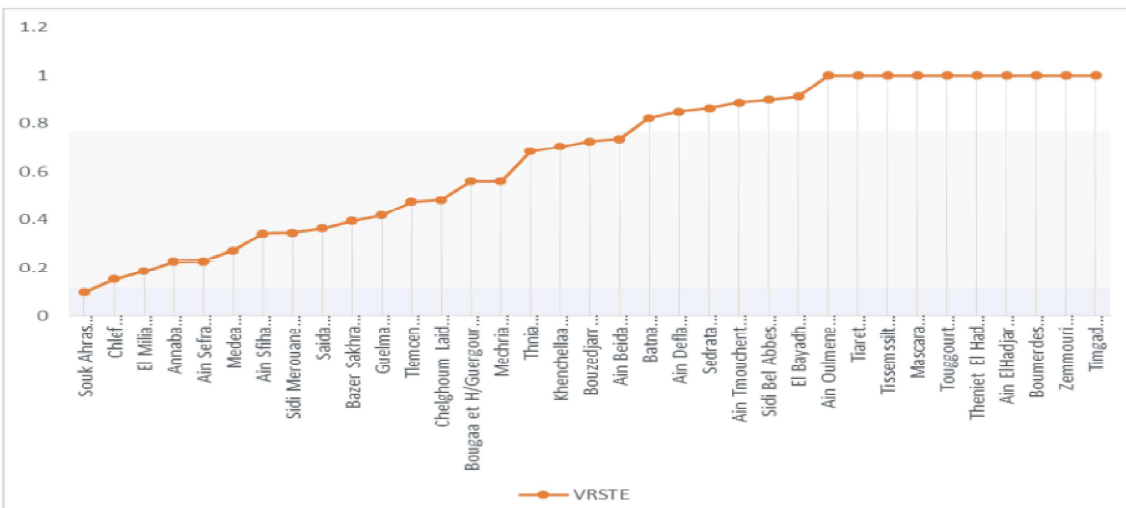

Fig. 4: Results of the plant technical efficiency based on the VRS model. The closer the value is to 1 the more efficient the plant

indicated that 10 out of 35 (i.e., 29 %) of the WWTPs had an efficiency of 100% (i.e., scores of 1). This was synonymous with good management with the observation that these are small-capacity WWTPs (Table 1). It should be noted that only 2 out of 35 WWTPs had a Scale core of 1, i.e., 100% scale efficiency, indicating that they operated at their optimal sizes. These were the Zemmouri and Timgad WWTPs (Figure 5).

The CRS model calculates technical efficiency (TE) known as constant return to scale. It is appropriate when all structures have reached their optimal size. It gives the overall efficiency of a structure. For the WWTPs the results are shown in Table 2.

Finally, 29 out of 35 WWTPs had a technical efficiency (i.e., CRSTE) of less than 80% (i.e., less than 0.8). As well as the average rate was only 44% with a great variation ranging from 0 .074 to 1.00 (Table 2). Since the lowest rate or score was 7.4%, this indicating that additional efforts, in terms technical efficiency, are necessary for the majority of these WWTPs.

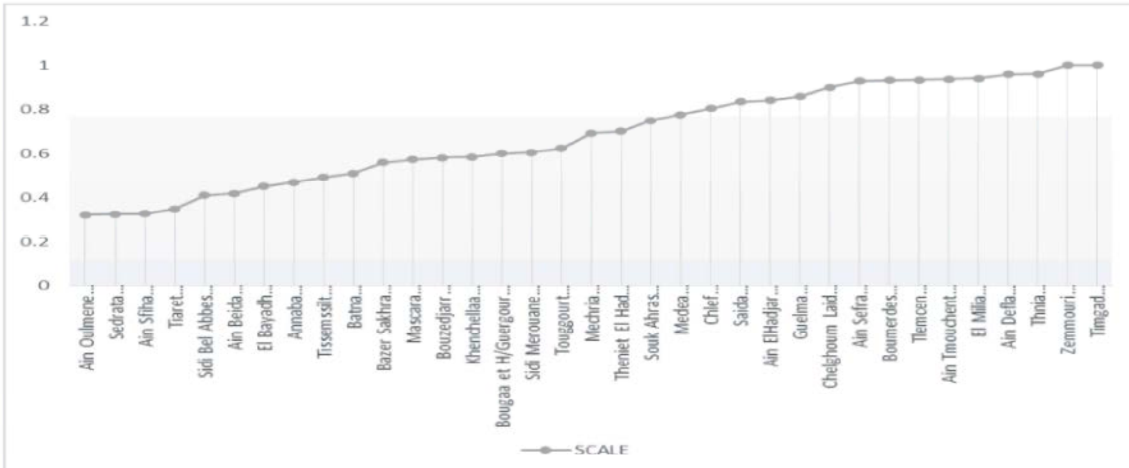

Fig. 5: Scale efficiency results.The closer the value is to 1 the more efficient the plant

Especially since more than 2 out of 3 WWTPs had a technical efficiency rate of less than 50% (i.e., CRSTE score less than 0.5) (Table 2).

CONCLUSION

Based on the wastewater treatment plants (WWTPs) examined, the Data Envelopment Analysis (DEA) method showed that 94% of the plants do not operate at their optimal sizes (i.e., efficiency scores less than 1). This indicated they were inefficient from a treatment capacity point of view. It can be argued that this reflected poormanagement, due possibly to a deficiency in the knowledge about the best operating conditions. In view of these results, it is prudent to revise, downwards, the theoretical purification capacities to allow those in charge to apply modified operating conditions and thus reduce costs. All WWTPs examined in this study received hydraulic loads and pollutant loads lower than their operating capacities.The DEA analysis indicated that small WWTPs are more efficient (i.e., scores closer to 1) compared to large ones. This should encourage decision-makers to choose for the construction of small or medium-sized wastewater treatment plants that are more manageable and can be operatedat their optimal size.

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