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Data envelopment analysis as a tool to assess the water demand minimization potential in industrial zones in the Vietnamese Delta

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ABSTRACT

This work employs the data envelopment analysis technique to assess the water use efficiency of companies and the water reduction potential of industrial categories in industrial zones. Fifty-eight companies were selected from four industrial categories: wearing apparel (*WA*,18), fabricated metal (*FM*,12), rubber and plastic (*RP*,12), and other manufacturing (*OM*,12) based on six variables: monthly water usage, two types of effluent contaminant loadings, monthly production capacity, number of employees, and surface occupied by a company. The results indicate that significant numbers of companies are inefficient in water use, namely *WA*(28%), *OM*(42%), *FM* (43%), and *RP*(46%). Implementing technical measures to improve water use efficiency at these companies offers a varying water reduction potential per industrial category, namely in the order *RP*(25%) > *FM*(17%) ≫ *WA*(7%) > *OM*(4%). These results show that improving water efficiency by water use minimization is not the only ptential measure for improving the industrial zone's water metabolism towards self-sufficiency.

1. Introduction

A global increase in water demand, water pollution, and climate change have negatively influenced worldwide freshwater availability [1]. This has led to competition for water use among agricultural, urban, and industrial sectors [2–6]. This issue has drawn the interest of international and national researchers who investigated this effect in Vietnam over the past two decades [7–10]. In Vietnam, like in many other emerging economies, a root cause of this competition is the increased demand due to a proliferation of industrial zones (IZs) [10–13]. Water imports from adjacent regions for the industry are now a frequent practice.

The approach of integrated industrial water resource management has been developed to resolve water competition. Here, sustainable industrial water supply is the main component [2,14,15]. Within sustainable industrial water supply, new ways to ensure water security are provided by accessing modern water supply technologies for processes and in-company sanitation, increasing water efficiency, and using alternative local resources [16]. Minimizing water demand through efficient appliances and methods adapted to the particular industry is an essential first step [17]. This strategy has been widely adopted to reduce processing water in many industries [18–24]. However, these studies did not address the water reduction potential (WRP) as a crucial indicator. They focused exclusively on minimizing waste through recycling and reuse. Secondly, previous studies were limited to minimizing water

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consumption at a specific industrial manufacturing type separately, e.g. food, palm oil, sugar plant, slaughterhouse, and other industries, and sometimes to the individual company level. The quantity of water used and potential reduction may vary significantly over several industry types and among the industries in one category [25–27]. Therefore, it is interesting to compare the water demand performances of groups of similar industries to identify the opportunities for minimizing water demand. By comparing these, one can assess the potential minimum amount of water needed by a company without straining its economic processing capacity. The amount of water used above such a minimal theoretical water requirement can be defined as water use inefficiency or water reduction potential. Thirdly, Agudelo-Vera et al. [28], who focused on urban water management, proposed that technology implementation is an option to achieve water demand minimization but did not indicate feasible benchmarks for the quantity of water to be reduced. Defining water minimization targets can give direction to which extent the technology should be implemented in specific situations, in their case, urban building [28], and in the case presented here, types of industries in IZs. Lastly, traditional attempts to evaluate efficiency often encounter technical difficulties when multiple variables need to be considered. Thus, a technique that can handle many variables and constraints within the complex problems in industrial water management is useful. To our knowledge, no prior studies have introduced such target for individual companies within industrial categories. Semi-structured interviews in 2017 revealed that industrial zone authorities (IZAs), which are operating the IZs in the Saigon River Delta, favor measures at the level of single industrial companies to reduce fresh (potable) water consumption. Such measures, for instance, by industrial technology improvement, can be practically implemented because (i) the scale of intervention measures is relatively small and much easier to implement than at the scale of the whole industrial zone; (ii) private companies are in the self-control of financial and technological aspects, e.g. measures can be implemented under their transparent management regime; and (iii) to arrive at freshwater use reduction beyond each company, the existing water infrastructure of IZs, would need to be drastically adjusted to adopt new water supply and associated technologies, and thus, reduction measures at single companies can be easily applied and framed within current legal arrangements between industrial zone authority and industry. For this, a quantitative method to assess water (in-)efficiency related to the water-saving potential of industrial companies is needed. Such a method could support organizations, e.g. industrial zone authorities, to evaluate the current water efficiency among companies in different sectors and implement policies to adopt water demand minimization strategies and make their IZs more water-efficient.

The objective of this study was to develop a method for assessing the WRP of industrial categories within IZs considering multiple variables. This work (i) provides a tool that water managers can use at various levels to assess the water use efficiencies of individual companies and the WRP of industrial categories in industrial zones (IZs); and (ii) proposes management actions that direct inefficient industrial companies to improve water use efficiency. By benchmarking and comparing industries belonging to the same category on their water usage, one can quantify the minimal theoretical water supply needed by a company without economic straining its processing performance. The overall aim is to investigate the feasibility of a demand minimization approach at the IZ level for selected companies as an example for other IZs in the Saigon River and other deltas.

2. Methods

The Data Envelopment Analysis (DEA) technique [29,30] was used to assess the water demand minimization potential in an IZ. Within the DEA, a Decision-Making-Unit (DMU) is defined as a single company within an IZ.

2.1. Three-step approach

The objective of this study was realized in three steps. Firstly, variables for the DEA were defined for assessing water use efficiency based on a literature review and semi-structured interviews with environmental experts employed at the environmental department in local universities, environmental consultancy companies, industrial zone infrastructure companies, and governmental agencies. The companies within studied IZs were selected based on their available variable data on monthly water usage, contaminant loadings, monthly production capacity, number of employees, and surface occupied by a company. Secondly, the defined variables for the DEA were collected through questionnaires filled out by selected industrial companies and industrial zone infrastructure companies. The variable data were collected from January to December 2017, and the mean value of each data was used in the DEA analysis. It is important to compare all the companies within one fixed time frame to have a correct assessment, as was done in this study. Repeating the assessment in five years could indicate trends in the development of the water use efficiency of industrial companies in an IZ. Lastly, water use efficiencies of single companies of the same type of industry were assessed with and without considering the effects of pollutants in the effluent using the DEA technique, as shown below. Thus, the methodology can only compare the companies of each specific industry and does not encompass companies among different categories. Based on the results, the water reduction potential was assessed for other companies and discussed in terms of significance for resolving water scarcity problems for IZs.

2.2. Industry type selection

Four industries categorized by the Standard for Industrial Classification issued by the Ministry of Planning and Investment of Vietnam were selected for DEA analysis. These were the manufacturing of (1) rubber and plastic (*RP*), (2) fabricated metal products (*FM*), (3) other manufacturings (*OM*), and (4) wearing apparel (*WA*). A limited range of industrial categories was chosen because of a requirement for the minimum number of companies in one category [31]. With three inputs and three outputs, the minimum number of companies in each type of industry was determined to be twelve, namely twice the sum of three inputs and three outputs [32]. With a sample size in each type of industry above twelve, there is a greater probability of capturing highly efficient companies in the water use

[33]. The three IZs, Tan Thuan (TTIZ), Hiep Phuoc (HPIZ), and Long Hau (LHIZ), have heterogenous industries' distribution and provide a sufficient sample for data analysis, which is: 13 companies for *RP* (TTIZ-9, HPIZ-1, LHIZ-3), 14 companies for *FM* (TTIZ-11, HPIZ-3), 12 companies for *OM* (TTIZ-10, LHIZ-2), and 18 companies for *WA* (TTIZ-15, LHIZ-3).

2.3. Data envelopment analysis

Charnes et al. [30] and Banker et al. [29] were the first who proposed the DEA technique for evaluating the performances of different entities for various activities and contexts in different countries. Many scholars have successfully applied the DEA technique to evaluate efficiency in education, health care, finances, car maintenance, etc. [34–37], and in water use [38].

The main advantage of DEA is that the technique (i) allows for evaluating the efficiency of multiple variables without reassigning weights and specifying any functioning form [30]; (ii) does not require an extensive observation like traditional statistical analysis methods; and (iii) allows the user to establish relative efficiency of each DMU within an observation set-up [39]. Depending on the evaluation purpose, multiple variables can be set as either input or output variables for the DEA to calculate efficiency. Since the dimensions of input and output variables are different, e.g. monthly freshwater use (m^3/month), number of employees (persons), etc., linear programming of the DEA converts multiple inputs and outputs into virtual input and virtual output, respectively, making these dimensionless [40]. The water use efficiency of the DMU to be evaluated, DMU_o, is calculated by the ratio of virtual output per virtual input as follows:

$$\theta_0 = \frac{virtual\ output}{virtual\ input} = \frac{\sum_{r=1}^{s} u_r y_{ro}}{\sum_{i=1}^{m} v_i x_{io}} = \frac{u_1 y_{1o} + \ldots + u_s y_{so}}{v_1 x_{1o} + \ldots + v_s x_{mo}} \leq 1 \qquad \text{Equation 1}$$

where θ_o is the measure of the efficiency of DMU_o with subscripts of *o* is the DMU being evaluated and $o=1,2, \ldots n$; *i* and *r* present that DMU_o uses $i=1,2, \ldots m$ inputs to generate $r=1,2, \ldots s$ outputs; x_{io} is the amount of input i^{th} for o^{th} DMU; y_{ro} is the amount of output r^{th} for the o^{th} DMU. *u* and *v* are the output and input weights generated in the solution of the DEA equations.

The industrial water use efficiency at a specific IZ was assessed by the initial basic frontier models CCR-I [30] and BCC-I [29] (Charnes-Cooper-Rhodes = CCR; Banker-Charnes-Cooper = BCC). The economy of scale does not play a role in the CCR-I model, whereas it does in the BCC-I model. Comparing CCR-I and BCC-I results could reveal the sources of inefficiency that a company under assessment might have. To evaluate the efficiency using linear programming it is advisable to apply the dual problem approach since (i) a computer can save time in solving dual problems, and (ii) dual problems are more straightforward to interpret results [40]. The argumentation behind using the dual problem approach is described in the supplementary material S1 of this article.

2.4. Efficiencies in water use: overall (CCR), technical (BCC), and scale (SE) efficiency and slack

In this study, the CCR-I and BCC-I assessment identified a group of efficient companies with regard to water use and assigned them a score of one. The variable data of this group serves as a "*benchmark*" to which all other companies are compared (Fig. S1, supplementary material S2). Efficiency scores were determined through DEA results as a target for the inefficient companies that have efficiency scores of less than one but greater than zero to take measures to improve their performance. The CCR-I model score is known as CCR or overall efficiency, while the BCC-I model score is called BCC or technical efficiency [40–42]. [40] took the term "technical efficiency" from the literature on economics to distinguish the "*technological*" aspects of production from other aspects, e.g. economic efficiency. If a company has a BCC efficiency score of 1 but a lower CCR score, then this company is operating technically efficient but not overall efficient due to a suboptimal scale. According to Cooper et al. [40] and Song et al. [42]:

Scale efficiency (SE)=CCR efficiency/BCC efficiency Equation 2

Equation (2) indicates that the smaller the SE value of a company the further off it is from its optimal scale [43].

An inefficient company has room to further improve its efficiency by taking measures to achieve full efficiency: this possibility to improve is referred to as slack. The slacks can be either a surplus in portions of inefficiency (as indicated by the distance from the BCC benchmark -along the input axis (input slack)- or a shortfall in portions of inefficiency -along the output axis (output slack) (Fig. S1, supplementary material S2). A company defined as BCC inefficient in water use indicates that managerial actions can improve the efficiency, e.g. by proportionally reducing inputs (monthly water use, effluent COD or ammonium loads or combinations of those) and combining this with maximizing output, for instance, by producing higher quantities of product. In this study, water use, COD load, and ammonium load slacks are expressed by s_1^- , s_2^-, and s_3^- respectively. Herein, the focus was on identifying the needs for measures addressing BCC inefficiencies since these are related to concrete actions in the operation of a company that can be demanded by IZAs. The scale inefficiency was not addressed here since this can only be overcome by adjusting the company's size, e.g. to a larger or lower size. This means dealing with the domain of the strategic business policies of companies themselves and cannot be influenced by the IZAs.

2.5. Input and output selection

In this study, the chosen DEA input variables were monthly water consumption (m^3/month) complemented with COD load (kg COD/month) and ammonium load (kg $N\_NH_4^+$/month) in the treated effluent of individual companies. Technically, a contaminant load is the product of water flow rate (monthly water consumption) and the concentration of a contaminant. When the water consumption is reduced, the effluent concentration of the contaminant would increase and could exceed the effluent standard. In this way, the input parameters of water use and contaminant loads are coupled in the efficiency analysis. The COD and ammonium were selected because they are key macro-pollutant parameters in the national technical regulations of Vietnam on industrial wastewater [56] and surface water quality [57]. In addition, COD is the main contaminant used to calculate the environmental protection fee for industrial wastewater treatment [55]. Later, other parameters, such as phosphate, specific chemical pollutants, organic micropollutants, etc., which exist in current regulations or emerging in future regulations, could be added. Besides, COD and ammonia were used as pollutant indicators to evaluate the industrial water use efficiency in terms of amounts of water pollutants generated. Discharges of these contaminants are inefficient as they deteriorate water resources in the local environment and diminish the availability of high-quality water [38,44]. In the first assessment, the present study considered three inputs for calculating efficiencies by the DEA, monthly water consumption, COD, and ammonium loads. In a second assessment, only monthly water consumption was used as the input. The effects of contaminants on water use assessment could be considered by comparing the two. The present study set production capacity (ton product/month or the number of product/month), the number of employees (employees/company), and surface area (m^2/company) as the output variables for the DEA. These outputs were chosen since they contribute to the water use efficiency of a company. In some industries, e.g. in FM, product capacity (ton/month or product/month) reflects the output benefit of industrial water resources, while that of other types of industry, e.g. WA, is reflected by the quantity of labor (person/company). Water is mainly consumed for floor or surface cleaning and toilet flushing in industries like the warehousing industry. Besides, all companies within the IZs boundary are requested to maintain at least 20% of their rented surface area as a green space. Thus, along with processing activities, sanitation, and cleaning, companies also consume water for irrigation. Individual companies of the same industrial category were ranked as more efficient when water input to serve these outputs was less than others.

This study emphasized reducing inputs (monthly water consumption, monthly loads of COD and ammonium in effluent water of companies) to achieve efficiency. An input-oriented version for both CCR and BCC models was considered appropriate for situations where the manager has control over the inputs [45]. Besides, it reflects the focus of the study on consuming water more efficiently rather than increasing production. The stages for assessing industrial water use are presented in Fig. 1. According to Equation (1), water use efficiency can be promoted by decreasing inputs (water usage and contaminant loads) in an input-oriented model.

2.6. *Identification of management situations to improve the water use efficiency*

According to DEA theory [40], the CCR efficiency score is the product of the BCC efficiency and scale efficiency scores: $\theta_{CCR} = \theta_{BCC} \times \theta_{SE}$. Four specific situations can be considered using this relationship: ***I) SE=CCR=BCC = 1:*** the company is at maximum efficiency; ***II) SE = 1 and BCC<1:*** the overall (CCR) inefficiency is primarily attributed to technical issues (BCC inefficiency). These companies are considered "close to optimal scale" and "non-intensive water users" [46]; ***III) BCC = 1 and SE < 1:*** the overall inefficiency is primarily attributed to scale effects (though SE inefficiencies are identified, these are not further elaborated on possible actions for earlier explained reasons); and ***IV) BCC<1 and SE < 1:*** the overall inefficiency is due to technical issues and scale effects. These four situations could be a basis for specific actions, as explained below.

2.7. *Data acquisition and analysis*

The IZs provided lists of all companies located in their zones. In the National Business Registration Portal of Vietnam, the business code was acquired with which these companies were registered at the system of the Ministry of Planning and Investment of Vietnam [47]. Industrial typologies of individual companies were classified according to this system.

For solving equations of the CCR-I and BCC-I models, the program DEA-Solver was used as a software [45]. Three steps were followed for screening the data to yield a reliable assessment. First, a mean normalization was applied to ensure that all inputs and outputs were of similar magnitude across and within the dataset [33]. This mean normalization was carried out through two sub-procedures: determining the mean of the dataset for each input and output variable and dividing each input or output by the

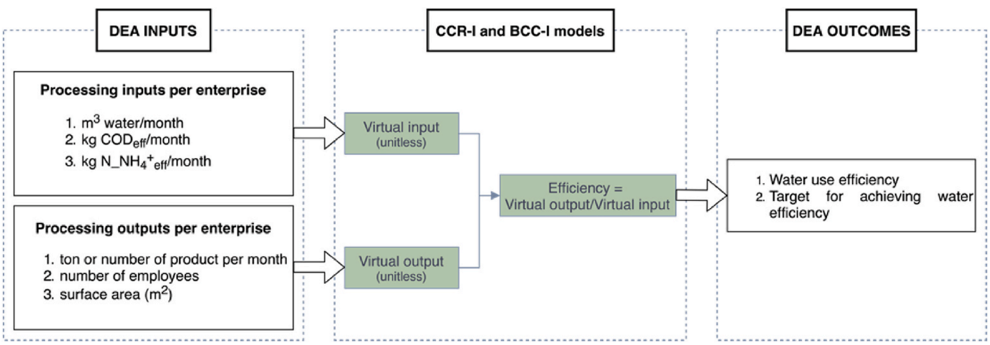

Fig. 1. Implementation steps for evaluating water use efficiency by the DEA as applied in this study; in the second comparative trial, contaminant inputs 2 and 3 were omitted.

defined mean value. Second, the super-efficiency DEA model, available in the DEA-Solver, was used as an outlier detection procedure. The super-efficiency model identifies companies whose super-efficiency scores exceed the pre-selected threshold of 1.3 as outliers [48–50]. Third, the companies identified as outliers were removed from the dataset, and the CCR-I and BCC-I models were calculated with the remaining companies.

3. Results and discussion

3.1. Industrial water use efficiency assessment through data envelopment analysis

The outcomes from the DEA efficiency assessment in Fig. 2 (a..d) depict the CCR-I, BCC-I, and SE scores concerning the water use of companies from four selected industrial categories. As Fig. 2a and b shows, five of thirteen companies in *RP* and six of fourteen companies in *FM* were CCR and BCC efficient (score of 1). Companies "7" and "8" in both categories were BCC efficient but CCR inefficient, while the remaining six companies in both industries were CCR and BCC inefficient. Within twelve companies in *OM*, only one company was identified as CCR and BCC efficient, six companies were found BCC efficient but CCR inefficient, and five companies were both CCR and BCC inefficient (Fig. 2c). Similarly, of the eighteen companies in *WA,* three were CCR and BCC efficient, five were CCR and BCC inefficient, and the ten remaining were BCC efficient but CCR inefficient (Fig. 2d).

The difference between CCR and BCC efficiencies indicates the existence of scale inefficiency in a company. Fig. 3 shows the relationship between the BCC efficiency score (X-axis) and scale efficiency (SE) score (Y-axis) of companies in four selected industrial categories. Fig. 4 explains a cluster of management actions needed for different cases. Action I is applied to companies obtaining BCC=SE=1. For these companies, no improvements need to be made. Action II is applied to companies obtaining SE = 1 and BCC<1. These companies need to reduce their input consumption by focusing on reducing monthly water consumption through better technology implementation or changes in internal water use behavior, such as less water being used for processing, cooling, toilet flushing, or floor cleaning [51,52]. Action III is applied to companies obtaining BCC = 1 and SE < 1. These companies have two options: either to go for an expansion or a shrinkage in production as a water efficiency increasing strategy [43]. Action IV is applied to companies obtaining BCC<1 and SE < 1. These companies need to take two types of measures: changing their consumption behavior by technical measures (as in action II) combined with an expansion or a shrinkage in production strategy (as in action III).

Results indicate that significant numbers of companies in the four categories are inefficient water use for **technical reasons**, namely 46%, 43%, 42%, and 28% of companies for *RP, FM, OM,* and *WA*, respectively. Fig. 3a, which shows BCC and SE scores of companies in the rubber and plastic industry (*RP*), is taken here as an example. Five companies have BCC and SE efficiency scores of one (*RP*9..13) and are defined as CCR efficient, meaning no action (action I, Fig. 4) needs to be taken. The company *RP*4 has BCC<1 and SE = 1 and needs to take action II (Fig. 4). Technical measures to reduce its water consumption should be taken to improve its BCC efficiency. In case BCC = 1 and SE < 1 (e.g. *RP*7,8), a company needs to take action III (Fig. 4) to improve its scale efficiency. If a company has BCC and SE efficiency scores of less than one (e.g. *RP*1,2,3,5,6), these companies need to take action IV (Fig. 4). This reasoning was applied to all four industrial categories. For *FM*, six companies were already fully efficient, and six companies

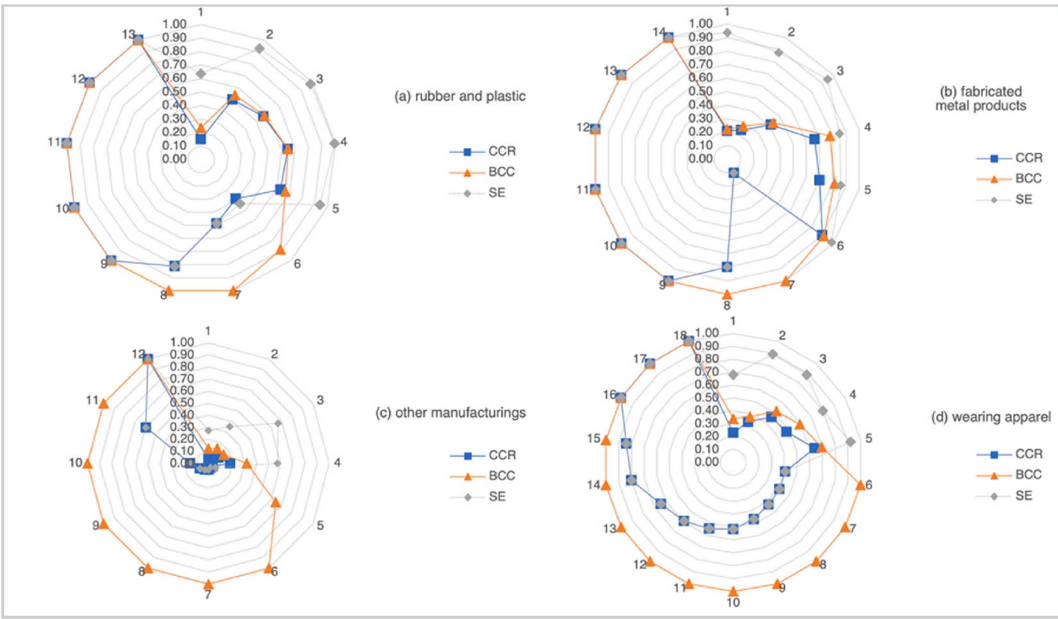

Fig. 2. CCR, BCC, and SE efficiency scores of companies for water use in four selected industries. Numbers 1 to 18 are DMUs within four industrial categories. The water-efficient companies are located on the outer grid of the radar chart; all others have inefficiencies.

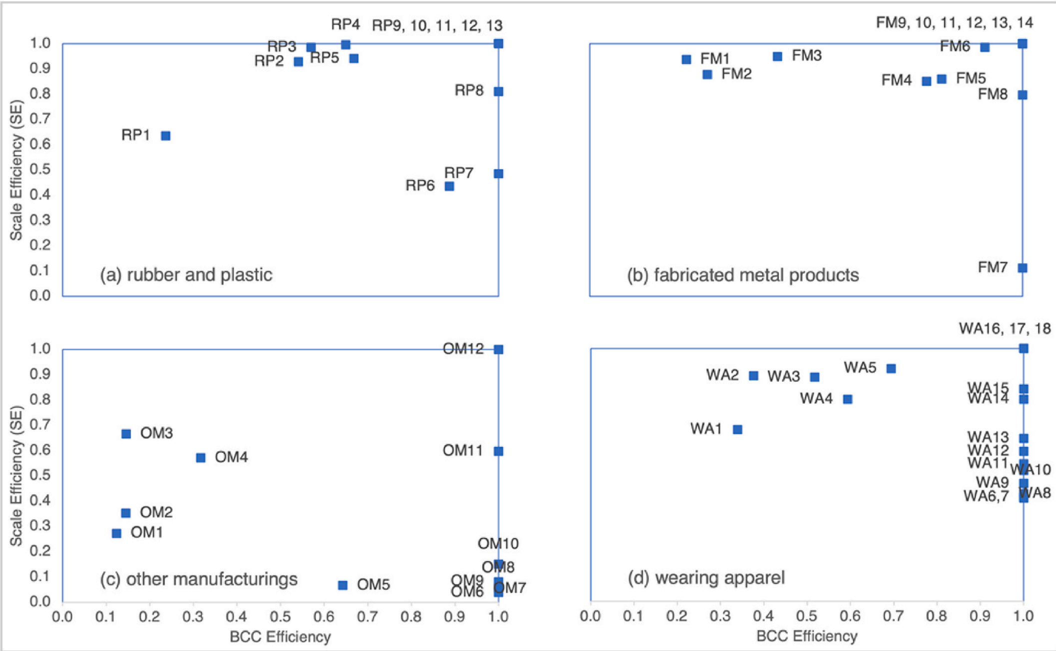

Fig. 3. BCC and SE scores of companies in four industrial categories.

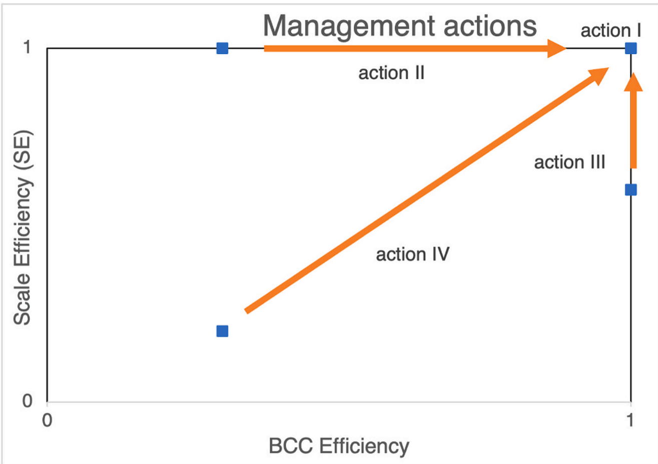

Fig. 4. Management actions for companies as identified by SE and BCC scores.

(*FM*1,2,3,4,5,6) could take technical measures to improve the (BCC) water efficiency. In comparison, two companies (*FM*7,8) should consider improving scale efficiency. The situation for *OM* is that only one company (*OM*12) is fully efficient, five companies (*OM*1,2,3,4,5) could take technical measures to improve the (BCC) water efficiency, and all companies under evaluation except for *OM*12 should consider improving scale efficiency by shrinking or expanding. For *WA*, three companies (*WA*16,17,18) were already fully efficient, and five companies (*WA*1,2,3,4,5) could take technical measures to improve the (BCC) water efficiency, while ten companies (*WA*6..15) should consider improving scale efficiency. These results indicate that for *RP* and *FM,* the focus needs to be primarily on improving BCC efficiency, thus taking technical measures, while in *OM* and *WA,* these measures are also required but a significant portion of the companies needs to consider strategic business measures to improve its scale efficiency.

The above method can help set a strategy for improving water use efficiency at different industrial levels, either an individual company, an industrial category, or all selected companies in a complete IZ. As said, the focus here is on actions II and IV: improving BCC efficiency by implementing innovative technologies or new production processes. This is a managerial problem that can be addressed by the industrial zone authorities in discussion with individual companies to investigate how fewer inputs can be used to produce a certain number of products.

3.2. Water use efficiency benchmark

To further analyze the potential effects of technical measures on water resource savings, which is the focus of this study, the relevant cases (*RP*1,2,3,4,5,6; *FM*1,2,3,4,5,6; *OM*1,2,3,4,5; *WA*1,2,3,4,5) were further benchmarked as explained by an example calculation in the supplementary material S3. In Table 1, the *RP*3 was taken as an example of water efficiency target calculation, including the effect of pollution loads, as explained in detail in supplementary material S4.

Efficiency targets expressed as required input reduction percentages for the companies in the *RP* industry were calculated using this approach and are depicted in Table 1.

The s_1^-, s_2^-, s_3^- are slacks related to water consumption, COD effluent loads, and ammonium effluent loads, respectively. In Table 1, companies *RP*7..13 are defined as BCC efficient because the BCC score is 1, and all input slacks are zero. The same procedure was applied to the other inefficient companies of the other three industrial categories, and the overall results per industrial category are presented in Table 2. Here, the efficiency target that is the sum of the various companies in that industry category is expressed as water reduction potential for the different industries.

Table 2 (columns 3 and 4) lists the overall water saving potential per industry considering contaminant loads as assessed by DEA (WRP3). For comparison, the water use efficiencies of inefficient companies were also determined without pollution loads and based on one input (WRP1), namely water consumption only (columns 5 and 6). Water reduction potential to reach the efficiency target through implementing technical measures (e.g. process optimization or effluent water treatment reducing pollutant emissions) at yet inefficient companies when including pollution loads (WRP3) sums up to 17%(*FM*), 25%(*RP*), 7%(*WA*), and 4%(*OM*) water saving.

Our method assumed that WRP in an industrial category significantly depends on the water consumption behavior of the efficient companies within that category. Fig. 2a and Table 1 indicate that some companies in *RP* may need to cut substantial amounts in their water demand to become fully efficient. For example, companies 6 and 1 of *RP* should decrease their monthly water consumption by 11% and 76%, respectively (Table 1, column 6). High percentage reductions may not be easily implemented in practice. Still, the DEA numbers give IZAs a good base for starting a discussion with a company and asking for further investigation into the cause of such high inefficiencies.

The theoretical finding (Table 2, column 4) is that WRP3 in industries ranges from 4% (*OM)* to 25% (*RP*) and that improving water use efficiency can be enhanced by cooperative efforts among different industrial companies in the technical innovation [53]. The total quantity of water to be saved per researched industrial sector (m^3/month) is determined by the amount of water used (m^3/month) and the WRP (%) and ranked in the order of $FM \gg RP > OM > WA$. The WRP provides limited but not to be ignored contributions to make these industries more self-sufficient in water use.

3.3. Water reduction potential effects of contaminant loads

When the contaminant loads were included (WRP3), water use efficiencies in selected industries were found lower than when contaminant loads were excluded (WRP1) (Table 2). The exclusion of contaminant loads as inputs shifts the quantitative WRPs from 25 to 27%(*RP*), 17–20%(*FM*), 4–6%(*OM*), and 7–14%(*WA*). Thus, the gap between the two efficiencies is small. The results of the two WRP scenarios, e.g. with and without considering contaminants, are presented in Fig. 5 for all companies being part of the DEA assessment.

As shown in Fig. 5, when including contaminant loads in the input of DEA, more companies were defined as fully efficient, and inefficient companies were more efficient than when excluding contaminant loads. This result is consistent with the findings of Xu et al. [38].

If the three inputs are used, the efficient companies (which have zero water-saving) outnumber the inefficient ones. But when only the monthly water consumption was applied as input, several efficient companies in the three-input case appeared to be inefficient, e.g. *RP*8,13, *FM*11, *OM*8, and *WA*7,9,10,11,12,14. When accounting for multiple input contaminants, efficient water management (by more optimal processes or contaminant removing treatment before discharge outside the boundaries of a company domain) trades off with measures oriented on quantitative water use efficiency. Thus, the potential for quantitative water saving is less than when contaminant loads are excluded. Although this goes at the cost of higher pollution of freshwater resources in the local environment, technical measures can also be taken to improve the company's performance. This shows that the fully efficient companies in the three-input DEA technique can be more efficient by including additional water-saving measures and pollutant emission reduction measures.

Table 1
BCC efficiency scores and input slacks across the rubber and plastic (*RP*) industry.

Company	BCC score	Input slacks (unitless)			Efficiency targets		
		s_1^-	s_2^-	s_3^-	Monthly water consumption reduction (%)	COD load reduction(%)	Ammonium load reduction(%)
*RP*1	0.24	0	0.915	0	76	96	76
*RP*2	0.54	0	0	0	46	46	46
*RP*3	0.57	0	0.434	0.553	43	86	80
*RP*4	0.65	0	0.179	0	35	87	35
*RP*5	0.67	0	0.556	0	33	85	33
*RP*6	0.89	0	1.35	2.893	11	77	83
*RP*7..13	1.00	0	0	0	0	0	0

Table 2
Monthly average water consumption and WRP across industrial categories.

	Water use[a]	WRP3[b]		WRP1[c]		WRP1 - WRP3	
	m^3/month	m^3/month	%	m^3/month	%	m^3/month	%
FM	105,325	18,199	17	20,581	20	2382	+3
RP	13,797	3385	25	3746	27	361	+2
OM	47,759	1841	4	2684	6	843	+2
WA	23,116	1663	7	3220	14	1557	+7

The notation "+" in the last column indicates the difference in water saving potential between three input and one input scenarios.
[a] Sum of actual monthly water consumption of all selected companies in each industry.
[b] Water reduction potential (WRP) with three input parameters: water use, COD, and ammonium effluent loading.
[c] Water reduction potential (WRP) with one input parameter: water use.

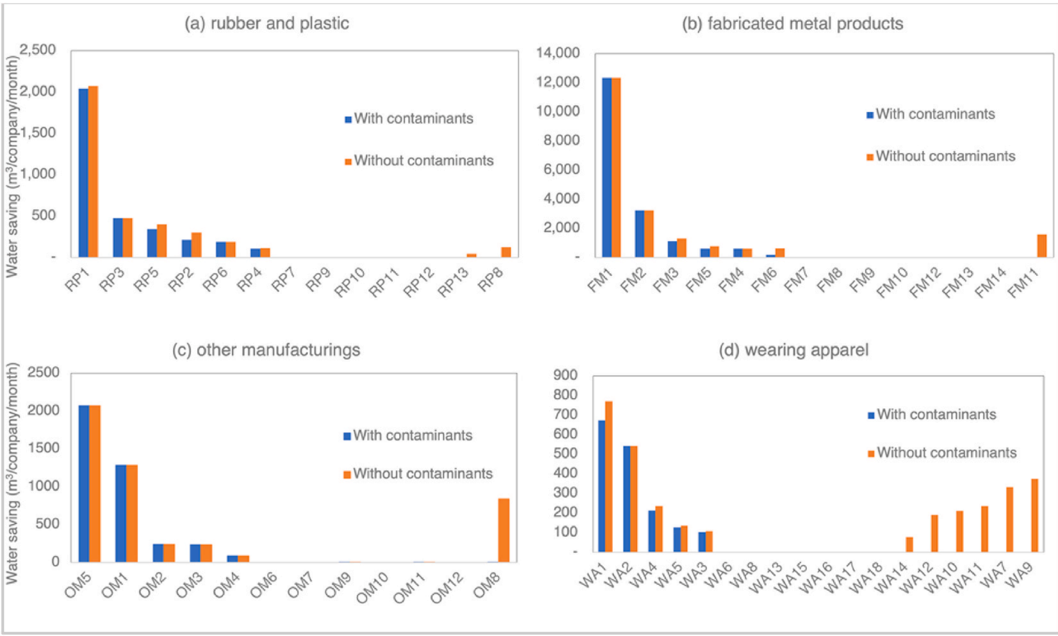

Fig. 5. Studied industrial companies' water saving with and without accounting for contaminant loads.

Therefore, the benchmark of BCC efficiency can be "*pushed*" to higher levels.

3.4. Potential for demand minimization

The DEA assessment estimates the water demand minimization indicated by the WRP of 4–25%. This is consistent with the observations of the TTIZ manager, who supported and encouraged the companies within the TTIZ to save water demand. The TTIZ advocates demand minimization as cost-effective and feasible; however, the maximal water-saving found by the TTIZ manager is limited to 20% of total water consumption per company. Thus, this DEA assessment study and IZAs findings in practice are consistent. This means that supplementary strategies are needed to make companies and IZs more self-sufficient in water provision. The comparison between 'with and without contaminant considerations' does not alter this central conclusion. Though an important first step demands minimization needs to be complemented with other measures. For that, one can consider two options that have not been applied yet by the companies under assessment in this study: (i) multi-sourcing, which includes rainwater harvesting, brackish water treatment and use, and (ii) recycling of water by wastewater effluent treatment, storage, and reuse. For this, physical, chemical, and biological treatment technologies are needed, combined with filtering in natural groundwater and wetland systems [54].

3.5. Utilization and implications for practice

The results of this theory underpinned the DEA study can be used to assess the current water use of a single company by incorporating multiple criteria into the analysis. Assessment of water use efficiency through benchmarking is an early attempt to define an industrial metabolic profile of companies and the IZ and design targeted demand minimization measures in the water management at an IZ. Based on the four management actions (Fig. 4), this article proposed a stepwise procedure that the decision-makers at various levels could consider to push the inefficient companies towards full efficiency. The first step is to reduce the input consumption of inefficient companies due to only technical issues (SE = 1 and BCC<1). The second step is to improve only the BCC efficiencies of companies having technical inefficiency and scale inefficiency (BCC<1 and SE < 1). In this way, the SE efficiency scores of these companies are still less than one, but the BCC scores move horizontally towards the BCC = 1 (Fig. 4). In the last step, scale inefficiency companies could decide to expand or shrink production to achieve full efficiency.

As shown, the potential of demand minimization is essential but limited to 25% at maximum. This WRP, i.e. the "*degree*" of water use efficiency, serves as a starting point for follow-up studies establishing a hierarchy of measures that guide prioritizing process changes. The hierarchy of measures may start with demand minimization (the highest priority level) by optimizing industrial processes and domestic water use. Therefore, other steps, such as multi-sourcing, cascading, and recycling, are needed to assist and guide an IZ to become less dependent on water imports outside the region. Moreover, multi-sourcing, cascading, and recycling will require an inter-plant network connecting demand-supply among potential companies, which needs to be designed and implemented, e.g. it requires treatment and transport infrastructural investments. Since these investments can help industrial zones, in general, to improve their self-sufficiency in water provision, the design and cost-effectiveness of these technical measures are the focus of follow-up studies.

3.6. Summarizing discussion

This study applied data envelopment analysis (DEA) to determine water use efficiency in four selected categories of industries in industrial zones (IZs) in the Saigon River Delta of Vietnam. The DEA technique served as a theory underpinned method for assessing water reduction potential for industrial categories. Effects of multiple perspectives and factors like monthly water consumption, pollutant loads, production capacity, company size, and the number of employees were combined and interrelated in one assessment requiring a limited number of companies for each of four industrial categories in the three IZs. The results revealed that several companies have already reached full efficiency, but a significant fraction can improve their water efficiency and contribute to water saving. Moreover, the DEA technique helps implement water demand minimization in IZs and resolve water competition among agricultural, urban, and industrial sectors. These are crucial first steps towards sustainability in industrial water provision in Vietnam.

The main shortcoming of this assessment is that it does not account for unused methods to further harvest the water reduction potential in the water-efficient companies. These companies can reduce water inputs by improving their internal processes, using less water, or upgrading and reusing produced water in internal recycles. The current water-efficient companies could further push the boundaries in harvesting the water reduction potential, and by this challenge other less efficient companies to take further measures. Hence, the DEA method can continuously be used to improve the industrial sector concerning water efficiency. Besides, the DEA technique evaluates the performance of individual companies under the same type of industry without considering their production technology which may vary according to the manufacturing profiles. Therefore, the DEA technique proposed in this article highlights that the water reduction potentials are linked to the actual context for evaluation. Further investigation of the contributions of individual companies can facilitate synergies in improving industrial water use. Such a further investigation may expand to external comparators to evaluate the effect of context on the water use efficiency of companies of similar type of production. This context may be different for different regions within a country or within a continent. The context contribution to water efficiency may be uncovered by including subsets of industries from the different regions (i.e. Southern, Central, and Northern Vietnam or other countries in Southeast Asia). Such a more comprehensive DEA application will allow for a regional and international comparison and benchmarking and may drive knowledge exchange and subsequent triggering of further innovations in water efficiency among industrial sectors in the region.

Further research should address the scaling-up from individual company to industrial zone scale to compare the water use efficiency of all companies within the same industrial zone, disregarding which type of industrial category a company belongs to. On a larger scale, one may find different trade-offs in water reduction potential between different industrial categories, which would open the path to inter-industry water exchange, i.e. cascading water from one industry to another. These cascading measures would further improve the water efficiency of an IZ. This is the direction of further ongoing studies being prepared for publication.

4. Conclusions

From the above-discussed results, two primary outcomes can be drawn:

1. The DEA technique can be applied successfully to support industrial zone authorities and governmental agencies to assess water efficiency and build their water-saving management and policies.
2. Demand minimization can yield a minimum of 4 and a maximum of 25% of water savings, depending on the industrial category. Therefore other measures such as multi-sourcing and water recycling are needed to reach higher levels of self-sufficiency in water provision at industrial zones in Vietnam and comparable deltas.

Furthermore, future studies should include industrial companies from the same category but from other regions in Vietnam or other countries to reveal the effects of different socio-economic or climatic contexts.

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CRediT author statement

Truong M. Le: Conceptualization, Methodology, Investigation, Formal analysis, Writing-Original draft preparation, Visualization. **Katarzyna Kujawa-Roeleveld:** Methodology, Validation, Formal analysis, Writing-Review & Editing, Supervision. **Dieu M. T. Tran:** Conceptualization, Resources. **Huub H. M. Rijnaarts:** Methodology, Validation, Formal analysis, Writing-Review & Editing, Project administration.

Data availability statement

The data that supports the findings of this study are available in the supplementary materials of this article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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