Production and Scale Efficiency of South African Water Utilities: The Case of Water Boards

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Abstract

South Africa is a water scarce country with deteriorating water resources. Faced with tight fiscal and water resource constraints, water utilities would have to adopt technically efficient water management technologies to meet developmental socio-economic objectives of universal coverage, aligned to the United Nation's Sustainable Development Goal 6 (SDG 6). It is important to measure the technical efficiency of utilities as accurately as possible in order to inform policy. We do this by using a non-parametric method known as Data Envelopment Analysis (DEA) to determine, measure, analyse and benchmark the technical efficiency of all water boards in South Africa. Our contribution to the literature is twofold: This is the first paper to model technical efficiency of water boards as utility suppliers and guardians of water services in South Africa, and second, we address the over- and under estimation issues of technical efficiency measurement in the water sector. We do this by modelling one of the most pronounced negative externalities from water provision (water losses) as an undesirable output using the approach developed by You & Yan (2011). We find on average, technical efficiency of water boards is 49 per cent, with only three of the nine water boards technically efficient. Six of the smaller water boards showed high levels of inefficiency. Six water boards operate at increasing returns to scale (IRS) and two are scale efficient. Only Rand and Sedibeng water boards exhibited decreasing returns to scale (DRS). Therefore, redirecting potential efficiency savings to optimal uses could result in technical and scale efficiency for the sector. Scale efficiency results seems to support larger regional water boards as small to medium-sized water boards are scale inefficient with low technical efficiency. The ratio model with undesirable output outperforms previous methods to deal with undesirable (bad) outputs, which either provide an over- or underestimation of technical efficiency.

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1. Introduction

The United Nations 2030 Agenda for Sustainable Development was adopted in September 2015. It established 17 Sustainable Development Goals (SDGs) relating to global development outcomes. The establishment of the SDG 6: ensuring availability and sustainable management of water and sanitation for all, reflects increased attention to water and sanitation on the global development agenda. The pillars of the SDG 6 are: achieving universal access to safe and affordable drinking water and sanitation by 2030, improving water quality, wastewater treatment and safe re-use, increasing water-use efficiency to ensure water security, especially in water stressed areas, and implementing integrated water resources management and adequate financing to meet the SDG 6 targets (United Nations, 2018).

According to the United Nations (2018), most countries are struggling to meet the SDG 6 targets. Despite this, the proportion of the global population using at least a basic drinking water service increased from 81 per cent in the year 2000 to 89 per cent in 2015. The proportion of the global population using at least a basic sanitation service increased from 59 per cent in 2000 to 68 per cent in 2015. Water quality problems are largely associated with developing countries; however, most countries have implemented integrated water management practices.

Table 1: South African Water Sector Indicators and Progress on SDG Goal 6

| Water resources availability and security	17% deficit: 3 800 million m³/a by 2030
	Average annual rainfall of 465 mm (half of the world average)
	Total annual runoff of approximately 49 000 million m³/a of which 63% is stored in large dams
	The current reliable yield of surface water at an acceptable assurance level of supply: 10 200 million m³/a nationally
	3 000 million m³/a is from ground water
	61% of water is used by Agriculture and 39% by domestic, industry, afforestation and other sectors
Water and sanitation access	Of 16.9 million households, 15.2 million or 89.9% have access to piped water with 83% having access to safe drinking water. 64% of households have relibale access to water supply services
	Average domestic water use is around 237 litres per person per day (world average: 173 litres per person per day)
	10.3 million or 61% of households have access to sewage connected flush toilets, with the additional 37% having access to some form of sanitation. Only, 14.1 million households have access to safe sanitation.
	Non-Revenue Water: 1 660 million m³ per year, R9.9 billion each year
Financing gap	R33 billion each year

Authors' Table adapted from DWS (2019).

Table 1 shows that South Africa is a water scarce and rainfall deprived country compared to the rest of the world, which makes South Africa a good candidate for analysis. This is also affirmed by Masindi and Duncker (2016). The country only receives 465 mm or 50 per cent of

the rainfall received by most countries in the world annually. Given its high reliance on surface water, there is a need to manage existing resources efficiently. According to the Department of Water and Sanitation (DWS) (2019), South Africa is facing a water crisis caused by insufficient water resources, and poor infrastructure maintenance and investment. The DWS alludes to plans to diversify the sources of water where water security is to be derived from ground water, water conservation and water demand management (given the high levels of technical distribution water losses-excluding non-technical losses like billing inefficiencies and non-collection, of more than 1 660 million m^3/a), water re-use, desalination and effective cross-boundary water management. DWS estimates the water infrastructure investment deficit to be R33 billion per annum (about $2.2 billion). The quality of rivers and ground water remains poor, signalling weaknesses in water resources management.

In terms of water use, the DWS (2019) reported that agriculture uses 61 per cent of allocated water while municipalities use 27 per cent. The remainder is consumed by other sectors, such as energy, industries, mining, livestock and forestry. As it relates to universal access to basic water services, South Africa is amongst the countries that are performing relatively well. Table 1 indicates that of the 16.9 million households or total population of 59.9 million, 89.9 per cent or 15.2 million households have access to piped water (also see Figure 1) while 61 per cent or 10.3 million household have access to flush toilets complemented by the other forms of sanitation. The Achilles Heel of the South African water sector is inadequate management of infrastructure, for example, the DWS (2019) indicated that approximately 56 per cent of over 1 150 municipal wastewater treatment works (WWTWs) and approximately 44 per cent of 962 water treatment works (WTWs) in the country are in a poor or critical condition, and 11 per cent of this infrastructure is completely dysfunctional. This poor management results in average technical distribution water losses of 36 per cent or 1 660 million m^3 by municipalities and 7 per cent by the water boards. On the consumption side, South African water users consume 237 litres per capita per day; 64 litres more than the average global daily consumption.

Figure 1: Provincial Household Access to Water
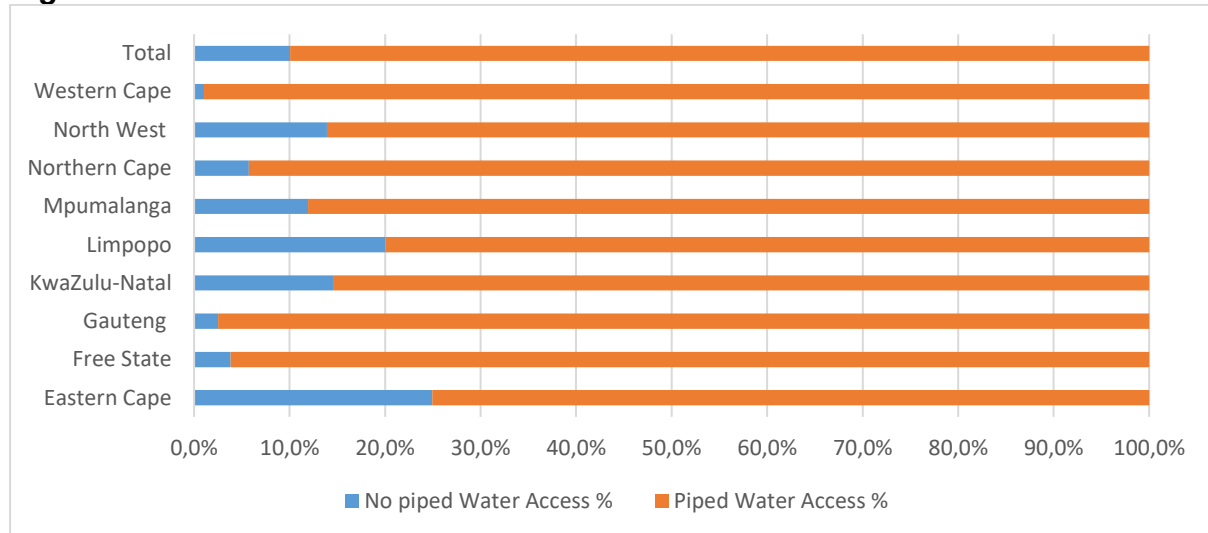
Source: Authors' Graph adapted from Statistics South Africa (2016).

Figure 2: Water Sector Institutional and Role Players
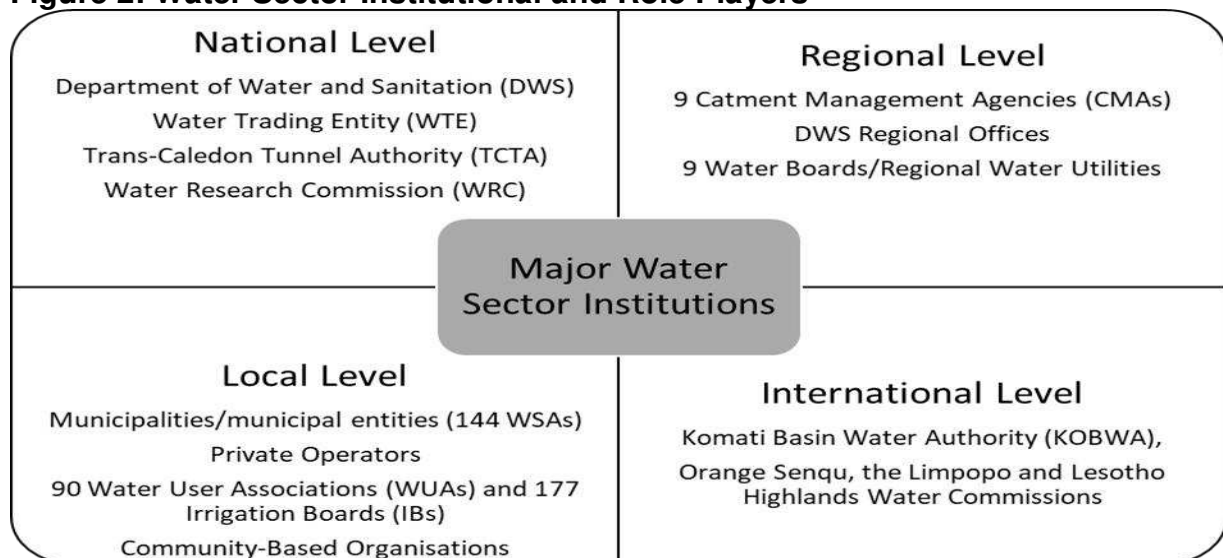
Sources: Authors' Diagram adapted from DWS (2019) and Beck et al. (2016).

The water sector value chain is comprised of national water resources, regional bulk and local retail water and sanitation services segments. According to Masindi and Duncker (2016), the DWS is the designated custodian of water resources by the National Water Act. It leads policy development and regulates the water and sanitation sector in South Africa. It is also responsible for planning and implementation of large water resource infrastructure projects, issuing of water-use licenses, allocating water, performing catchment management functions, river systems management, water storage and abstraction and return-flow management. At a regional level, according to Masindi and Duncker (2016), there are nine water boards mainly responsible for bulk water purification and distribution, however, some municipalities and the

DWS also perform this function. The National Treasury (2019) stated that water boards are mandated by the Water Services Act to provide bulk industrial and potable water services to municipalities and industries within their legislated areas of supply. The water boards vary in size, activities, customer mix, revenue base and operational capacity. As opposed to municipalities, the bulk distribution networks of water boards are generally in good condition, with acceptable levels of total water losses (about 7 per cent), showing good management of infrastructure. In terms of the Constitution, municipalities have sole powers to reticulate water to households. However, where there is no capacity to deliver, they appoint other service providers such as water boards and private sector operators to implement on their behalf. The mandates of the other water institutions are summarised in Table 2, which also outlines their high-level operational performance.

Table 2: Summary of Operations of Key Water Sector Institutions, 2020/21

Institutions	Mandate	Revenue (R'000)	Expenditure (R'000)	Carrying Value of Assets (R'000)	Net volumes
DWS	The DWS is responsible for water sector policy, support and regulation. Wholly funded by the national governement	17 000 000	17 000 000	2 000 000	-
WTE	The WTE deals with the management of water infrastructure and resources, and the sale of raw water. Largely funded from water tariffs and augmented through the national budget for public interest functions. The Department's asset register indicates a total pipe network of 1 070 km and canal systems of 8 100 km. Of the 5 248 registered dams in South Africa, the DWS/WTE only owns 6% (320), but they account for 86.4% of the retained water	16 000 000	14 000 000	98 000 000	19 142 million m³/a sold.
TCTA	The TCTA is responsible for financing and implementing the development of bulk raw water infrastructure, and providing treasury management services to the DWS. The authority plays an important role in providing: financial advisory services such as structuring and raising project finance, managing debt and setting tariffs; project implementation services; and other technical support to the department and water boards. Funded through the WTE from raw water sales revenue.	5 000 000	6 000 000	-	-
9 CMAs	The CMA's mandate is the management of water resources. Funded from water resource management charges and losses subsidised by the DWS through the WTE	753 000	753 000	-	19 142 million m³/a managed.
9 Water Boards	Water Boards provide water services (bulk potable and bulk waste water) to other water services institutions. They own large bulk distribution pipelines, reservoirs and water and waste water treatment plant and serve municipalities and industries	29 000 000	24 000 000	75 000 000	2 528 million m³/a sold net losses of 7% .
146 Municipalities	Authorised municipalities (WSAs) are responsible for bulk and retail water supply. They purchase bulk water from water boards or directly from the DWS. Municipal water reticulation infrastructure includes more than 290 000 km of pipelines supplying water to 89.9% of the population.	76 000 000	69 000 000	33 400 137	4 980 million m³/a produced, 36% or 1 660 million m³/a lost.
Total		143 753 000	130 753 000	208 400 137	-

Authors' Table adapted from National Treasury (2020a,2020b), DWS (2019), Statistics South Africa (2020, 2016), Beck et al. (2016) and Water Research Commission (2012).

Masindi and Duncker (2016) and DWS (2019), indicated that some challenges facing the water boards, municipalities and DWS include weak governance, lack of adequate funding coupled with inefficient operations to meet and sustain investment requirements, inappropriate financing and pricing arrangements and lack of accountability. Moreover, water is severely under-priced and cost recovery is not being achieved. This results in ineffective operations and maintenance of water supply infrastructure. Gupta, et al. (2012) advised that if the water and sanitation supply revenue from user charges falls short of expenditure (financing and investment gap), it causes assets to deteriorate and threatens the sustainable supply of water and sanitation services.

According to Table 2, the scale of operations of municipal water businesses in the water and sanitation services supply space performed by approximately 146 authorised municipalities, exceed that of the nine water boards. The consolidated water revenue and expenditure of these municipalities is 3 times that of the nine water boards; however, the carrying value of assets of the water boards is 2 times larger than that of the municipalities. According to the DWS (2018), the DWS, water boards and municipalities and other state departments own about 854 dams, mostly with high storage capacity and the private sector owns about 4 657 small dams. From Table 2, it is further evident that the nine water boards own large bulk distribution pipelines, reservoirs and water and waste water treatment plants used to serve municipalities and industries. Municipal water reticulation infrastructure includes more than 290 000 kilometres of pipelines currently supplying water to 89.9 per cent of the population. In terms of the volumes produced and sold, the water boards sell about 2 528 million m^3 per annum after accounting for 7 per cent average distribution losses while municipalities produce 4 980 million m^3 per annum, but, sell about 3 187 million m^3 per annum after accounting for 36 per cent average technical losses. This implies that water boards provide about 50 per cent of municipal bulk water requirements while municipalities self-produce the remainder. The Water Trading Entity (WTE), Catchment Management Agencies (CMAs) and the Trans-Caledon Tunnel Authority (TCTA) collectively construct and manage water resources assets such as dams, canals, pipelines and conveyancing systems valued at R98 billion producing and distributing 19 142 million m^3 per annum, of which 61 per cent is used by the agricultural sector and the rest by other sectors, including municipalities and water boards as reported earlier.

It is clear that the South African water value chain is inextricably linked with the water resources and water and sanitation services components complementing each other. Despite the financial value of the municipal water business being the largest in the value chain, their efficiency in the supply of water and sanitation services has been widely studied. See Murwirapachena, et al. (2019), Brettenny and Sharp (2016), Monkam (2014), Mahabir (2014) and Dollery and Van der Westhuizen (2009). However, we could not find a study on the technical efficiency of water boards in South Africa, except for a paper by Ngobeni and Breitenbach (2020). For this reason, we opted to analyse the efficiency of water boards in South Africa. Our paper differs from the paper by Ngobeni and Breitenbach (2020) in that we use a methodology developed by You and Yan (2011) to adequately include a very significant undesirable (bad) output related to water provision, namely water losses, in our model (ratio model) and we compare the results with traditional models to illustrate the biased efficiency results from the traditional models. You and Yan have shown that the results from their model provide results superior to other methods of dealing with undesirable outputs. This is discussed more fully under the methodology section.

We analyse the technical efficiency of water boards by applying a non-parametric benchmarking tool called Data Envelopment Analysis (DEA). DEA is ideal to measure and compare the technical efficiency of the nine water boards as they operate in similar conditions. It is easy to compare their production technologies to determine efficiency. Gupta et al. (2012) recommended the use of DEA for determining the technical efficiency of decision-making units (DMUs). They argued that despite other techniques such as the ordinary least square (OLS) and stochastic frontier analysis (SFA) being used in analysing the technical efficiency of the water industry, DEA is the most appropriate. The OLS technique is easy to use and simple to interpret, however, it suffers from the problem of specifying the functional form for the production technology and is unable to provide information on frontier performance. The SFA, although able to solve the latter problem by specifying a composed error term and splitting the error term into two different parts as a data noise term and error due to the inefficiency, it also suffers from the problem of specifying the functional form and requires specification of the distribution patterns of the inherent error terms. DEA is devoid of these deficiencies. The aims of the study are achieved by analysing data related to expenditure used by the nine water boards and the efficiency outcomes they achieve during the study period, 2018/19, in producing the prevailing bulk water volumes at going tariff rates while taking into consideration water losses. We provide policy makers with information on how well a particular water board is performing relative to its peers, to identify good and bad practices, and finally find more efficient approaches to achieve financial sustainability and reliable water and sanitation supply in the pursuance of national and the SDG 6 objectives.

The rest of the paper is organised as follows: Sections 2 and 3 deal with the literature and methodological specification respectively, Section 4 with the data, Section 5 with the results and Section 6 concludes the study.

2. Literature review

As stated above, DEA has been extensively used globally to analyse technical efficiency in the water sector. However, to the best of our knowledge, this is the maiden study to use DEA or any other modelling technique to analyse the efficiency of water boards in South Africa while considering "bad outputs" like water losses which are a central feature of such production processes. In regards to the water sector efficiency literature, Ali, et al. (2018) used the constant returns to scale (CRS) along with an input-minimisation DEA to analyse the performance of 4 water supply units in Pakistan over a three-year period (2013-2015). The study adopted a six-variable production technology consisting of two outputs (number of consumers served and revenue) and four inputs (management, maintenance, operations and energy costs). They found that only 3 units were efficient. The average technical efficiency scores of 89, 92 and 97 per cent were respectively observed for the three years. Lannier and

Porcher (2014) used an input-minimisation DEA based on the variable returns to scale (VRS) in stage 1 and a Stochastic Frontier Analysis (SFA) in stages 2 and 3. They assessed the relative technical efficiency of 177 water supply DMUs in France. Revenue was used as a proxy for costs. The volume of billed water, number of customers and length of water pipes were used as outputs. Network performance was included as a quality output. They found that private utilities were on average slightly less efficient than public utilities due to difference in resource management. The first-stage DEA yielded an average technical efficiency score of 75.4 per cent and 84.1 per cent. After factoring the environmental variables, the public management scores were on average 0.88 while the private management scores were 0.82. The third stage DEA yielded average technical efficiency scores of 90 per cent.

Kulshrestha and Vishwakarma (2013) used a DEA model to determine the water supply efficiency of 20 urban municipalities in the state of Madhya Pradesh, in India. Three input-oriented DEA models were used in efficiency evaluation. Each model had three outputs (number of connections, length of distribution network and average daily water production), while the number of inputs varied from one to three (staff per 1000 connections, operating expenditure and non-revenue water) consecutively in each model. The results of the analysis indicated significant inefficiencies amongst various municipalities that supply water. It was found that larger cities exhibited better efficiencies than the smaller ones. The average technical efficiency score in Model 1 was 49 per cent with the highest score of 83 per cent observed in Model 3. Alsharif, et al. (2008) used DEA to measure the technical efficiency of 33 Palestinian municipalities for the years, 1999–2002. They found that the Gaza Strip efficiency scores were considerably lower than those of the West Bank. Water losses were the major source of the inefficiency, indicated by the large slacks on this input. Another study by Gupta, et al. (2012) applied an output-oriented DEA to assess the productive efficiency of urban water supply systems in 27 selected Indian cities. The study used expenditure as an input and total water served by a water utility as a function of revenue, expenditure and water production capacity. Two cities were efficient under the CRS while 6 reached the efficiency frontier under the VRS. The efficiency results had implications for urban domestic water pricing. Most water utilities were operating under decreasing returns to scale (DRS), implying that water should be priced at a marginal cost of supply.

Singh, et al. (2014) applied DEA to determine the relative efficiency of 12 selected Indian urban water utilities (municipal bodies) of Maharashtra state/province. They used an input-oriented CRS DEA model with total expenditure and staff size as two inputs and water supplied and the number of connections as two outputs. Only a third of the DMUs were efficient. Marques, et al. (2014) applied DEA to 5,538 observations of 1,144 utilities that supplied drinking water between 2004 and 2007 in Japan. The models considered three inputs and two

outputs. The inputs included capital, staff, and other operational expenditures. For outputs, the volume of water and the number of customers were adopted. They found that the average level of inefficiency (weighted by volume) was 57 per cent in the CRS model, but only 24 per cent for the VRS model. Lombardi, et al. (2019) used DEA to determine the efficiency of a selected sample of 68 Italian water utility companies from 2011 to 2013. The study used water distributed percentage of the water delivery network length as an output. The cost of material, services, leases and capital were used as inputs. Under the output-oriented models, the mean technical efficiency score was 0.85 under the VRS and 0.65 under the CRS. From an input-minimisation perspective, the scores were 0.74 and 0.63 respectively for the VRS and the CRS.

As it pertains to South Africa, Brettenny and Sharp (2016) studied the efficiency of 88 authorised water services local and metropolitan municipalities. The paper used an input-oriented DEA with operating costs and system input volume as sole input and output variables. Of the 44 urban water services authorities, 10 were efficient under the VRS and 4 under the CRS. Of the rural water services authorities, 5 were efficient under the VRS and only 1 under the CRS. The performances yielded an average technical efficiency of 63.6 per cent for urban municipalities and 52.6 per cent for rural municipalities. This indicated that, on average, 36.4 per cent less expenditure could be used in urban municipalities and 47.4 per cent less expenditure in rural municipalities to achieve the given levels of water service delivery nationwide. Murwirapachena, et al. (2019) adopted DEA, SFA and stochastic non-parametric envelopment of data (StoNED) methods to analyse efficiency, based on cross-sectional data from 102 South African water utilities in the period 2013/14. They obtained varying results under the different methods. The study used total cost as a single input, water output, total connections and the length of mains as outputs, with population served as an environmental output variable. The study estimated an input-oriented DEA, which assumed the VRS to deal with size variability. The maximum average efficiency scores under each method were as follows: Stoned (MM): 68.1 per cent, SFA: 66.2 per cent and DEA: 44.7 per cent for all utilities, 58.7 per cent for the big ones and 46.1 per cent for the small utilities. In another paper, Monkam (2014) used DEA and SFA to analyse the efficiency of 231 local municipalities in South Africa. The study adopted municipal operating expenditure as an input and 5 output variables: the number of consumer units receiving water, sewerage and sanitation, solid waste management and electricity and the total population per municipality. The results showed that on average, B1 and B3 category municipalities could have theoretically achieved the same level of basic services with about 16 and 80 per cent fewer resources respectively.

Mahabir (2014) used the Free Disposable Hull (FDH) technique to measure the technical efficiency of 129 municipalities in the provision of water from 2005 to 2009. The selected input

was municipal expenditure per capita and the selected outputs were, access to piped water, grid electricity connections, a ventilated pit latrine and a flushable toilet and removal of solid waste at least once a week. The study concluded that over the period, 4 municipalities remained constantly efficient: Thembisile in Mpumalanga, Polokwane in Limpopo, Mangaung in the Free State and eThekwini in Kwazulu-Natal. The average technical efficiency score was 0.3 in 2005/06, peaking at 0.39 in 2007/08, and declining to 0.35 in 2008/09. This suggested that on average, municipalities in the sample could obtain the same level of output with at least 60 to 70 per cent less inputs (resources). Dollery and Van der Westhuizen (2009) used DEA to determine the productive efficiency of 231 local municipalities and 46 district municipalities in the delivery of basic services covering the period 2006/2007. The study used 2 inputs: operating income and staff costs and 5 outputs, number of households, water, sanitation, refuse and electricity. The study determined the efficiency estimates under the CRS and the VRS; embracing output-orientated and input-orientated approaches. Under the output-orientated approach, the district municipalities were on average only 30.5 per cent efficient under the CRS, 58 per cent efficient under the VRS and 48 per cent scale efficient. Two municipalities were operating at DRS - they were operating at a too large scale in efficiency terms. Under the input-orientated approach, the district municipalities were on average 47 per cent technically efficient in the case of the VRS and 64.1 per cent scale efficient. With regard to the returns to scale, 32 municipalities were operating under IRS, implying they were operating on a scale that was too small in efficiency terms. Only two district municipalities were operating at the optimal scale. The remaining district municipalities were operating at DRS. In terms of local municipalities, those with the highest average technical efficiency scores under the output-maximisation and input-minimisation measures for both the CRS and VRS were in Gauteng, with respective average technical efficiency scores of 67.7, 79.4, 67.7 and 76.7 per cent.

3. Methodology

In this paper, we use the VRS approach reported by Gavurova et al. (2017) and developed in 1984 by Banker, Charnes and Cooper to allow for consideration of scale efficiency analysis. This is called the Banker, Charnes and Cooper (BCC) model. The terminology "envelopment" in DEA refers to the ability of the efficiency production frontier to tightly enclose the production technology (input and output variables). Cooper et al. (2007) and McWilliams et al. (2005) state that DEA was developed in a microeconomic setting and applied to firms to convert inputs into outputs. However, in efficiency determination, the term "firm" is often replaced by the more encompassing DMU. DEA is an appropriate method of computing the efficiency of institutions employing multivariate production technologies. Aristovnik (2012) and Martić, et al. (2009) state that there are input-minimisation and output-maximisation DEA models. The

former determines the quantity of inputs that could be curtailed without reducing the prevailing level of outputs. The latter expands the outputs of DMUs to reach the production possibility frontier while holding inputs constant. However, the selection of each orientation is study-specific. In this paper, we select the input minimisation orientation for the four models. DEA basically erects a production frontier consisting of most relatively technically efficient DMUs in the sample. This process generates technical efficiency measures for each unit in the sample by comparing observed values to optimal values of outputs and inputs. A score of 1, represents the best performing unit in the sample and a score of less than 1 implies that the unit is not performing as well as its efficient peers. DEA determines how much inputs could have been saved and the extent of outputs that could have been improved by inefficient DMUs by emulating the production processes of efficient DMUs.

According to Taylor and Harris (2004), DEA is a comparative efficiency measurement tool that evaluates the efficiency of homogeneous DMUs operating in similar environmental conditions, for example, DMUs dealing with bulk water supply and where the relationship between inputs and outputs is unknown. Wang and Alvi (2011) report that DEA only uses the information used in a particular study to determine efficiency and does not consider exogenous factors. DEA measures the distance of production functions by determining the radial extent of DMUs to the efficiency frontiers. It does so by categorising the DMUs into extremely efficient and inefficient performers. In terms of the DEA methodology, the current study uses the BCC model with the ratio of DMUs complying with the norms of at least being 2 to 3 times the combined number of inputs and outputs.

3.1 Treating Undesirable Outputs

DEA models have found increasing use in efficiency analysis applications where at least one output in the production process is an undesirable output, e.g. pollution or water losses. There is considerable research published on the undesirable aspects of production outputs. However, You and Yan (2011) have found that the economic implications and the suitability of DEA models incorporating the undesirable outputs should be carefully considered as the results may either under- or overstate efficiency if modelled incorrectly. Breitenbach et al. (2020) recently used this approach to consider the efficiency of healthcare systems in managing the COVID-19 pandemic and used deaths and infections as undesirable outputs.

The first way that undesirable outputs are dealt with in the traditional DEA model, is to ignore the undesirable output (Nakashima et al, 2006; Hua and Bian, 2007; Lu and Lo, 2007a, b). It is not however, appropriate to ignore the reality of e.g. pollution or water losses during production since undesirable outputs and desirable outputs are generated simultaneously in the production process. Dyckhoff and Allen (2001) dealt with undesirable outputs by modelling them as inputs. However, treating undesirable outputs as inputs fails to reflect the true

production process, this is the same approach adopted by Ngobeni and Breitenbach (2020). There is a specific production technology that links inputs to outputs, and taking an undesirable output as an input in the production process leads to misspecification and misinterpretation, for example, when modelling the pollution as an input using an output-oriented measure, ecological inefficiencies remain undetected. Golany and Roll (1989) suggested a data transformation approach where an undesirable output is converted into a 'normal' output by a monotonic decreasing function. The undesirable outputs (carbon and nitrogen emissions) are treated as normal outputs by taking their reciprocals. Although the pollutant is treated as output, the scale and intervals of the original data get lost and problem with zero values is that it does not have a reciprocal value. The Linear monotonic decreasing transformation was suggested by Seiford and Zhu (2002). A sufficiently large positive scalar βi is added to the reciprocal additive transformation of the undesirable output i so that the final values are positive for each DMU$_k$. This model is criticised for its invariance to data transformation within the DEA model (Lu and Lo, 2007a, b). Färe et al., (1989) treats undesirable factors in a non-linear DEA model based on the weak disposability of undesirable outputs (Zhou et al, 2007). Weak disposability assumes that to reduce undesirable outputs it is costly because simultaneously, it increases the inputs or decreases desirable outputs (Yang et al, 2008). It tends to increase the desirable output and undesirable output concurrently. Regardless of the form of transformation, as long as the final value of undesirable output included in the DEA calculation remains positive, it increases the efficiency of the DMU. An undesirable output should bring either a negative or positive impact to the performance of DMU; therefore, it is not appropriate for the undesirable output to solely favour the efficiency score.

After comparing the performance of the models discussed above, You and Yan (2011) developed the ratio model, which outperformed all five of these models developed for dealing with undesirable outputs. We therefore opted to adopt the ratio model for the current paper. The ratio model is different from the previous approaches in that the undesirable output is aggregated in a ratio form with the desirable output. From the conventional BCC DEA model and assuming that there are R DMU$_r$ ($r = 1, 2, \ldots, R$), that convert m inputs to n outputs, DMU$_k$ is one of the R DMUs being evaluated. It is further assumed that DMU$_k$ consumes m inputs X_t^k ($i = 1, 2, \ldots, m$) to produce n outputs Y_j^k ($j = 1, 2, \ldots, n$) and all these outputs are assumed to be desirable. The measure of efficiency of DMU$_k$ is then obtained by:

min θ subject to

$$\sum_{r=1}^{R} \lambda_r X_i^r - \theta X_i^k + s_i^- = 0 \qquad\qquad i = 1, 2, \ldots, m$$

$$\sum_{r=1}^{R} \lambda_r \, Y_j^r - s_j^+ = Y_j^k \qquad\qquad j = 1, 2, \ldots, n$$

$$\sum_{r=1}^{R} \lambda_r = 1$$

$$\lambda_r, s_i^-, s_j^+ \geq 0 \qquad\qquad r = 1, \ldots, R \qquad\qquad (3)$$

where DMU_r = the rth DMU, $r = 1,2,\ldots, R$; DMU_k = the kth DMU being evaluated; X_i^r, Y_j^r = the inputs and outputs of every DMU_r; $i = 1, 2, \ldots, m$, $\mathrm{j} = 1,2, \ldots, n$; θ = the efficiency of DMU_k; λ_r = the dual variable corresponding to the other inequality constraint of the primal;

s_i^-, s_j^+ = the slack variables that turn the inequality constraint into an equal form; $\lambda_r^*, s_i^{-*}, s_j^{+*}$ = the optimal solutions when the relative efficiency of DMU_k is $\theta^* = 1$ and $s_i^{-*} = s_j^{+*} = 0$.

In the ratio model, the undesirable output and desirable output are defined as O_q^- ($q = 1.2, \ldots, n_1$) and O_p^+ ($p = 1, 2, \ldots, n_2$), respectively ($n_1 + n_2 = n$). For DMU_k, the undesirable outputs O_q^- ($q = 1, 2, \ldots, n_1$) are treated as a new variable ψ_k, which is called the penalty parameter and is written as:

$$\psi_k = \rho_1 O_{1k}^- + \cdots + \rho_{n1} O_{n1k}^- \qquad\qquad (4)$$

where ψ_k = penalty parameter for DMU_k; ρ_q = the penalty for individual undesirable output ($q = 1, 2, \ldots, n_1$); O_q^- = the undesirable output ($q = 1, 2, \ldots, n_1$). Since ρ_q is the penalty charged for producing the outputs, the ψ_k obtained from problem (4) gives a measure of the total monetary value of undesirable outputs. From the definition of ψ_k, the greater the amount of undesirable output, the greater is the value of the penalty parameter. Further, the respective value of ρ_q is associated with the individual undesirable output, therefore ρ_q has the same value for every DMU. With this model, desirable and undesirable outputs can relate to one another, regardless of disagreement in the units. With the new approach of treating the undesirable outputs in (4), the desirable output p ($p = 1, 2, \ldots, n_2$) of DMU_k in the ration model is modified as :

$$Y_\rho' = \frac{1}{\psi_k} O_p^+, \qquad\qquad (p = 1, 2, \ldots, n_2) \qquad\qquad (5)$$

where O_p^+ = the desirable output ($p = 1, 2, \ldots, n_2$); Y_ρ' = the modified output ($p = 1, 2, \ldots, n_2$). The ratio model computes desirable and undesirable outputs as fractions, where undesirable output O_q^- is the denominator and desirable output O_p^+ the numerator. Here the value of the output is interpreted as a ratio of desirable to undesirable output. Using ratios provides a simple and easy way to expose the impact of undesirable outputs in a DEA. The ratio form of

the DEA model can satisfy the restrictions of the conventional DEA, which the output variable states must be a positive value. Moreover, the ratio form provides a more distinct way for the desirable and desirable output to describe the presence of an undesirable output on DMU efficiency.

In order to check the stability of our model results, we ran four different model specifications and compared the results. In Model I, we use expenditure as financial input, bulk water tariffs as financial output and water losses (bad output) and bulk water sales volumes as physical outputs (we ignore the effect of bad outputs). In Model II, we use the same variables while excluding the water losses variable from the model (we use only good outputs, ignoring the bad output). In Model III, we use expenditure as the financial input and the ratio of bulk water tariffs to water losses and bulk water sales volumes to water losses as physical outputs (ratio model). Model IV, uses expenditure as financial input and water losses as a physical input, bulk water tariffs as financial output and bulk water sales volumes as physical output (we use the bad output as an input).

4. Data

Our data was obtained from different sources. The data for the total expenditure, water losses (technical and non-technical) and bulk water tariffs were extracted from the 2018/19 audited annual reports of the water boards and volumes sold were obtained from the National Treasury (2020b). The sample consists of the nine water boards, 1 financial input: expenditure, 1 financial output: bulk water tariffs and 2 physical outputs (water losses and volumes sold). From Table 3 it is clear that there is substantial variation between the variables with Rand Water an outlier at the higher end and Overberg an outlier at the lower end of the spectrum.

Table 3: Data and Descriptive Statistics

Water Boards	Expenditure (R'000)	Water losses %	Bulk Water Tariffs (R/kl)	Volumes sold (million m³/a)
Amatola Water	434 914	14	11	31 432
Bloem Water	757 552	9	8	81 118
Lepelle Water	656 372	5	6	89 440
Magalies	609 125	6	7	92 321
Mhlathuze	624 985	4	4	45 106
Overberg Water	52 006	9	7	3 265
Rand Water	12 221 051	3	9	1 714 308
Sedibeng Water	1 590 743	8	9	122 551
Umgeni Water	2 388 440	2	7	471 801
Mean	2 148 354	7	8	294 594
Standard Deviation	3 621 058	4	2	518 709
Minimum	52 006	2	4	3 265
Maximum	12 221 051	14	11	1 714 308

Sources: National Treasury (2020b, 2019, 2018), Amatola Water (2019), Bloem Water (2019) Lepelle Northern Water (2015), Magalies Water (2019) Mhlathuze Water (2019), Overberg Water (2019) Sedibeng Water (2019) Rand Water (2019) and Umgeni Water (2019).

The standard deviation is therefore quite large with most variables. For example, with expenditure, the mean value is R2 148 354 with a maximum of R12 221 051 and a minimum of R52 006 whereas Volumes sold has a mean value of 294 594 million m³/a with Rand Water an outlier at the higher end of 1 714 308 million m3/a and Overberg an outlier at the lower end of the spectrum of 3 265 million m3/a. The water board utilities are dominated by three large water boards, while the rest have relatively small shares of the market.

5. Results

The results of the four model variants are provided in Table 4 below. The mean technical efficiency scores of the nine DMUs range between 29 to 79 per cent across the four variant models, implying the need to improve efficiency by 21 to 71 per cent by the inefficient DMUs in all models. The average technical efficiency score is the same when water losses are included and omitted in Models I and II respectively. In line with You and Yan (2011), we conclude that Model variants I and II do not accurately capture the state of technology and that by omitting the bad output or by modelling the bad output as a positive output, we cannot accept the results as a true reflection of the state of technology and technical efficiency outcomes. The efficiency results in Models I and II are therefore hugely overstated. In Model III (the ratio model), the mean technical efficiency score of water boards is 49 per cent.

Table 4: Technical Efficiency Scores

Water Board	Model I	Model II	Model III	Model IV
Amatola	1,00	1,00	0,16	1,00
Bloem	0,66	0,66	0,18	0,20
Lepelle	0,73	0,73	0,34	0,08
Magalies	0,81	0,81	0,33	0,09
Mhlathuze	0,42	0,42	0,26	0,08
Overberg	1,00	1,00	1,00	1,00
Rand	1,00	1,00	1,00	0,02
Sedibeng	0,48	0,48	0,13	0,15
Umgeni	1,00	1,00	1,00	0,02
Mean	0,79	0,79	0,49	0,29
No. of efficient units	4	4	3	2

Sources: DEA efficiency results.

That is, with the correct inclusion of water losses as an undesirable output, the average technical efficiency score declines by 30 per cent. Put differently, ignoring the bad output (water losses) by just including or omitting it as an output in the water board production process overstates the average technical efficiency score by 30 per cent. This is a substantial distortion of the efficiency estimates. Model IV is the last of the input minimisation model variants; it shows that using a bad output (water losses) as an input (as in Ngobeni and Breitenbach, 2020) completely alters the production technology by decreasing the average technical efficiency of water boards by 20 per cent to a score of 29 per cent. Therefore, just incorporating a negative output as an input materially underestimates the efficiency scores. As a result, we

follow You and Yan (2011) and adopt the best performing Ratio Model III, for the discussion of the results and formulation of the recommendations associated with the input minimisation objective. Using the other three input minimisation models (Models I, II and IV), does not accurately capture a very crucial undesirable output (water losses) and is an inappropriate DEA application that may lead to incorrect conclusions and policy recommendations. The lower technical efficiency scores obtained for water boards across all the models are in line with the results by Murwirapachena, et al. (2019), Brettenny and Sharp (2016), Monkam (2014), Mahabir (2014) and Dollery and Van der Westhuizen (2009) for municipal water and sanitation supply services in South Africa.

Their results also over-estimated the technical efficiency scores when bad outputs were not considered, as in our Models I and II. Overall, this implies that the general technical efficiency of municipalities may be much lower than previously believed. In regard to water boards, we have shown above that by modelling water losses as an undesirable output, true efficiency is lower than if we choose to omit it in our estimation or incorrectly model it as a positive output. This has important policy implications when technical efficiency is substantially lower than initially thought and estimated and policy actions also based on these over- or understated efficiency values.

The above technical efficiency results do not mean much if not interpreted together with the inefficiency factors (radials and slacks). Coelli et al. (2005) defined slacks as input excesses and output shortfalls that are required over and above the initial radial movements to push DMUs to efficiency levels. Both the slack and radial movements are associated only with the inefficient DMUs.

Table 5: Radial and Slack Movements

Water Board	Prevailing spending (R'000)		Inefficient spending (R'000)	Rate of Inefficiency	Benchmarked efficient spending (R'000)	Rate of Efficiency	DMU Peers for Improvements
Amatola	434 914	-	364 239	-84%	70 675	16%	Overberg and Umgeni
Bloem	757 552	-	619 741	-82%	137 811	18%	Umgeni and Overberg
Lepelle	656 372	-	430 526	-66%	225 846	34%	Umgeni and Overberg
Magalies	609 125	-	408 087	-67%	201 038	33%	Umgeni and Overberg
Mhlathuze	624 985	-	464 717	-74%	160 268	26%	Umgeni and Overberg
Overberg	52 006		-	0%	52 006	100%	Overberg
Rand	12 221 051		-	0%	12 221 051	100%	Rand
Sedibeng	1 590 743	-	1 390 380	-87%	200 363	13%	Umgeni and Overberg
Umgeni	2 388 440		-	0%	2 388 440	100%	Rand
Total	19 335 188	-	3 677 690	-51%	15 657 498	49%	

Sources: DEA efficiency results from National Treasury (2020b, 2019, 2018), Amatola Water (2019), Bloem Water (2019) Lepelle Northern Water (2015), Magalies Water (2019) Mhlathuze Water (2019), Overberg Water (2019) Sedibeng Water (2019) Rand Water (2019) and Umgeni Water (2019).

The radial movements are initial input contractions or output expansions that are required for a firm to become efficient. Therefore, using the Model III results, the average technical inefficiency rate is 51 per cent with the six inefficient water boards needing to reach the optimal efficiency frontier depicted by the Overberg, Rand and Umgeni water boards. Table 5 summarises the efficiency and inefficiency rates as they relate to expenditure. The input minimisation implies using the same or less inputs while maintaining the same levels of outputs. For Model III, The inefficiency rate of 51 per cent is equivalent to wastage in expenditure of R3.7 billion by the six inefficient water boards. The three efficient water boards serve as peers for the inefficient ones. However, given the high levels of water and sanitation coverage backlogs in provinces where the inefficient water boards operate and the financing gap for the water sector, it is proposed that the individual inefficient water boards conduct a detailed review of their expenditure items such as personnel and operational costs through a benchmarking exercise with the efficient peers for improvements. The prospective savings from moving to the efficiency frontier could also be used to extend service coverage given the backlogs in service delivery depicted in Figure 1. Therefore, the study recommends efficiency improvements that could assist to achieve the SDG 6 targets and objectives.

In order to illustrate the relative inefficiency of the smaller water boards below the inefficiency frontier more clearly, one can perform a simple comparison with one of the larger water boards that operate on the efficiency frontier. In Table 6, we chose to compare three of the smaller water boards with Umgeni Water – the second largest water board that also happens to be scale efficient. We only discuss two of them to illustrate the relative inefficiency.

Table 6: Inputs and outputs relative to the benchmark (Umgeni Water)

| Water Board	VRSTE	Total Expenditure (R)	Water Losses (%)	Bulk Water Tariff (R)	Volumes sold (million m³/a)
Umgeni Water	1	2388440	2	7	471801
Amatola Water	0.16	434914	14	11	31432
Bloem Water	0.18	757552	9	8	81118
Lepelle Water	0.34	656372	5	6	89440
Comparison with Umgeni					
Amatola/Umgeni		0.182091239	7	1.571428571	0.066621309
Bloem/Umgeni		0.31717439	4.5	1.142857143	0.171932658
Lepelle/Umgeni		0.274812011	2.5	0.857142857	0.189571451

Source: Calculated from model results and raw data.

From Table 6, the inefficiency of the smaller water boards become more apparent. Amatola Water with an efficiency score of only 16% for example, has a total expenditure of 18% of that of Umgeni, but sells only 6.7% of the quantity sold by Umgeni. Amatola also has seven times the proportion of water losses compared to Umgeni and charges 1.5 times the tariff of Umgeni. In the case of Lepelle Water, which has an efficiency score of 34%, total expenditure is 27%

of that of Umgeni Water, yet they only sell 18.9% of the volume sold by Umgeni. Water losses are 2.5 times that of Umgeni, but they do however have a lower water tariff than Umgeni.

Of more importance in the case of the water boards however, is the scale efficiency of the water boards' production technology. The average scale efficiency scores of water boards across the four models range from 62 to 92 per cent. As illustrated in Figure 3, the highest scale efficiency scores are recorded in Model III. The most prevalent form of scale is the increasing returns to scale (IRS) returns to scale (there is potential to improve the extent of operations: an increase in inputs will result in a more than proportional increase in output). Only the Overberg and Umgeni water boards were scale efficient in Model III. The only water board with a scale efficiency of less than 50 per cent is Rand Water. The other water boards surpass the 95 per cent scale efficiency mark.

Figure 3: Scale Efficiency Scores
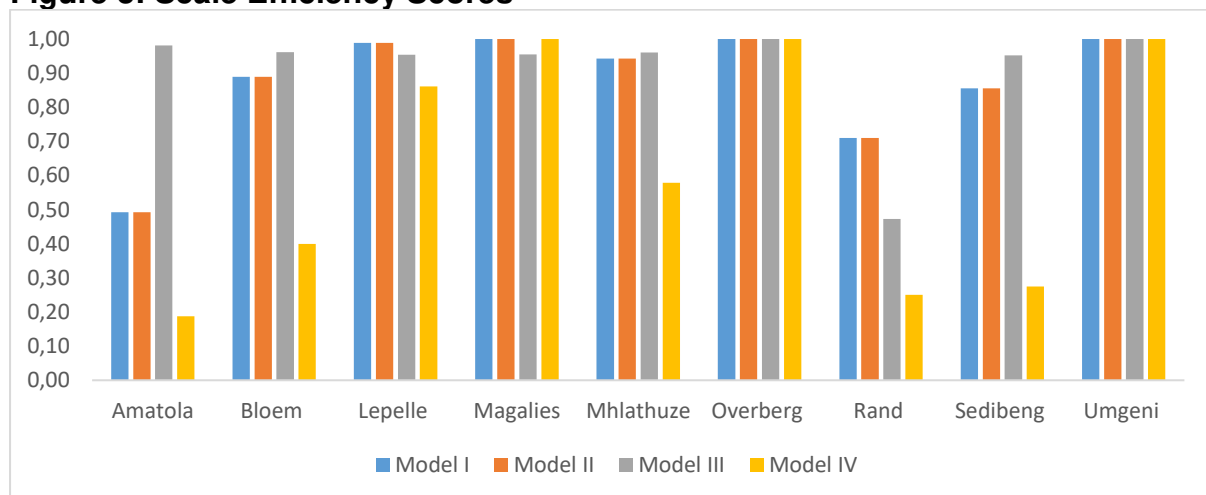
Sources: DEA efficiency results.

Only the Rand and Sedibeng water boards recorded decreasing returns to scale (an increase in inputs will lead to a less than proportional increase in output: the extent of operations is bigger than is required). Therefore, the water boards operating on the IRS frontier could combine the efficiency savings with private financing or future tariff increases to improve the scale of their operations and expand operational footprint. Those operating at DRS should benchmark with the scale efficient water boards for improvements. In sum, we are not recommending for a reduction in the current expenditure levels of all water boards despite some being inefficient. We are recommending for the efficient use of resources to improve the current operational levels. This implies improved scale efficiency for the seven water boards that are scale inefficient. Policy makers should also consider fast-tracking the reform to merge some of the smaller to medium-sized water boards into large regional water utilities as they operate on less than optimal scale. This is an ideal water board's model for operations, funding

and sustainability. However, this reform should be preceded by a detailed benchmarking of operational practices with peer water boards to avoid merging inefficient operations.

6. Conclusions

The study used four comparative input-oriented DEA models to analyse the technical efficiency of the nine water boards' expenditure efficiency while maintaining the current levels of bulk water tariffs and sales volumes. We used a novel DEA ratio model developed by You and Yan (2011), which treat undesirable outputs by dividing the positive outputs (tariffs and volumes) by water losses to convert them into a ratio that eliminates biased efficiency estimates. Only 3 or 33 per cent of the water boards were efficient. Despite six water boards being inefficient, the inefficiency rate was 51 per cent due to the much larger water boards - Rand and Umgeni Water - accounting for the bulk of the spending and water supply in the sector. Given the results from the scale efficiency, the main policy implication is that the smaller water boards would need to increase the scale of operations to become scale efficient, while the largest and third largest water boards are experiencing decreasing returns to scale, meaning that they need to reduce their scale of operations to attain scale efficiency. The results suggest that holding the outputs fixed, six small to medium-sized water boards could be merged after an efficiency benchmarking exercise to improve scale efficiency. The results from the scale efficiency seems to support larger regional water boards as small to medium-sized water boards are scale inefficient.

In this paper we have demonstrated the importance of modelling bad or undesirable outputs by comparing the results of the ratio model with other model variants as suggested by You and Yan (2011). Our results (in line with You and Yan (2011), confirm the fact that the ratio model more accurately captures the impact of undesirable outputs in the production technology on technical efficiency and eliminates over- and underestimation resulting from incorrect specification of the production technology in traditional models. This method can therefore be recommended for policy applications in other country studies or cross-country studies with confidence.

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