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Investment in drinking water and sanitation infrastructure and its impact on waterborne diseases dissemination: The Brazilian case

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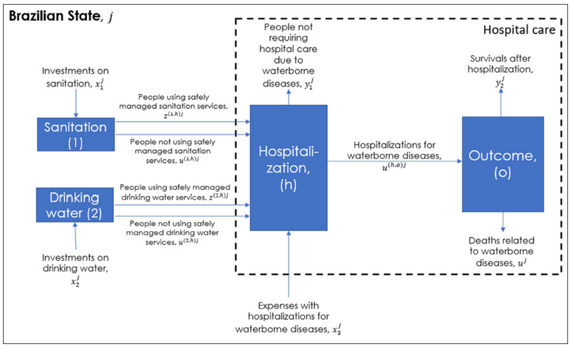
HIGHLIGHTS

- The relationship between WSS investment and waterborne diseases (WD) was evaluated
- A network-DEA model was used
- Brazil was the case study
- Marginal products associated with WSS investment were estimated
- Universal coverage of WSS in Brazil could mean minimal WD cases

GRAPHICAL ABSTRACT



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ABSTRACT

Investment in sanitation and drinking water infrastructure is essential for universal access to these services in developing countries. Universal coverage of water and sanitation services (WSS) can prevent the dissemination of waterborne diseases and mitigate their adverse effects. These diseases are responsible for many deaths worldwide, especially among the disadvantaged population and children. A causal effect can be established between WSS investment and hospital admissions due to waterborne diseases. Therefore, we considered an innovative network-DEA approach that models the link between serially connected subsystems (upstream investment and downstream hospitalizations). This approach allowed us: to measure the efficiency of both subsystems; estimate the amount of (efficient) investment necessary to universalize the access to proper WSS infrastructure; and mitigate hospital admissions due to waterborne diseases. We used the Brazil case study to test our model. On average, Brazilian states could increase the number of people not requiring hospitalizations due to waterborne diseases by 157 thousand per R$100 million invested in sanitation and 26 thousand per R$100 million invested in drinking water. Our results suggest that relatively small (efficient) investment in those two infrastructure types has a massive impact on hospitalizations. This impact would be more significant than the investment in WSS coverage. Therefore, if safely managed, WSS would cover all citizens, and Brazil would come closer to developed countries.

1. Introduction

In the vicious circle of poverty and disease, Water and Sanitation Services (WSS) (or lack of them) are, among others, both the cause and effect of these problems. The sequelae linked to WSS systems inefficiency and ineffectiveness exacerbate poverty and hinder

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economic development (Guerrant et al., 2013). The WSS coverage must be carried out by network and is especially crucial for densely populated or more impoverished areas (Berendes et al., 2017). Indeed, the United Nations proposed the Sustainable Development Goals (SDG) to be accomplished by 2030 for "*a better and more sustainable future for all*" (UN, 2017). SDGs 1 (no poverty), 3 (good health and well-being), and 6 (clean water and sanitation) are thus relevant in the context of WSS development in developing countries. It is worth noting that global goals that involve health and well-being issues are fundamental to direct and homogenize public policies that may influence local governance. Large countries, such as Brazil, with significant inequities in accessing WSS, facilitate homogenization of actions when committing themselves to global agendas.

Recent research, such as Freeman et al. (2017) and Wolf et al. (2018), concluded that WSS improvements did not produce the expected immediate effects on nutritional aspects. However, these interventions have been shown to improve other benefits such as equity, dignity, security, time savings, and economic development, both nationally and globally (Sclar et al., 2017).

The lack of WSS, or even their fragility in terms of structure, efficiency, and quality, can induce a scenario of calamity with an exponential increase in diseases, especially waterborne ones (Medeiros et al., 2021). For example, diarrhea is responsible for approximately 1.4 million annual deaths worldwide (Lozano et al., 2012; Prüss-Ustün et al., 2014). Although the percentage of people with access to better WSS conditions has increased, and the percentage of open defecation has dropped in the past few years, the situation still needs attention (UNICEF, 2015). There are still 4.5 billion people without access to safe WSS, and 2.3 billion of them continue to be lacking those essential services (UNICEF, 2015). This figure includes 600 million people who share a bathroom or latrine with other households and 892 million people (mainly in rural areas) defecating in the open. According to Otaki et al. (2021), as proper management of onsite WSSs would be critical to reducing waterborne viral risk, it is necessary to reach out to the residents who are unaware of the importance and necessity of using proper sanitation systems (whenever appropriate).

According to Herrera (2019), an international effort has been made for approximately a century to improve access and WSS conditions in developing countries. Declarations such as the Dublin Statement on Water and Sustainable Development (1992) and the United Nations' Resolution 64/292 of the Human Rights Council on the Right to Water (2010) are examples of these initiatives aiming at the success of actions related to the improvement of living conditions and safe access to WSS. There are, however, gaps in WSS between developed and underdeveloped countries due to socioeconomic factors (Adelodun et al., 2021). The aimed approximation between those two groups of countries by improving the latter's WSS infrastructure is still far from reality. Therefore, it requires an analysis to understand the reasons behind such a situation.

There is an opportunity to investigate the relationship between trends involving the vicious circle of poverty and disease in developing countries. After all, a weak economic situation induces health problems because it forces the population to live in harsh environments, making people sick due to the absence of clean water or inadequate sanitation. Moreover, in line with Kotsila and Saravanan (2017), preventing waterborne diseases through WSS depends on the political context.

Although it shows a better situation than some of the countries composing the Global South, Brazil still faces several challenges to achieve universal access to WSS. Despite technological and political advances in WSS (Heller, 2009), Brazil remains at an incipient stage in meeting the basic needs of part of its population. Therefore, the main objective of this study is to answer the question, "*To what extent will more investment in sanitation and drinking water infrastructure in Brazil reflect into greater coverage of the population and less spread of waterborne diseases?*" In other words, we intend to assess the impact of upstream investment in WSS infrastructure in the prevention or eradication of waterborne diseases, namely by finding out how much investment could be reduced by holding the number of infections and hospitalizations. Strictly speaking, we expect that efficient investment in WSS makes substantial contributions to improve the position of Brazil for the United Nations SDGs 1, 3, and 6. More specifically, we try to obtain answers to the following research questions:

(1) How many more citizens can enjoy safely managed sanitation services per each R$1 additionally invested? How much money should be invested to cover the entire population?

(2) How many more citizens can enjoy safely managed drinking water services per each R$1 additionally invested? How much money should be invested to cover the entire population?

(3) What is the impact of investment in WSS in terms of the number of people who do not need health care resulting from waterborne diseases? Can we quantify it?

(4) What is the impact of investment in WSS in terms of hospitalizations? Can we quantify the minimum investment required to prevent hospitalizations due to waterborne infectious diseases?

We propose using a benchmarking tool (network Data Envelopment Analysis [network DEA]). It compares the different Brazilian states in terms of their performance in covering the population of WSS and mitigating hospitalizations due to waterborne diseases, such as diarrhea, dengue, or yellow fever. To this end, we assume the existence of a cause-effect relationship in which the lack of WSS coverage (upstream) leads to hospital admissions that can result in deaths (downstream). The network model derived from DEA seems appropriate since it manages to model the interactions between the various segments that make up the chain mentioned above. With the multiplier version of the network-DEA model, we can establish a set of equations providing us with marginal products in each segment of the chain and answering each of the previous questions. Using these marginal products, we can measure the extent of output change (hospitalizations) when the input (investment in WSS) increases. We allow for diminishing returns due to the presence of undesirable events such as waterborne disease-related deaths.

Although twenty years have gone since the introduction of network DEA, the number of empirical applications is still scarce. Examples of sectors in which authors used this model include: healthcare (Kawaguchi et al., 2014; Khushalani and Ozcan, 2017; Ozcan and Khushalani, 2017; Mitropoulos, 2019); retail (Vaz et al., 2010); banking (Chen et al., 2017); provision of public services (Moreno and Lozano, 2016); accounting firms (Hsiao et al., 2017); education (Lee and Worthington, 2016; Bostian et al., 2019); and hospitality (Yin et al., 2020). However, none have analyzed the impact of upstream investment in WSS provision in the waterborne disease spreading, using a network DEA model. The innovation of the current study lies in applying a rarely addressed (but robust) methodology to answer the previous research questions. These answers might have a meaningful impact on low-income societies. Based on WSS coverage and data referring to waterborne diseases in 2017, the 26 Brazilian states and the Federal District were included in this research.

2. Materials and methods

2.1. WSS investments and coverage in Brazil

2.1.1. Coverage

One of Brazil's most significant governmental challenges is to guarantee the WSS universalization, regardless of all geographical difficulties for providing services in certain regions. It is necessary to reinforce the links between social and environmental conditions along with the trends and social impact of environmental policies, human life value, equity, employment, access to information, and public participation in the process of decision-making. The absence of adequate WSS is one of the leading causes of pollution and water contamination for the drinking supply. Therefore, the lack of WSS coverage contributes to the worsening of waterborne disease dissemination (Ercumen et al., 2014).

Although WSS access conditions have improved in the last fifty years, Brazil's WSS infrastructure is still deficient (SNIS, 2017). In wastewater collection, only 49.84% of Brazilian households are connected to the sewers, which means that half of the households dump their wastewater in inappropriate places. The water supply system is more widespread than sanitation, even though its access is not universal yet. It reaches around 84.4% of households (SNIS, 2017).

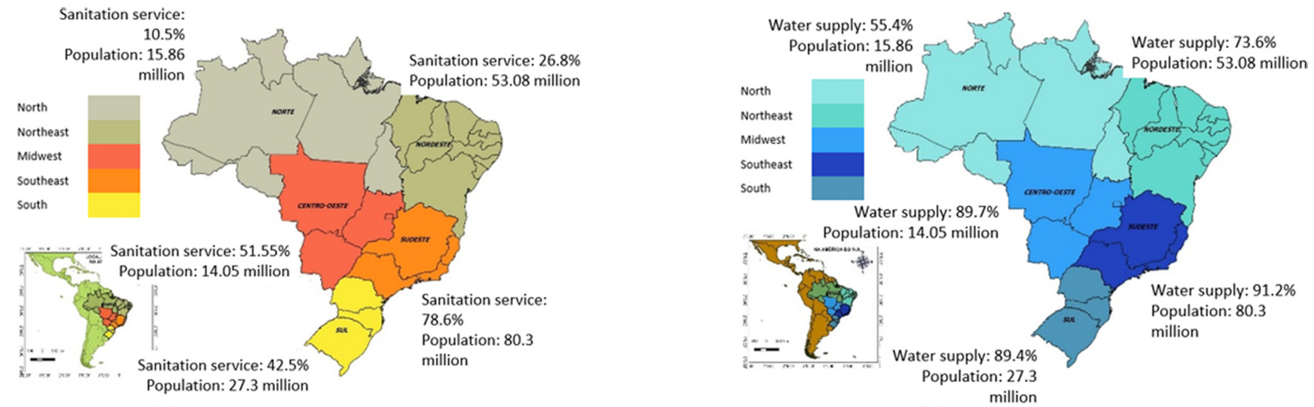
According to the (Brazilian) National Basic Water and Sanitation Plan of 2019, the government aims to increase from 79% to 85% (until 2023) of the urban households served by sewerage or septic tanks (PLANSAB, 2019). Also, one should increase wastewater treatment from 69% to 79%. However, more significant investment is needed to universalize sanitation services since these rates do not include the rural population. These values express a national reality. Furthermore, when adopting the perspective of interterritorial analysis, significant regional inequalities are perceived: Brazil is a continental country with a vast territorial dimension and heterogeneous characteristics, both natural and socioeconomic. South and Southeast regions are completely different from the North and Northeast regions and the metropolitan areas and big cities and the small municipalities in rural areas are also diverse in the entire country. Both biophysical and socioeconomic indicators and their interactions influence a lot the sustainability of the country and the quality of life of the population and, particularly, the provision of public services, such as health and basic sanitation. Therefore, these differentiations affect substantially the form and quality of access to WSS (Cetrulo et al., 2020).

Fig. 1(a) and (b) illustrates the regional differences in terms of WSS coverage. Brazil's North and Northeast regions have lower WSS coverage and, consequently, concentrate many hospital admissions due to waterborne diseases. These regions have the worst rates in Brazil, both in water supply and wastewater collection and treatment. The disparity reaches ten times in the Southeast and North regions of the country. Compared to the Northeast, the Southeast has about three times more sewers. Such heterogeneity within the same country jeopardizes achieving the United Nations SDG 6 and indirectly the SDGs 1 and 3. Brazil's socioeconomic inequalities are considerable when one intends to develop a scenario for implementing public policies with remarkable impact.

Most of the population lives in urban regions, often in unfavorable socio-environmental conditions, vulnerable to diverse diseases. It is worth noting that this situation is not restricted to developing countries. However, this reality has been getting worse since 2007. The urban population surpassed the rural one due to the natural population growth and the accelerated rural migration to cities (UN, 2018). The predominance of the lack of WSS remains one of the critical problems in urban areas. In 2009, the percentage of low-income households without infrastructure was six times higher than that of high-income households (Jaitman, 2015). For the most part, these are problems of households considered urban flaws, compromising their quality of life, mainly due to waterborne diseases.

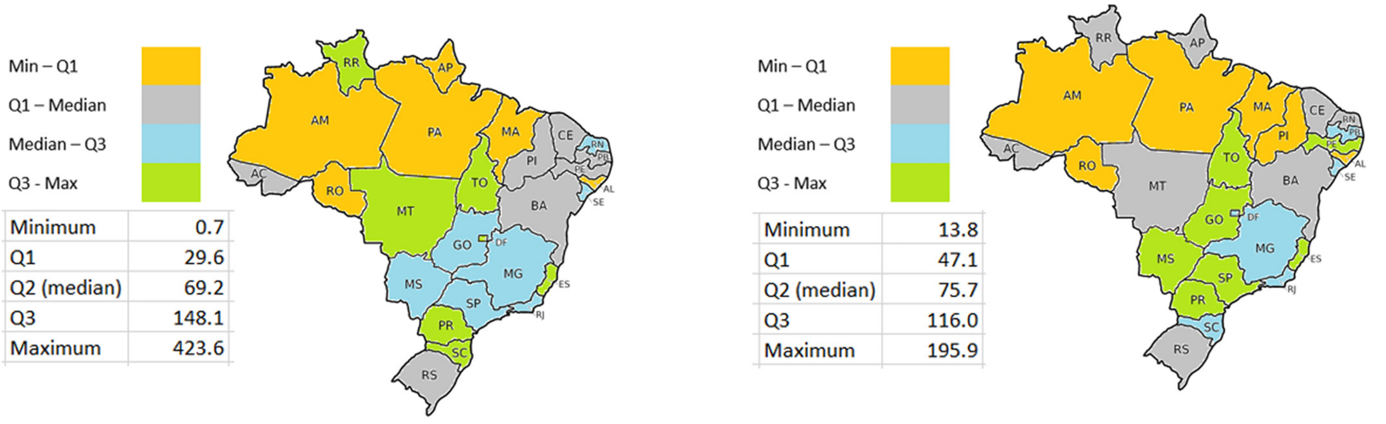
2.1.2. Investment in WSS infrastructure

Large amounts of investment in WSS infrastructure are required. Such amounts demand coordinated management to make them efficient and effective in universal access and disease prevention. The National Plan for water and sanitation (PLANSAB), for the period 2014-2033, proposes the means to achieve this objective, including the role of stakeholder participation and the necessary social



(a) Sanitation services coverage

(b) Drinking water coverage



(c) Sanitation investment (R$) per capita

(d) Drinking water investment (R$) per capita

Fig. 1. Regional differences in coverage and investment in sanitation and drinking water supply. Note: investment updated to 2017 prices.
Source: the authors based on data from Sistema Nacional de Informações sobre Saneamento and Trata Brasil, URL: www.painelsaneamento.org.br [accessed: January 10, 2020].

instruments and grants. According to PLANSAB, the annual federal investment in WSS (about R$10 billion, on average in the last decade) should be reduced to R$9 billion until 2023 and then increased to R $19.2 billion until 2033.

In Brazil, the investment in WSS infrastructure may have four primary sources: (a) WSS provider, either municipal or state; (b) municipality; (c) State Government; and (d) the Union. In 2016, 91.67% of the total investment came from the WSS providers (SNIS, 2020). However, it is not necessarily valid for all States. For instance, the State investment outweighs the other sources in the States of Acre (99.46%), Roraima (94.88%), Pará (72.89%), Paraíba (73.42%), and Alagoas (62.60%). The remaining States tend to be positioned at the other extreme, favoring the investment from the WSS provider. Indeed, in some States, this is the only source of investment (*e.g.*, São Paulo, Paraná, Distrito Federal, to name a few). In other cases, like Rondônia, Piauí, Pernambuco, Espírito Santo, and Rio de Janeiro, although that is the primary source of investment, the other two may also be meaningful. For instance, 27.43% of the investment in WSS in Piauí is municipal, and nearly a third of the investment in Rondônia is statutory.

There is a lack of investment in WSS in Brazil, and the political commitment to reverse this scenario is worrying. The absence of WSS infrastructure with adequate quality is a direct consequence of this context which contributes effectively to the perpetuation of diseases and epidemics already eradicated in much of the West. The rationality for directing investment is essential to increase their efficiency.

Table 1 presents some statistics about the investment in WSS infrastructure in Brazil, 2013–2016. According to the total investment displayed in the table, the drinking water supply investment rose about 36.7% ($= (5925 - 4332) / 4332$) from 2013 to 2016. In opposition, it decreased by 34.3% ($= (6446 - 4235) / 6446$) in sanitation. Overall, the total investment in WSS infrastructure dropped 5.54% since 2013. The average weight of each utility remained nearly unchanged during the four years. Since 2015, the investment in the drinking water supply has surpassed the investment in sanitation.

Despite the investment made in WSS infrastructure, there is still a marked heterogeneity among Brazilian states. Such heterogeneity is significant as the coefficient of variation is larger than 100%, often close to or higher than 200%, regardless of the utility (see Table 1). It implies that some States invest much more than others in WSS infrastructure. This may be a result of differences in size, population, or the existing infrastructure. However, Figs. 1(c) and (d), displaying the investment *per capita*, show that Northern and Northeastern states are the ones in which the investment *per capita* is the lowest, below R$29.6 *per capita* in sanitation and R$47.1 *per capita* in drinking water services (2017 prices). In opposition, States in the South, Southeast, and Midwest tend to invest more per inhabitant, reaching R$423.6 in sanitation and R$195.9 in drinking water. The average investment *per capita* in Brazil in 2016 was R$55.74.

By comparing Fig. 1(a) with 1(c) and Fig. 1(b) with 1(d), we conclude that lower investment in WSS *per capita* is associated with fewer people covered by those essential services. We used data from SNIS concerning 2016 to verify whether the total investment *per capita* was positively and significantly correlated to the share of people using safely managed sanitation and drinking water services. We observed: $r = 0.6175$ and $r = 0.6699$, where r stands for Pearson's correlation coefficient (p-values lower than 5%).[1] Therefore, there is a positive correlation between WSS investment and coverage. Nevertheless, there are other factors that may explain the lack of success in the universalization of WSS in Brazil. One of those factors is the inefficient use of investment, which should be improved.

Table 1
Investment in WSS infrastructure in Brazil (2013–2016).
Source: authors computations based on data from PLANSAB (2019).

	2013	2014	2015	2016
Drinking water supply				
Total (R$ million)	4332	5062	5728	5925
Average (R$ million)	160	187	212	228
Standard deviation (R$ million)	236	283	442	513
Coefficient of variation (%)	147%	151%	208%	225%
Maximum (R$ million)	1170	1428	2294	2732
Minimum (R$ million)	2	5	2	4
Sanitation				
Total (R$ million)	6446	5607	5273	4235
Average (R$ million)	269	208	195	163
Standard deviation (R$ million)	550	394	334	258
Coefficient of variation (%)	205%	190%	171%	158%
Maximum (R$ million)	2667	1935	1434	1321
Minimum (R$ million)	0	0	0	0
Total investment in WSS				
Total (R$ million)	10,778	10,669	11,001	10,160
Relative change (%)	–	−1.01	3.11	−7.64
Weight of sanitation in total investment				
Average	43%	43%	44%	46%

2.2. Waterborne diseases in Brazil

Water quality problems persist all over the world. Waterborne diseases remain a burden of significant morbidity among vulnerable and disadvantaged groups worldwide, especially among low-income economies (Alirol et al., 2011). In these cases, 4% of the population (25.5 million people) experienced diarrhea episodes in 2015, among which 60% were children under five (WHO, 2019). For example, in the global context, diarrhea is the most significant cause of infant mortality (Liu et al., 2012; Vos et al., 2015). Children under five are the most affected by waterborne diseases (Fontoura et al., 2018).

In developing countries, the precarious conditions of WSS infrastructure are reflected in water bodies' quality and, consequently, in spreading waterborne diseases. The reasons for these circumstances include the increase in emerging pollutants, the spread of invasive species, and the impacts associated with hydro-morphological changes. For instance, fecal matter is a primary source of water contamination (Bain et al., 2014). Low quality of WSS directly affects people depending on these sources, increasing health risks related to water, not to mention their quality of life in general (CEVS, 2020). It is, thus, a public health problem. Therefore, the WSS infrastructure serves as a primary barrier to mitigate individual and community exposure to waterborne diseases' vectors (Freeman et al., 2017).

Several waterborne diseases, including cholera and schistosomiasis, are common in many developing countries, including Brazil. For example, schistosomiasis is a disease closely associated with poverty and low socioeconomic conditions, including poor sanitation and the lack of access to drinking water (Raso et al., 2007). The lack of appropriate WSS causes several negative externalities for society. Hospital admissions and recurrent expenses for waterborne diseases confirm the association between socioeconomic vulnerability, low coverage to safely managed WSS, significant hospitalization rates, and the proportion of expenses (Paiva and Souza, 2018). It is straightforward to conclude that water treatment and improved sanitation conditions effectively prevent the proliferation of waterborne diseases (Kumar and Vollmer, 2013; Gonçalves, 2014). Thus, there is a strong link between upstream WSS investment and downstream hospitalizations due to waterborne diseases that an adequate investment in WSS infrastructure would be expected to reduce the number of hospital admissions for these reason.

Fig. 2(a) portrays the evolution of waterborne disease-related hospital admissions in Brazil from 2010 until 2017. There is a noticeable

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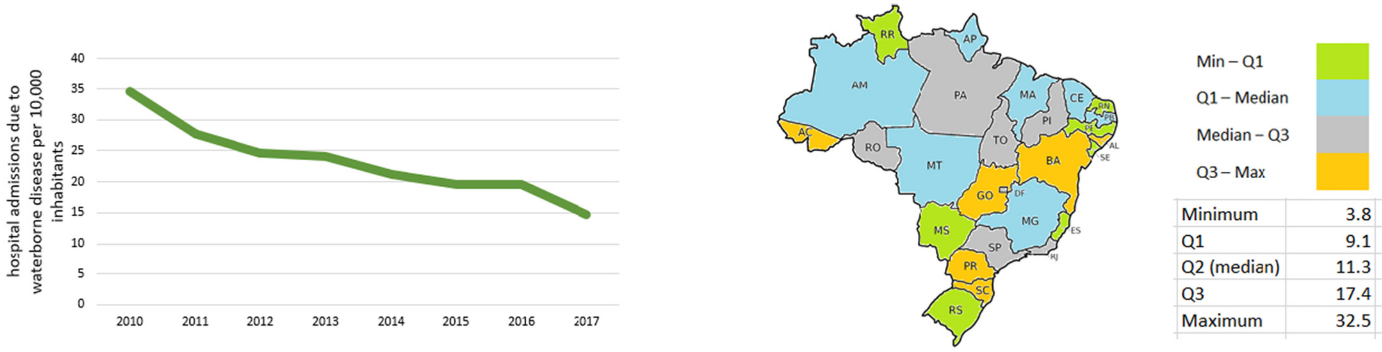
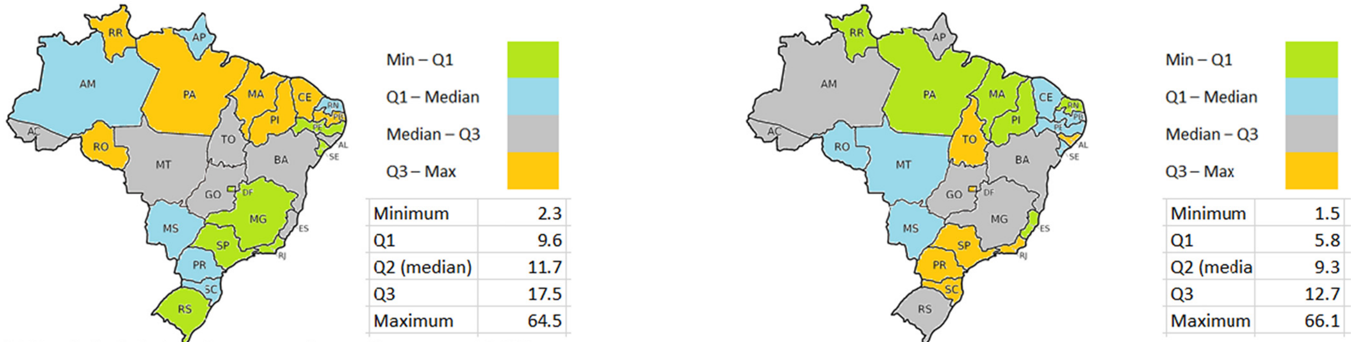
[1] The normality assumed by the Pearson's correlation coefficient was tested using both the Kolmogorov-Smirnov ($p = 0.7108$ and 0.6640) and the Shapiro-Wilk ($p = 0.6449$ and 0.6561) tests. Therefore, the null hypothesis of normality was not rejected.



(a) Evolution of waterborne disease-related hospital admissions (2010-2017)

(c) Waterborne diseases related deaths per million inhabitants (2017)



(b) Hospital admissions due to waterborne diseases per 10,000 inhabitants (2017)

(d) Deaths per 1,000 inpatients hospitalized due to waterborne diseases (2017)

Fig. 2. Evolution and distribution of waterborne disease-related hospital admissions in Brazil.
Source: the authors based on Trata Brasil, URL: www.painelsaneamento.org.br [accessed: May 08, 2019].

decreasing trend of admissions to hospital wards in the considered period. However, there are still about 15 hospital admissions per 10,000 inhabitants (2017), equivalent to >314 thousand people admitted in Brazil, assuming 209.5 million inhabitants, and that each citizen can be admitted just once. This amount of people potentially affected by waterborne diseases places a huge pressure on the public health system.

We considered three leading performance indicators to describe the incidence of waterborne diseases in Brazil and give a sketch showing the prone areas in the country: (1) hospital admissions per 10,000 inhabitants; (2) Deaths per million people; and (3) Death-to-inpatient ratio. The three are meant to be minimized.

Fig. 2(b), (c), and (d) shows the distributions per State of those indicators. We used quartiles, Q, to classify each State into four categories of performance: *very poor* (yellow, Q3–Maximum); *poor* (grey, Q2–Q3); *fair* (blue, Q1–Q2); and *good* (green, Minimum–Q1). For instance, a State exhibiting >17.5 hospital admissions per 10,000 inhabitants has a *very poor* performance level. We do not define *very good* or *excellent* levels because they would mean that one indicator was zero (or close enough) in a State. These three performance indicators exhibit quite distinct distributions across Brazil. For instance, the Northern and Northeastern States seem to have the poorest performance in hospital admissions, while the South and Southeastern ones exhibit the best levels. Nonetheless, having higher death-to-inpatient rates, the latter are outperformed by the States in the North and Northeast (some of them have good performance levels). In this indicator, States in the Midwest exhibit fair performance. In terms of deaths per inhabitant, this distinction between North and South is more challenging to watch as we may find States with good and poor performance levels in each region.

Overall, some States seem to outperform the others regarding the three indicators, reaching a fair or good evaluation in each. They are Mato Grosso do Sul (MG), Pernambuco (PE), Rio Grande do Norte (RN), and Sergipe (SE). The State of Espírito Santo (ES) is not included here because it has poor hospital admissions performance. However, it accomplished a good performance regarding both deaths per inhabitant and deaths per inpatient. In opposition, some States seem to be positioned at the bottom when talking about waterborne disease epidemiology. Being always classified as poor or very poor, they are the States of Acre (AC), Alagoas (AL), Goiás (GO), and Tocantins (TO). Close to them are Paraná (PR) and Santa Catarina (SC), which exhibit very poor performance in the last two indicators but being fair in the first one.

Despite the reduction in the incidence of these diseases in Brazil (see Fig. 2(a)), there is still heterogeneity among the different Brazilian states, resulting from inequalities related to WSS coverage. Table 2 shows some basic statistics on five major non-gastrointestinal waterborne diseases in Brazil in 2016. As the coefficients of variation illustrate, the dissemination of diseases is quite heterogeneous within

Table 2
Causes of hospital admissions (non-gastrointestinal diseases): statistics about five primary waterborne diseases in Brazil (2016).
Data retrieved from Trata Brasil (2019).

	Cause of hospital admission				
	Yellow fever	*Dengue*	*Leptospirosis*	*Malaria*	*Schistosomiasis*
Number of admissions	750	19,461	2067	2043	186
Average	28.85	748.50	79.50	78.58	7.15
Standard deviation	98.75	863.17	120.71	125.51	10.89
Coefficient of variation (%)	342%	115%	152%	160%	152%
Weight of disease in total	3%	79%	8%	8%	1%
Maximum	481	3309	498	402	37
Minimum	0	39	0	0	0

Brazil. Compared to the other three diseases, dengue appears as the leading cause of hospital admissions in Brazil, accounting for nearly 80%. However, leptospirosis and malaria cases continue to be meaningful, both accounting for one-sixth of internments.

The five diseases identified in Table 2 (yellow fever, dengue, leptospirosis, malaria, and schistosomiasis) have the same origins: poor health conditions and low WSS infrastructure coverage. However, they are transmitted in different ways. Yellow fever, dengue, and malaria all have mosquitoes as their primary transmission vector. The conditions of the drinking water supply and the water quality provide the proliferation of these vectors. The intermittency in water supply induces the population to store water, often in the wrong way, which leads to the creation of an environment conducive to the proliferation of vectors. Both yellow fever and dengue are transmitted by the bite of the *Aedes aegyptil* mosquito. Even though yellow fever was eradicated from Brazil in 1942, the country confirmed 772 cases of the disease (1980–2009), with 339 deaths (lethality of 51.7%) (CEVS, 2020). Dengue was also eliminated in 1955. Nevertheless, due to primary WSS coverage failure, the disease was reintroduced into Brazilian territory 21 years later. In 2019, until April, 451,685 probable cases of dengue were registered in the country, resulting in an increase of 339.9% over the same period last year (Ministry of Health, 2019).

Leptospirosis is an infectious disease transmitted by contact, direct or indirect, with rats from sewers among the most common vectors. In Brazil, nearly 30 thousand human leptospirosis cases and 2498 deaths (8.4%) were identified from January 2010 to September 2017. There are also approximately 200 thousand cases of malaria annually. Between January and June 2018, 88,565 cases had already been registered, representing an increase of 26% compared to the same period in 2017 (Ministry of Health, 2018). According to 2015 data from the Brazilian Ministry of Health, 25 million Brazilians live in areas at risk of contracting malaria. In Brazil, schistosomiasis is popularly known as "*schistose*," "*water belly*," or "*snail disease*." The person becomes infected when contacting freshwater with snails infected by worms that act as vectors of schistosomiasis. There is still dumping of many effluents in water bodies in Brazil without proper treatment, making water environments favorable to transmit this disease.

Gastrointestinal diseases, including diarrhea, are also prevalent in Brazil and may result from inadequate access to safely managed WSS. According to the Trata Brasil Institute:

- In 2013, diarrhea and vomit lead to 14 million cases of sick leave, of which 340 thousand cases were admitted to the hospital (about R $121 million to the national health system);
- Each sick leave due to diarrhea or vomit results in an average productivity loss of more than three working days (overall, nearly 50 million working days or a cost of unworked hours of R$ 870 million, in 2013);
- In Brazil, fecal-oral transmission diseases (diarrhea, enteric fevers, and hepatitis A) were responsible for more than three-quarters of hospital admissions caused by inadequate WSS in the first decade of the 21st century;
- There is an enormous gap among Brazilian cities regarding hospital admissions cases due to diarrhea. The worst ten cities observed three times more hospital admissions per inhabitant than the top ten cities (190 *vs.* 69/ 100 thousand inhabitants).

2.3. Calculation: on relating investment, coverage, and waterborne diseases using a network DEA approach

2.3.1. Overview

Färe and Grosskopf (1996, 2000) first proposed the network-DEA approach to model the intricated interconnections within a system whose efficiency was being evaluated. Until then, the DEA models assumed that such a system was like a *black box*, only receiving resources (or inputs) and delivering services or goods (outputs). For instance, Kao and Hwang (2008, 2011) showed that this kind of model is necessary because a unit cannot be efficient if its inner structures are inefficient. Since the introduction of the network DEA model, numerous versions have been proposed in the literature: independent model, system/process/factor distance measure model, slacks-based measure model, ratio-form system/process efficiency model, game-theoretical model, and value-based model; see Kao (2014) for details. The model adopted in this study follows the series structure, which refers to several processes (or stages) connected in sequence (Wei et al., 2011; Lee and Johnson, 2012). Each process consumes both exogenous inputs and intermediate products from the preceding stage. It produces outputs that can leave the system (exogenous outputs) or be intermediate inputs for the succeeding stage (Tsutsui and Goto, 2009; Matthews, 2013; Nouri et al., 2013).

2.3.2. A serial model for modeling the upstream investments in WSS and the downstream hospitalizations due to waterborne diseases

One of the main topics underpinning the investment in WSS is the need to cover the entire population and reduce waterborne diseases associated with inadequate coverage and ineffective investment. Putting it differently, we may define a network relating these concepts in a serial system. It comprises three main steps or stages (coverage, hospitalization, and outcomes), all receiving inputs and delivering outputs. That is to say that we must assess the (partial) efficiency per step to understand the overall performance of each Brazilian state j (for $j = 1, \ldots, 27$). Fig. 3 portrays such a network system:

i. Stage I (Coverage), composed of two parallel services: sanitation (1) and drinking water (2); both receive investment, x_r^j. Their outputs are the number of citizens either using, $z^{(r,h)j}$, or not, $u^{(r,h)j}$, safely managed services, for $r = 1$ (sanitation) or $r = 2$ (drinking water). The number of people not using safely managed WSS is an undesirable output. Additionally, $z^{(1,h)j} + u^{(1,h)j} = z^{(2,h)j} + u^{(2,h)j}$, for any State $j = 1, \ldots, 27$.
ii. Stage II (hospitalization), which receives the entire population, $z^{(1,h)j}$ and $u^{(1,h)j}$, and financial resources to treat the cases related to waterborne diseases, x_3^j, as inputs. The outputs are the population not requiring hospital care due to those diseases, y_1^j, and the number of associated hospitalizations, $u^{(h,o)j}$.
iii. Stage III (outcomes), which handles the inpatients admitted for waterborne diseases, addresses them in the best possible way. Two main outputs may result from this step: survivals, y_2^j (desirable), and deaths, u^j (undesirable). The serial subsystem composed of Stages II and III is the so-called hospital care level related to the investment made upstream.

The performance of a State k in a given stage receiving m distinct inputs, x_p^k $(p = 1, \ldots, m)$, and producing s types of outputs (either services or goods), y_q^k $(q = 1, \ldots, s)$, can be written as the weighted average of the outputs divided by the weighted average of the inputs:

$$P^k = \frac{\sum_{q=1}^{s} \eta_q^k y_q^k}{\sum_{p=1}^{m} \lambda_p^k x_p^k}, \tag{1}$$

where λ_p^k and η_q^k are the weights (multipliers) associated with the pth input and the qth output, respectively, and the State k. Note that multipliers can be either nonnegative (should the variable be desirable) or unconstrained in sign (otherwise). Indeed, in some cases, undesirable variables should be considered for efficiency assessment as they are part of the production process. Since these variables can exhibit negative multipliers (weights), they tend to decrease performance (working as penalties). These multipliers obey the constraint "$>-\infty$."

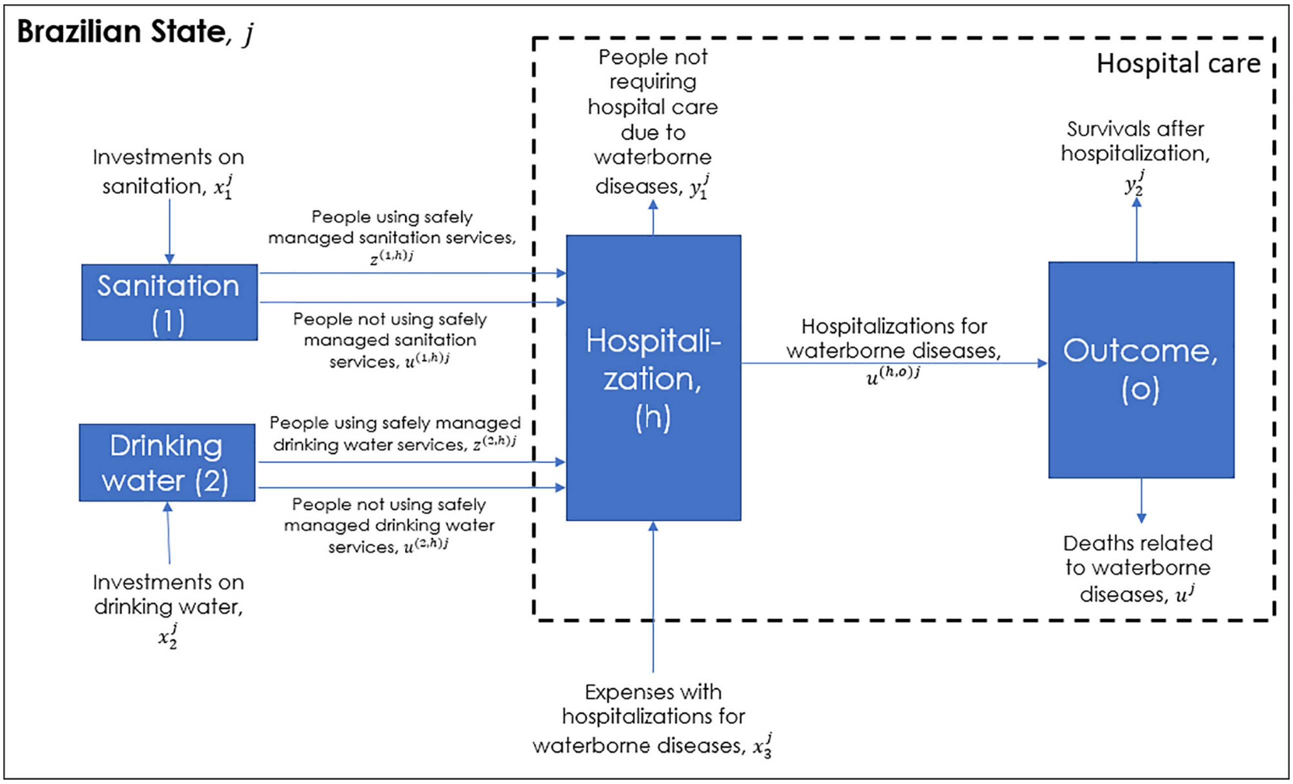


Fig. 3. A theoretical model relating WSS investment and the outcomes of hospital care. Note: x stands for inputs (to minimize), y for desirable outputs (to maximize), and u for undesirable outputs (to minimize). The Brazilian State invests on WSS and, thus, covers only a share of the total population, who, in turn, may require hospital admission due to waterborne diseases. Some patients may perish, while others may survive after appropriate and safe care.

2.3.3. The network-DEA mathematical formulation

Each State k has its own set of weights to be optimized. Let us assume that P^k ranges from 0 to 1, where the latter denotes the best performance level. This implies that the following inequity must hold: $\sum_{q=1}^{s}\eta_q^k y_q^j - \sum_{p=1}^{m}\lambda_p^k x_p^j \le 0$ for any State $j = 1, \ldots, 27$. Adopting the relational network model of Kao (2014, 2017) and keeping that inequity in mind, we may establish a benchmarking model relating investment in WSS to health care services outcomes in terms of waterborne diseases. To sum up, this model reflects a State's performance on evading and treating such a kind of disease. According to the relational model, if a variable plays the role of an output of a stage and an input in the next one, then multipliers must remain the same from stage to stage. Each stage defines at least one constraint of the relational model.

2.3.3.1. Stage I, sanitation. At this stage, the State j receives investment, x_1^j, to serve its population. The service covers a portion of those citizens, $z^{(1,h)j}$, but not the remaining ones, $u^{(1,h)j}$. Therefore, the constraint associated with Stage I (sanitation) is:

$$\gamma_1^k z^{(1,h)j} + \delta_1^k u^{(1,h)j} - \lambda_1^k x_1^j \le 0, \tag{2}$$

being γ_1^k and λ_1^k both nonnegative (because x_1^j and $z^{(1,h)j}$ are desirable) and $\delta_1^k > -\infty$ (because $u^{(1,h)j}$ is undesirable). The performance of State k in Stage I (sanitation) is, according to Eq. (1),

$$P_{\mathrm{I}(1)}^k = \frac{\gamma_1^k z^{(1,h)k} + \delta_1^k u^{(1,h)k}}{\lambda_1^k x_1^k}.$$

2.3.3.2. Stage I, drinking water. As in the previous case, we can straightforwardly establish the following constraint for Stage I (drinking water):

$$\gamma_2^k z^{(2h)j} + \delta_2^k u^{(2h)j} - \lambda_2^k x_2^j \le 0;\ \text{s.t.}\ \gamma_2^k,\ \lambda_2^k \ge 0;\ \delta_2^k > -\infty. \tag{3}$$

The performance at this stage is as before:

$$P_{\mathrm{I}(2)}^k = \frac{\gamma_2^k z^{(2,h)k} + \delta_2^k u^{(2,h)k}}{\lambda_2^k x_2^k}.$$

2.3.3.3. Stage II, hospitalization. Because Stage II receives the population (served and unserved) and some extra financial resources as inputs for hospitalizations and people not requiring health care as outputs, the constraint associated with this stage becomes:

$$\eta_1^k y_1^j + \delta_3^k u^{(h,o)j} - \lambda_3^k x_3^j - \gamma_1^k z^{(1,h)j} - \delta_1^k u^{(1,h)j} \le 0, \tag{4}$$

provided that multipliers η_1^k, γ_3^k, and γ_1^k are all nonnegative and δ_1^k and δ_3^k are unconstrainted (note that hospitalizations should be avoided). However, since $z^{(1,h)j} + u^{(1,h)j} = z^{(2,h)j} + u^{(2,h)j}$ for any State j (*vide supra*), we should also include the following constraint (equation):

$$\gamma_1^k z^{(1,h)j} + \delta_1^k u^{(1,h)j} = \gamma_2^k z^{(2,h)j} + \delta_2^k u^{(2,h)j}. \tag{5}$$

The performance of State k at Stage II is:

$$P_{\mathrm{II}}^k = \frac{\eta_1^k y_1^k + \delta_3^k u^{(h,o)k}}{\lambda_3^k x_3^k + \gamma_1^k z^{(1,h)k} + \delta_1^k u^{(1,h)k}}.$$

2.3.3.4. Stage III, outcomes of healthcare. Stage III measures the capacity (effectiveness) of "transforming" hospitalizations into survivors or deaths due to waterborne disease. The following constraint models this stage:

$$\eta_2^k y_2^j + \delta_4^k u^j - \delta_3^k u^{(h,o)j} \leq 0; \text{s.t.} \eta_2^k \geq 0; \delta_3^k, \delta_4^k > -\infty. \tag{6}$$

The performance of State k at Stage III is:

$$P_{\text{III}}^k = \frac{\eta_2^k y_2^k + \delta_4^k u^k}{\delta_3^k u^{(h,o)k}}.$$

We may use these multipliers to estimate the performance at the hospital care level:

$$P_{\text{hospital care}}^k = \frac{\eta_1^k y_1^k + \eta_2^k y_2^k + \delta_4^k u^k}{\lambda_3^k x_3^k + \gamma_1^k z^{(1,h)k} + \delta_1^k u^{(1,h)k}},$$

as well as to relate it to both P_{II}^k and P_{III}^k. Indeed, if $\xi^j = \lambda_3^k x_3^j + \gamma_1^k z^{(1,h)j} + \delta_1^k u^{(1,h)j}$ and $\sigma^j = \xi^j / \delta_3^k u^{(h,o)j}$, then $P_{\text{II}}^j + P_{\text{III}}^j - \frac{1}{\sigma^j} = \sigma^j P_{\text{hospital care}}^j$.

Considering the variables entering the system (inputs x_1, x_2, and x_3) and the ones leaving it (outputs y_1, y_2, and u), the overall performance of State k is:

$$P_{\text{overall}}^k = \frac{\eta_1^k y_1^k + \eta_2^k y_2^k + \delta_4^k u^k}{\lambda_1^k x_1^k + \lambda_2^k x_2^k + \lambda_3^k x_3^k} = \frac{\xi^k}{\lambda_1^k x_1^k + \lambda_2^k x_2^k + \lambda_3^k x_3^k} P_{\text{hospital care}}^k. \tag{7}$$

As we can see, the performance of a system depends on a set of multipliers. We employ a linear programming problem based on constraints (2)–(6) to optimize those multipliers. We also require an objective function. However, we face two main points of view: economic *vs.* prevention and treatment.

2.3.3.5. Economic point of view. According to this standpoint, to be efficient, the State k should reduce WSS investment, keeping the outputs unchanged. This rationale is equivalent to the input-oriented relational model, whose objective function is:

$$\text{Maximize } \eta_1^k y_1^k + \eta_2^k y_2^k + \delta_4^k u^k \tag{8}$$

associated with an additional constraint:

$$\lambda_1^k x_1^k + \lambda_2^k x_2^k + \lambda_3^k x_3^k = 1. \tag{9}$$

This point of view emphasizes the reduction of investment wastefulness. Plugging Eqs. (8) and (9) into Eq. (7), we obtain $P_{\text{overall}}^k = \eta_1^k y_1^k + \eta_2^k y_2^k + \delta_4^k u^k$, which is smaller than or equal to 1.

2.3.3.6. Prevention and treatment point of view. In some cases, the interest may be reducing the incidence of waterborne diseases, on the one hand, and improving the effectiveness of health care on handling admitted inpatients for waterborne-related services, on the other hand. It is the output-oriented relational model, and its objective function is

$$\text{Minimize } \lambda_1^k x_1^k + \lambda_2^k x_2^k + \lambda_3^k x_3^k \tag{10}$$

associated with an additional constraint

$$\eta_1^k y_1^k + \eta_2^k y_2^k + \delta_4^k u^k = 1. \tag{11}$$

From Eqs. (7), (10), and (11), the overall performance of State k is $P_{\text{overall}}^k = \frac{1}{\lambda_1^k x_1^k + \lambda_2^k x_2^k + \lambda_3^k x_3^k}$.

2.3.4. Marginal products associated with the WSS investment effectiveness

After this, given that the main goal of this study is to estimate investment waste for the provided service level, we considered the economic point of view. Thus, we formulate our network-DEA model by assuming Eq. (8) as the objective function and Eqs. (2), (3), (4), (5), (6), and (9) as constraints.

Multipliers play an essential role other than estimating the efficiency of a system and its levels. We can determine how much of an efficient investment is required to cover the entire population or how many deaths could be avoided with the appropriate investment. Following Sueyoshi (2003) and Sueyoshi and Sekitani (2009), the hyperplane $\sum_r u_{rk} y_{rj} - \sum_i v_{ik} x_{ij} - \mu = 0$ is associated with the marginal product $MP(x_{ik}, y_{rk}) = \partial y_{rk} / \partial x_{ik} = v_{ik} / u_{rk}$. In short, this marginal product translates the growth of the output y per unit of input x that increases for the decision unit k. We now recall the research questions elicited in the introduction and provide the mathematical formulation to answer them. In short, we consider the hyperplanes modeled by the constraints featuring the stages of the Brazilian system illustrated in Fig. 3. Such constraints are rewritten as equations, defining one variable as a differentiable function of others.

2.3.4.1. Research question 1. How many more citizens can enjoy safely managed sanitation services per each R$1 additionally invested? How much money should be invested to cover the entire population?

To answer these questions, we look at the inequity of Eq. (2), which can be transformed into an equation *via* the so-called slacks (nonnegative unknown quantities, $s_{\text{I}(1)}^j$): $\gamma_1^k z^{(1,h)j} + \delta_1^k u^{(1,h)j} - \lambda_1^k x_1^j + s_{\text{I}(1)}^j = 0$, which is equivalent to $z^{(1,h)k} = \frac{\lambda_1^k}{\gamma_1^k} x_1^k - \delta_1^k u^{(1,h)k} - s_{\text{I}(1)}^k$ for the case $j = k$. Because the population served by the sanitation services is a function of the investment made, we can differentiate the dependent variable and obtain:

$$\frac{\partial z^{(1,h)k}}{\partial x_1^k} = \frac{\lambda_1^k}{\gamma_1^k}, \tag{12}$$

which is strictly positive because of the non-negativity of both the multipliers λ_1^k and γ_1^k. Eq. (12) estimates the number of additional citizens covered by sanitation services per additional R$1 invested. It answers the first question. Furthermore, the quantity $\partial x_1^k / \partial z^{(1,h)k} = (\partial z^{(1,h)k} / \partial x_1^k)^{-1} = (\lambda_1^k / \gamma_1^k)^{-1}$ measures how much money should be efficiently invested to extend the sanitation coverage to another person. Since $u^{(1,h)k}$ is the number of citizens who have no access to safely managed sanitation services in State k, the total amount of efficient investment that this State should carry out is simply $\Sigma_{\text{I}(1)}^k = \left(\frac{\lambda_1^k}{\gamma_1^k}\right)^{-1} u^{(1,h)k}$, which answers the second question. Note that we use the (optimal) multipliers resulting from the optimization problem described above.

2.3.4.2. Research question 2. How many more citizens can enjoy safely managed drinking water services per each R$1 additionally invested? How much money should be invested to cover the entire population?

Mutatis mutandis, we use Eq. (3) to conclude that the total amount of money that State k should invest to cover the entire population in terms of drinking water services is $\Sigma_{\text{I}(2)}^k = \left(\frac{\lambda_2^k}{\gamma_2^k}\right)^{-1} u^{(2,h)k}$. Additionally, $\frac{\partial z^{(2,h)k}}{\partial x_2^k} = \frac{\lambda_2^k}{\gamma_2^k}$ estimates the number of additional citizens covered by drinking water services per further R$1 efficiently invested.

2.3.4.3. Research question 3. What is the impact of investment in WSS on the number of people not requiring health care resulting from waterborne diseases? Can we quantify it?

To answer these questions, we observe that inequity in Eq. (4) can be rewritten as $\eta_1^k y_1^k + \delta_3^k u^{(h,o)j} - \lambda_3^k x_3^j - \gamma_1^k z^{(1,h)j} - \delta_1^k u^{(1,h)j} + s_{\text{II}}^j = 0$, being s_{II}^j a nonnegative and unknown slack associated with the State $j = 1, \ldots, 27$. However, this equation does not relate investment to the number of citizens that do not require health care services due to waterborne diseases. We have verified before that $\gamma_1^k z^{(1,h)j} + \delta_1^k u^{(1,h)}$

$^j - \lambda_1^k x_1^j + s_{\mathrm{I}(1)}^j = 0$, which is equivalent to $\gamma_1^k z^{(1,h)j} + \delta_1^k u^{(1,h)j} = \lambda_1^k x_1{}^j - s_{\mathrm{I}(1)}^j$. This equation can be plugged in Eq. (4), resulting in $\eta_1^k y_1^j + \delta_3^k u^{(h,o)j} - \lambda_3^k x_3^j - \lambda_1^k x_1^j + s_{\mathrm{I}(1)}^j + s_{\mathrm{II}}^j = 0$, or $y_1^j = -\frac{\delta_3^k}{\eta_1^k} u^{(h,o)j} + \frac{\lambda_3^k}{\eta_1^k} x_3^j + \frac{\lambda_1^k}{\eta_1^k} x_1^j - \frac{1}{\eta_1^k} s_{\mathrm{I}(1)}^j - \frac{1}{\eta_1^k} s_{\mathrm{II}}^j$. Differentiating it in order of x_1^j, we obtain (for $j = k$):

$$\frac{\partial y_1^k}{\partial x_1^k} = \frac{\lambda_1^k}{\eta_1^k}, \tag{13}$$

which is, *ceteris paribus*, a nonnegative quantity identifying the additional number of citizens that would not require health care services for waterborne diseases if R$1 was additionally and efficiently invested in safely managed sanitation services. We do a similar exercise for the case of drinking water services, reaching $\frac{\partial y_1^k}{\partial x_2^k} = \frac{\lambda_2^k}{\eta_1^k}$.

2.3.4.4. Research question 4. What is the impact of investment in WSS in terms of hospitalizations? Can we quantify the minimum investment required to prevent hospitalizations due to waterborne infectious diseases?

Provided that $\eta_1^k y_1^j + \delta_3^k u^{(h,o)j} - \lambda_3^k x_3^j - \lambda_1^k x_1^j + s_{\mathrm{I}(1)}^j + s_{\mathrm{II}}^j = 0$ (*vide supra*), we have $\delta_3^k u^{(h,o)j} = -\eta_1^k y_1^j + \lambda_3^k x_3^j + \lambda_1^k x_1^j - s_{\mathrm{I}(1)}^j - s_{\mathrm{II}}^j$, which means that $\frac{\partial u^{(h,o)k}}{\partial x_1^k} = \frac{\lambda_1^k}{\delta_3^k}$. Since $\lambda_1^k > 0$ and $\delta_3^k < 0$ (because $u^{(h,o)j}$ is undesirable for any State j), that ratio is negative. In other words, the additional and efficient investment of R$1 on sanitation leads *ceteris paribus* to the decreasing of $\left|\frac{\lambda_1^k}{\delta_3^k}\right|$ inpatients due to waterborne diseases. The same applies to investment in drinking water as $\frac{\partial u^{(h,o)k}}{\partial x_2^k} = \frac{\lambda_2^k}{\delta_3^k}$. These results immediately yield to the investment required to prevent hospitalizations and, by extension, in-hospital deaths due to waterborne infectious diseases: $\left|\frac{\lambda_1^k}{\delta_3^k}\right|^{-1} \cdot u^{(h,o)k}$ for sanitation and $\left|\frac{\lambda_2^k}{\delta_3^k}\right|^{-1} \cdot u^{(h,o)k}$ for drinking water.

3. Results and discussion

3.1. Sample and data

Brazil is the world's fifth-largest and most populous country, composed of twenty-seven states (or administrative divisions) and more than five thousand municipalities. It also has the eighth highest gross domestic product worldwide. Brazil's real gross domestic product (at constant prices) in 2017 was 2,943,783.5 million of 2011 US dollars.[2] Of course, other indicators such as natural capital accounting or gross ecosystem product would be more beneficial to guide investments in ecosystem conservation and restoration. This happens because the standard gross domestic product "*fails to capture the contributions of nature to economic activity and human well-being*" (Ouyang et al., 2020). Unfortunately, the gross ecosystem product, as a recent indicator, is unavailable for Brazil yet.

Nonetheless, Brazil remains an emerging economy. Our unit of analysis (also named decision-making unit) is each Brazilian State; thus, our sample comprises twenty-seven observations from 2016. However, five of them need a careful analysis as they have been classified as potential "outliers" in terms of investment: Minas Gerais (MG), Paraná (PR), Pernambuco (PE), Rio de Janeiro (RJ), and São Paulo (SP). Together, they represented nearly 65% of Brazil's total investment regarding WSS between 2013 and 2015. Considering the whole sample of States would lead to remarkably high inefficiency levels since there is a considerable technology gap (frontier shift) between both groups. Brazilian benchmarks would mostly belong to the group of "outliers," placing the admissible (meta)frontier representing the production function in a region that is empirically inaccessible to the remaining states. Therefore, we consider two distinct clusters of states and conduct two analyses, one per cluster:

- Cluster "*heavyweights*": states MG, PR, PE, RJ, and SP;
- Cluster "*lightweights*": the remaining twenty-two Brazilian states.

Table 3 provides some basic statistics about WSS in Brazil and health care services associated with the inpatients resulting from waterborne diseases (infectious gastrointestinal diseases and others).[3] "*Heavyweights*" are the ones investing more in both WSS, also exhibiting better coverage levels when compared to the other Brazilian States. However, no statistical differences between those clusters were detected by the Kruskal-Wallis regarding costs related to hospital admissions due to waterborne diseases ($p = .053$) as well as inpatient admissions ($p = .1046$) and in-hospital deaths for that reason ($p = .4727$). It suggests that "*heavyweights*" are expectedly more efficient upstream of the system but not necessarily downstream than "*lightweights*."

3.2. Main results and discussion

Table 4 presents some basic statistics associated with the results displayed in Table A.1 (Appendix A), which, in turn, details the individual efficiency levels achieved through the network-based model and other relevant results related to the research questions.

In general, Brazilian administrative divisions are very inefficient in the upstream of the serial model, *i.e.*, delivering WSS to their citizens. On average, 26–28% of investment was wasted. Thus, if efficiently managed, these could be effectively used to increase coverage. Although some heterogeneity can be observed regarding WSS efficiency profiles among the States, "*heavyweights*" clearly outperform the remaining 22 administrative divisions, as expected (*vide supra*). About the former, Rio de Janeiro appears to be very inefficient in sanitation, as nearly half of the investment was inappropriately used when compared to the other four states of the very same cluster. The same can be said about Pernambuco for drinking water services, despite the trim inefficiency level. The "*Lightweights*" cluster, composed of the Brazilian states with the smallest investment in WSS, has the most inefficient states using that investment. Only a quarter of these states are efficient on both services, making them overall efficient: Bahia, Distrito Federal, Mato Grosso do Sul, Rio Grande do Sul, and Roraima. The network-DEA model's requisite is that global efficiency occurs when the observation reaches unitary efficiency scores in all stages of Fig. 3 (investment and coverage, hospitalization, and outcome). If the Brazilian state verifies inefficiency (score smaller than one) in one of those stages, it cannot be considered globally or overall efficient.

WSS are two fields demanding colossal investment all over the country. Between these two services, sanitation is the one that requires more investment. This is an expected result as it is also the service with the most negligible coverage levels in Brazil and requires costlier infrastructure than drinking water services. All states together must invest more than R$215 billion (US$57 billion) in sanitation and nearly R$140 billion (US$37 billion) in drinking water to cover the entire population in an efficient and, by extension, in an effective way. Overall, about R$355 billion must be invested to provide those two services to the population, which represents R$1700 (US$450) per inhabitant. Note that potential economies of scope resulting from the joint provision of these two services were inherently accounted for by the serial-based network model elicited before. An enormous heterogeneity of investment among Brazilian states stands out. On average, each State alone must invest R$8 billion in sanitation and R$5 billion in drinking water to provide universal services. However, such levels triple for the five "*heavyweights*." As we have highlighted before, these states

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[2] See https://fred.stlouisfed.org/series/RGDPNABRA666NRUG; accessed January 03, 2021.

[3] The group of other diseases related to poor WSS includes the yellow fever, dengue fever, leptospirosis, malaria, and schistosomiasis.

Table 3
Basic statistics about sanitation, drinking water, and related hospital services for Brazil.
Source: authors computations.

		Min	Mean	Max	Std. dev.	CV[a]
"*Heavyweights*"	Safely managed sanitation services					
	Investment (2013–2015)/R$1,000,000[b]	401	2247	4094	1410	63%
	Coverage (2016)/%[c]	32%	70%	93%	20%	–
	Safely managed drinking water services					
	Investment (2013–2015)/R$1,000,000	1033	1970	4892	1472	75%
	Coverage (2016)/%	91%	95%	100%	4%	–
	Hospital services					
	Costs related to hospital admissions due to waterborne diseases/R$1,000,000	2	5	8	2	39%
	Episodes of care (inpatients) resulting from infectious gastrointestinal diseases	3331	10,626	15,479	4397	41%
	Episodes of care (inpatients) resulting from other diseases associated with lack of sanitation	435	1063	2342	713	67%
	In-hospital deaths resulting from those hospital admissions	10	39	80	27	70%
"*Lightweights*"	Safely managed sanitation services					
	Investment (2013–2015)/R$1,000,000	0.10	191	612	180	94%
	Coverage (2016)/%	6%	33%	85%	20%	–
	Safely managed drinking water services					
	Investment (2013–2015)/R$1,000,000	11	203	623	167	82%
	Coverage (2016)/%	40%	86%	100%	16%	–
	Hospital services					
	Costs related to hospital admissions due to waterborne diseases/R$1,000,000	0.27	3	15	4	113%
	Episodes of care (inpatients) resulting from infectious gastrointestinal diseases	491	8220	42,811	10,229	124%
	Episodes of care (inpatients) resulting from other diseases associated with lack of sanitation	71	888	3330	907	102%
	In-hospital deaths resulting from those hospital admissions	0	92	493	114	124%
Brazil	Safely managed sanitation services					
	Investment (2013–2015)/R$1,000,000	0.52	642	4094	1010	157%
	Coverage (2016)/%	6%	40%	93%	25%	–
	Safely managed drinking water services					
	Investment (2013–2015)/R$1,000,000	16	560	4892	939	168%
	Coverage (2016)/%	44%	88%	100%	15%	–
	Hospital services					
	Costs related to hospital admissions due to waterborne diseases/R$1,000,000	0.27	4	15	4	97%
	Episodes of care (inpatients) resulting from infectious gastrointestinal diseases	491	8666	42,811	9472	109%
	Episodes of care (inpatients) resulting from other diseases associated with lack of sanitation	71	920	3330	877	95%
	In-hospital deaths resulting from those hospital admissions	0	82	493	106	129%

[a] CV (coefficient of variation) relates to the standard deviation, σ, and the average, $\bar{x}$: $\mathrm{CV} = \sigma/\bar{x}$. Values of CV larger than 25% identify high heterogeneity.

[b] Investment effects extend over time; thus, the investment made before 2016 must be considered. Only medium-long term investment should be accounted for (leaving investment made in 2016 out of our analysis). Therefore, we considered the cumulative investment of the triennium 2013–2015, adequately adjusted by the GDP deflator (basis: 2016).

[c] Coverage is the proportion of people using safely managed services (either sanitation or drinking water).

represent 65% of the total investment undertaken all over the country. Hence, it is not surprising that the demanded investment to cover the entire population with safely managed WSS ranges from 60 to 70% of Brazil's total required investment. Although "*heavyweights*" are more efficient than the remaining ones, they figure among Brazil's most populous states and still have a considerable share of the unserved population.

These five "*heavyweights*" need higher investment to cover a certain quantity of citizens when compared with the other twenty-two states. Indeed, suppose that the former efficiently invest ten additional million R$ in WSS. In that case, they can increase the number of inhabitants enjoying safely managed services by at least eight (ten) thousand on average. Those figures increase for the case of the "*lightweight*" states: 21.6 and 23.8 thousand. The gaps in these two groups suggest that investment in the most populous (and more densely inhabited) regions is less efficient than in the other regions. These figures may find support on coverage asymmetries within the same State. Let us consider a populous "*heavyweight*" state. Typically, most of its citizens live in a metropolis with no major WSS coverage faults. However, part of the population lives in rural areas without access to those essential services. Providing services without the proper infrastructure to the rural inhabitants becomes more complex and costly. Topography and even urban configuration can influence this context. For example, there are irregular occupations in Brazilian populous urban areas that encompass riverbeds, dunes and slopes. These features may incur the cost of grid and supply facilities and, even more, the structure to provide WSS.

In terms of hospitalizations, the stage "receives" covered and uncovered citizens and financial resources devoted to waterborne disease treatment as inputs and "delivers" population requiring and not requiring hospital admission as outputs. Brazilian states seem to be quite efficient at this stage. It can result from the so-called curse of dimensionality due to the number of variables considered to model the stage compared with the sample size. Another reason is that patients' weight admitted to waterborne diseases is relatively small, meaning that the variable has no significant discriminatory power. Note that the optimization of multipliers undertaken by the linear program underlying the network DEA aims to maximize efficiency. Hence, the second stage score has no empirical meaning (the hospital care performance should be assessed *via* the third stage instead).

Brazilian states seem to exhibit very high-efficiency levels, considering the outcomes stage. Indeed, those levels do not represent efficiency *per se*, but effectiveness instead. The latter defines the capacity of saving inpatients and avoiding their death. In-hospital deaths due to waterborne diseases represent <1% of the total patient admissions for the same reasons. Thus, no wonder those states could be considered effective.

Nonetheless, due to the second stage, expenses with hospital care are inputs whose waste should be minimized. Because the serial-based stage "hospital care," composed of the second and third stages, is inefficient/ineffective, that wastefulness of resources is not null. Provided that states were deemed efficient in the second stage, hospital care performance is measured by the effectiveness (*i.e.*, the performance in stage three). The minimum effectiveness level was 0.9336 in Santa Catarina. This one could reduce expenses with secondary health care by 7% for equivalent levels of inpatients and survivors. It is interesting to note that this State is among the worst performers because of the

Table 4
Basic statistics regarding the main results. Note: ∂z/∂x denotes the derivative of a variable z in order to x (marginal product).
Source: authors computations.

		Efficiency levels				Question 1 (sanitation services)		Question 2 (drinking water services)		Question 3		Question 4	
		Sanitation	Drinking water	Hospitalization	Outcomes	$\frac{\partial(10^6 z^{(1,h)})}{\partial(10^6 x_1)}$	Demanded investment (million R$)	$\frac{\partial(10^6 z^{(2,h)})}{\partial(10^6 x_2)}$	Demanded investment (million R$)	Sanitation, $\frac{\partial(10^6 y_1)}{\partial(10^6 x_1)}$	Water services, $\frac{\partial(10^6 y_1)}{\partial(10^6 x_2)}$	Investment in sanitation (100 R$)	Investment in drinking water (100 R$)
Heavyweights	Average	0.9083	0.9279	1.0000	0.9977	0.0081	2655.30	0.0105	1931.71	0.0126	0.0110	1,499,618	1,082,455
	Standard deviation	0.1834	0.1208	0.0000	0.0020	0.0035	1505.29	0.0030	1518.13	0.0056	0.0033	1,516,520	502,996
	CV*	20%	13%	0%	0%	43%	57%	29%	79%	45%	30%	101%	46%
	Maximum	1.0000	1.0000	1.0000	1.0000	0.0115	4561.16	0.0147	4961.72	0.0189	0.0156	4,404,005	1,750,777
	Minimum	0.5416	0.6893	0.9999	0.9952	0.0021	1233.48	0.0066	1081.52	0.0027	0.0073	207,054	212,974
	Total	–	–	–	–	–	13,276.49	0.0523	9658.56	0.0628	0.0551	7,498,092	5,412,276
Lightweights	Average	0.6865	0.7007	1.0000	0.9863	0.0216	378.97	0.0238	191.96	0.1901	0.0293	237,283	324,400
	Standard deviation	0.3433	0.2506	0.0001	0.0182	0.0231	389.79	0.0092	187.19	0.3507	0.0148	313,415	383,143
	CV	50%	36%	0%	2%	107%	103%	39%	98%	184%	50%	132%	118%
	Maximum	1.0000	1.0000	1.0000	1.0000	0.1007	1509.38	0.0506	787.25	1.3663	0.0812	1,454,251	1,454,327
	Minimum	0.1414	0.2105	0.9997	0.9336	0.0014	7.09	0.0083	19.38	0.0025	0.0083	431	13,993
	Total	–	–	–	–	–	8337.43	0.5242	4223.15	4.1824	0.6443	5,220,234	7,136,805
Brazil	Average	0.7276	0.7427	1.0000	0.9884	0.0191	800.52	0.0214	514.14	0.1572	0.0259	471,049	464,781
	Standard deviation	0.3312	0.2484	0.0001	0.0170	0.0216	1151.21	0.0099	955.02	0.3240	0.0152	863,931	503,166
	CV	46%	33%	0%	2%	113%	144%	46%	186%	206%	59%	183%	108%
	Maximum	1.0000	1.0000	1.0000	1.0000	0.1007	4561.16	0.0506	4961.72	1.3663	0.0812	4,404,005	1,750,777
	Minimum	0.1414	0.2105	0.9997	0.9336	0.0014	7.09	0.0066	19.38	0.0025	0.0073	431	13,993
	Total	–	–	–	–	–	21,613.92	0.5765	13,881.71	4.2452	0.6994	12,718,326	12,549,081

* CV — coefficient of variation (= standard deviation / average).

observed death levels, either regarding the number of inhabitants or the number of inpatients admitted because of waterborne diseases.

Although no meaningful discrimination regarding efficiency and effectiveness was achieved, the linear model optimal multipliers helps answer the third and fourth research questions. We can use them to assess whether the upstream investment in WSS impacts the number of citizens not requiring hospital care for waterborne diseases. On average, Brazilian states could increase the number of people not requiring hospitalizations due to waterborne diseases by 157 thousand per R$100 million invested in sanitation and 26 thousand per R$100 million invested in drinking water. In other words, sanitation investment plays a more relevant role in hospitalization prevention than investment in drinking water. Thus, the lack of safely managed sanitation appears as the most relevant determinant of waterborne disease dissemination. If efficiently applied, then the investment required to cover the entire population would suffice to avoid hospitalizations, reducing them to the minimum. This "minimum" investment to safeguard citizens from widespread waterborne diseases is nearly R$1300 million in the "*heavyweights*" cluster and, similarly, R$1200 million in the "*lightweights*" cluster. Together, these figures represent 7% of the total investment required to provide safely managed WSS to all Brazilian citizens.

Most studies on this subject tend to evaluate the success of investment in these utilities based on their returns, *e.g.,* through the returns-to-investment indicator. An apparent social return on investment is the reduction of mortality due to waterborne diseases. For instance, Cutler and Miller (2005) concluded that the rate of returns-to-investment in WSS in some US cities was 23 to 1, *i.e.*, $1 invested returned $23 in social terms (child mortality reduction by half after technical improvements in WSS). The World Health Organization is less optimistic, concluding for a $4.3 return in reduced expenses with healthcare. This heterogeneity in results from various sources may arise out of the difficulty of estimating human life value. Therefore, instead of looking at the return-to-investment rate as the success indicator of WSS enhancement, we estimated the marginal products associated with such investment that measures the expected change in epidemics and mortality when a single dollar is efficiently invested on WSS. It is worth mentioning that efficiency on resource usage was not considered in the studies mentioned above. Thus, our results are not directly comparable with them. To the best of our knowledge, neither other study has evaluated the marginal products nor has it estimated the total investment required to mitigate those diseases.

No hospitalizations due to those diseases imply deaths or survivals for those causes. It would be naïve to believe that erasing such diseases is possible, especially in a tropical weather country. Furthermore, Burström et al. (2005) suggest that the water and wastewater access improvements alone are insufficient to reduce waterborne mortality; these improvements must be followed by public education and sanitary laws to create synergies between the utilities (Helgertz and Önnerfors, 2019). Mitigating hospitalizations and, more critical, deaths is possible in theory with the due investment, but erasing the dissemination of those diseases is hardly possible. As we can see, relatively small (efficient) investment in WSS significantly impacts hospitalizations. This impact is more expressive than the investment in WSS coverage. Therefore, if safely managed WSS covered all citizens, Brazil would come close to developed countries like the USA and the European ones. In these countries, infectious diseases such as yellow fever, dengue fever, leptospirosis, malaria, and schistosomiasis have never been observed or have already been eradicated. For instance, Juntunen et al. (2017) concluded that current waterborne diseases related risks in Finnish waterways were found to be low. Although we do not observe meaningful waterborne diseases spread in developed countries, these have already watched similar epidemic outbreaks (Ferrie and Troesken, 2008; Beach et al., 2016; Kesztenbaum and Rosenthal, 2017).

In practical terms, the success of developed countries in broadening the coverage of WSS for their citizens results from complementary advances in critical elements, such as (Caravati et al., 2009): (*i*) energy use in source collection, conveyance systems, distribution, treatment, either biological or chemical; (*ii*) chemical treatment of water and wastewater; (*iii*) subsidies to ensure acceptance and regulation to set standards for WSS provision; (*iv*) capital as WSS are high capital and maintenance demanding; (*v*) property ownership to protect the WSS infrastructure system; and (*vi*) social acceptance. In developing countries, like Brazil, however, one or more of these elements are missing, *e.g.*, governments lack the authority and resources to implement this kind of programs, the revenues are insufficient to cover operating expenses, there is a lack of subsidies along with considerable economic and regulatory needs (Caravati et al., 2009). According to Gleick (2000), the governments in developing nations avoid subsidizing WSS investment, shifting such a responsibility to regional or local governments, or even allowing privatization of these services. As suggested by Bayliss and McKinley (2007), sometimes privatization is a widespread failure because private investors are more focused on cost recovery than on providing services with quality and at fair prices. Therefore, investment in WSS by itself, without improvements regarding technical issues (energy, chemical treatments, pumps, among others), regulatory frameworks, and social awareness to use the infrastructure, is unlikely to produce the desired effects of public health.

Regulation assumes a primary role here. Cairncross and Valdmanis (2006) suggested that health benefits constitute a positive externality of interventions in WSS. According to them, "*the function of the health sector is one of regulation, advocacy, and provision of supplementary inputs, as appropriate, to ensure that potential health benefits of water supply are realized to the optimal extent*." Therefore, regulation must ensure the quality of the water supply service, especially in terms of supplied quantity, continuity, coverage, and control of sanitary hazards. Regulation must also control the prices that should be equitable and, simultaneously, cover the operating expenses associated with WSS (Marques, 2010). Regarding sanitation, it is vital to ensure that people are aware of the risks associated with open defecation and that they have latrines and use and maintain them appropriately. Provided that some of these strategies are implemented together with massive investment in WSS infrastructure, we may expect that Brazil approaches itself to the United Nations SDGs 1, 3, and 6.

We should remark that the impact of the coverage of WSS infrastructure on health is multifactorial. WSS interventions alone may not be sufficient to mitigate disease transmission (Fuller and Eisenberg, 2016). It means that any strategy undertaken to enlarge citizens' coverage of essential WSS should account for these factors or determinants, and investment must be adjusted accordingly. Potential determinants of investments and hospitalizations include WSS infrastructure ownership structure, size, diversification and geographical location (Guerrini et al., 2011), climate (Levy et al., 2018; Lai et al., 2020), origin and quality of water supply (Cesa et al., 2016), governance (Marques et al., 2015) and age, household income, and average education of the target population (Siqueira et al., 2017), to name a few. Besides, territorial characteristics, including soil type, climatic aspects, population hygiene, and even cultural conditions, should potentially determine WSS's role in mitigating the health burden (Stenberg et al., 2014).

Other countries facing similar problems of low WSS coverage and substantial hospital admissions due to waterborne diseases may take advantage of the network-DEA results. Although the appropriate adjustment for the operational environment was missing, allowing to conduct a more reliable benchmarking exercise, the truth is that those countries may compare themselves with the appropriate Brazilian State. In that vein, they may use the optimized marginal products associated with the coverage (boosting the universalization goal that most wish) and inpatients/deaths (reducing the burden over each national health system). By "appropriate," we mean the State with the most similar features to each country, typically evaluated through the WSS performance determinants, as mentioned before. So, for instance, a developing country with similar features to the State of Amazonas (AM) should expect to spend about R$22 (=1/0.0441; see Table A.1) and $R38 to provide sanitation and drinking water services, respectively, to one more citizen. Nonetheless, each country may look at the average of those marginal products, assuming it as a central tendency of the relationship between efficient investment in WSS, covered people, hospitalizations, and deaths. Such a tendency is likely to be valid for those countries, primarily if their water and health utilities work in similar environments as Brazilian utilities do.

As with any empirical analysis, this study is not entirely flawless as some shortcomings related to both data and model should not be overlooked. Although more robust than the traditional DEA model, its network version cannot couple the input-output data with the information about the operational environment or conditions that each Brazilian State faces in providing both WSS and hospitalizations resulting from waterborne diseases. Without these adjustments, a bias source may exist related to unfair comparisons undertaken by the benchmarking model. The clustering *lightweights/heavyweights* could contribute to minimizing this bias. However, the only feasible way to avoid it is to consider a complete set of dimensions, deemed determinants for investment in WSS and waterborne hospitalizations (*vide supra*), and appropriately correct efficiency scores and marginal products for heterogeneity within Brazil (Romano et al., 2020). Of course, this exercise would be limited by the sample size, which is small in our case. It is well-known that non-parametric benchmarking models, like network-DEA, are sensitive to small samples (Ferreira et al., 2020). It constitutes another limitation of this study. Alternatives to enhance the robustness of our findings and mitigate the impact of these potential limitations are discussed further ahead in Section 3.4.

A final remark related to our data is about the number of hospitalizations due to waterborne diseases. According to Mor et al. (2014), it may not constitute the actual number of people affected by those diseases because of three main reasons: some people have just mild symptoms of short duration, not seeking medical care; those seeking will probably not have appropriate tests for the etiology; and not all confirmed cases are reported to the surveillance system. Although it is an insurmountable problem, it implies that our efficiency estimates are perhaps slightly overestimated. A solution to mitigate the impact of this uncertainty on data is to simulate data points within a specific domain of that variable and apply a procedure like the one proposed by Ferreira et al. (2018).

3.3. Summary of economic implications

A straightforward way of measuring the impact of upstream WSS investment is to estimate its marginal products associated with covered citizens, admitted patients, and deaths. Our results pointed towards a demanded investment of nearly R$14 billion in drinking water and more than R$21 billion in sanitation to efficiently cover all Brazilian citizens. In 2018, Brazil had 209.5 million citizens, which means that the overall investment *per capita* would be about R$169, corresponding to 0.5% of the gross domestic product *per capita* in that year. Provided that at least 26 thousand people would avoid hospitalization due to waterborne diseases per R$100 million, such an investment would be enough to reduce the number of hospitalizations by more than nine million, a value largely surpassing the observed demand for healthcare in waterborne disease cases. It would minimize the number of related deaths to near zero. More precisely:

(1) On average, an efficient investment of R$1 on safely managed sanitation services would increase the coverage of 0.0191 people; alternatively, each citizen demands, on average, an investment of R$52. The total estimated investment in safely managed sanitation services across Brazil for the universal coverage was R$21.6 billion.
(2) On average, an efficient investment of R$1 on safely managed drinking water services would increase the coverage of 0.0214 people; alternatively, each citizen demands, on average, an investment of R$47. The total estimated investment in safely managed drinking water services across Brazil for the universal coverage was R$13.9 billion.
(3) On average, in Brazil, an efficient investment of R$1 in sanitation would decrease hospitalizations by 0.1572 cases, while the same investment in drinking water would decrease such a figure by 0.0259.
(4) The impact of the upstream investment in WSS is massive concerning hospitalizations and resulting deaths; the estimated minimum and efficient investment to reduce deaths towards zero would be R$1.27 billion in sanitation and R$1.25 billion in drinking water services.

3.4. Directions for future research

Our study considered the hypothesis of holding the number of infections and hospitalizations by waterborne diseases, thus evaluating how much money could be saved in upstream investments and turning WSS infrastructure more efficient. It means that, from an economic point of view, we have adopted an input-oriented network-DEA model to provide answers to our research questions. Naturally, *there are two sides of the same coin*. One could also look at the same problem by trying to find how many deaths and hospitalizations could be reduced if the Brazilian states would be more output-oriented efficient, *i.e.*, holding the investments. Although closely related, following similar benchmarking models, the two standpoints are distinct and prone to different results. This time, we should conduct new research following an output-oriented network-DEA to check for the consistency of the results of the present study, particularly the marginal products that helped us answer the research questions.

When discussing our results, we pointed out two main shortcomings limiting their validity: the absence of correction by the operational conditions in which Brazilian states operate and the sample size. The inclusion of a broad set of dimensions to turn homogeneous the observations for the benchmarking exercise imposes that the sample must be sufficiently large to alleviate dimensionality effects. Although we considered the Brazilian States as the observations in this study, we expect to go beyond and obtain a more comprehensive set of variables for the 5580 Brazilian municipalities. These variables should contain information about WSS investment, access to these essential services, waterborne disease hospitalizations and deaths, and others related to geography and socioeconomics. The inclusion of the latter may imply adopting different models like those estimating partial frontiers, thus being less sensitive to outliers and the sample size (Ibrahim et al., 2019).

4. Concluding remarks

In a period featured by the appearance of pandemic outbreaks demanding a high volume of resources to save lives, other diseases might be ignored, despite their impact on citizens' quality of life and each country's gross ecosystem product. As shown in a myriad of studies, the environment and the resources management have a meaningful impact on disseminating these diseases and the capacity to treat the infected people.

This study showed that Brazil's spreading of waterborne diseases could be mitigated if Brazilian states drastically improve their investment efficiency to guarantee all citizens' coverage. Likewise, one could prevent hospital admissions resulting from waterborne diseases if all citizens had access to those essential water-related services. The results of our study suggest that relatively small (efficient) investment in WSS infrastructure has a massive impact on hospitalizations due to waterborne diseases. As we have seen, hospitalizations caused by waterborne diseases have a deleterious impact on national productivity (because of unworked hours). Therefore, reducing or even eradicating these diseases should improve such productivity and the internal product, reducing the sick leave costs and the unworked hours.

CRediT authorship contribution statement

Diogo Cunha Ferreira: Conceptualization, Methodology, Software, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Ingrid Graziele:** Conceptualization, Investigation, Resources, Data curation. **Rui Cunha Marques:** Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Jorge Gonçalves:** Validation, Formal analysis, Supervision.

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

Table A.1
Results per State: answering the five research questions. Source: authors computations. Note: ∂z/∂x denotes the derivative of a variable z in order to x (marginal product).

State	Efficiency levels				Question 1 (sanitation services)		Question 2 (drinking water services)		Question 3		Question 4		
	Sanitation	Drinking water	Hospitalization	Outcomes	$\frac{\partial z^{(1,h)}}{\partial x_1}$	Demanded investment (million R $)	$\frac{\partial z^{(2,h)}}{\partial x_2}$	Demanded investment (million R $)	Sanitation, $\frac{\partial(10^6 y_1)}{\partial(10^6 x_1)}$	Water services, $\frac{\partial(10^6 y_1)}{\partial(10^6 x_2)}$	Investment in sanitation (100 R$)	Investment in drinking water (100 R$)	Minimum (100 R$)
Minas Gerais (MG)	1.0000	0.9502	0.9999	0.9952	0.0115	1572.99	0.0133	1356.66	0.0145	0.0144	982,518	994,053	982,518
Paraná (PR)	1.0000	1.0000	1.0000	0.9958	0.0021	4561.16	0.0090	1081.52	0.0027	0.0090	4,404,005	1,306,727	1,306,727
Pernambuco (PE)	1.0000	0.6893	1.0000	0.9975	0.0062	1233.48	0.0066	1156.35	0.0189	0.0073	439,240	1,147,745	439,240
Rio de Janeiro (RJ)	0.5416	1.0000	1.0000	1.0000	0.0109	1483.84	0.0147	1102.31	0.0161	0.0156	207,054	212,974	207,054
São Paulo (SP)	1.0000	1.0000	1.0000	1.0000	0.0098	4425.02	0.0087	4961.72	0.0106	0.0088	1,465,275	1,750,777	1,465,275
Acre (AC)	1.0000	0.5083	1.0000	0.9932	0.0033	180.94	0.0216	27.76	0.0224	0.0330	44,086	29,938	29,938
Alagoas (AL)	1.0000	0.6586	1.0000	0.9880	0.0305	81.90	0.0338	73.94	0.1376	0.0380	35,657	129,047	35,657
Amapá (AP)	1.0000	0.4232	1.0000	1.0000	0.1007	7.09	0.0170	41.89	1.3663	0.0421	431	13,993	431
Amazonas (AM)	1.0000	0.7456	1.0000	0.9919	0.0441	72.97	0.0265	121.67	0.4068	0.0299	9242	125,730	9242
Bahia (BA)	1.0000	1.0000	1.0000	0.9912	0.0074	1509.38	0.0141	787.25	0.0149	0.0149	1,454,251	1,454,327	1,454,251
Ceará (CE)	0.7622	0.6935	0.9999	0.9970	0.0121	560.39	0.0194	350.72	0.0365	0.0242	389,806	587,662	389,806
Distrito Federal (DF)	1.0000	1.0000	1.0000	0.9883	0.0027	1083.94	0.0145	202.51	0.0032	0.0147	457,810	99,208	99,208
Espírito Santo (ES)	0.5128	0.3345	1.0000	0.9694	0.0049	687.09	0.0252	133.70	0.0081	0.0277	448,654	131,506	131,506
Goiás (GO)	1.0000	0.5910	1.0000	0.9940	0.0069	894.73	0.0173	354.50	0.0119	0.0177	552,300	371,190	371,190
Maranhão (MA)	0.4341	0.8249	0.9997	1.0000	0.0200	220.74	0.0241	183.79	0.1153	0.0323	371,336	1,326,328	371,336
Mato Grosso (MT)	0.1918	0.5092	1.0000	0.9948	0.0154	177.82	0.0195	140.27	0.0396	0.0200	95,170	188,551	95,170
Mato Grosso do Sul (MS)	1.0000	1.0000	0.9999	0.9378	0.0053	437.32	0.0083	281.36	0.0097	0.0083	275,453	320,439	275,453
Pará (PA)	0.1418	0.6074	1.0000	0.9995	0.0336	169.80	0.0241	236.54	0.4052	0.0421	71,062	684,182	71,062
Paraíba (PB)	1.0000	0.6478	0.9999	0.9754	0.0143	213.97	0.0268	113.96	0.0317	0.0291	224,145	243,963	224,145
Piauí (PI)	0.4904	1.0000	0.9998	0.9797	0.0360	59.00	0.0378	56.13	0.2411	0.0390	47,968	296,642	47,968
Rio Grande do Norte (RN)	0.4665	0.5334	1.0000	0.9776	0.0191	143.69	0.0296	92.50	0.0647	0.0325	59,569	118,746	59,569
Rio Grande do Sul (RS)	1.0000	1.0000	1.0000	0.9982	0.0112	861.31	0.0172	560.65	0.0312	0.0177	257,730	455,188	257,730
Rondônia (RO)	0.5580	1.0000	1.0000	0.9994	0.0660	20.33	0.0506	26.52	1.0944	0.0812	2989	40,292	2989
Roraima (RR)	1.0000	1.0000	1.0000	1.0000	0.0014	294.27	0.0207	19.38	0.0025	0.0207	196,626	23,703	23,703
Santa Catarina (SC)	0.1414	0.8094	1.0000	0.9336	0.0135	440.22	0.0191	311.40	0.0507	0.0196	145,467	376,399	145,467
Sergipe (SE)	0.2221	0.2105	1.0000	0.9888	0.0171	98.89	0.0366	46.28	0.0577	0.0388	29,205	43,504	29,205
Tocantins (TO)	0.1825	0.3170	1.0000	1.0000	0.0101	121.64	0.0204	60.43	0.0309	0.0208	51,277	76,267	51,277

References

Adelodun, B., Ajibade, F.O., Ighalo, J.O., Odey, G., Ibrahim, R.G., Kareem, K.Y., Bakare, H.O., Tiamiyu, A.O., Ajibade, T., Abdulkadir, T.S., Adeniran, K.A., Choi, K.S., 2021. Assessment of socioeconomic inequality based on virus-contaminated water usage in developing countries: a review. Environ. Res. 192, 110309.

Alirol, E., Getaz, L., Stoll, B., Chappuis, F., Loutan, L., 2011. Urbanisation and infectious diseases in a globalised world. Lancet Infect. Dis. 11 (2), 131–141.

Bain, R., Cronk, R., Hossain, R., Bonjour, S., Onda, K., Wright, J., Yang, H., Slaymaker, T., Hunter, P., Prüss-Ustün, A., Bartram, J., 2014. Global assessment of exposure to faecal contamination through drinking water based on a systematic review. Tropical Med. Int. Health 19, 917–927.

Bayliss, K., & McKinley, T. (2007). Privatising basic utilities in sub-Saharan Africa: the MDG impact. United Nations Development Programme and International Policy Center Policy Research Brief No. 3. 2007.

Beach, B., Ferrie, J., Saavedra, M., Troesken, W., 2016. Typhoid fever, water quality, and human capital formation. J. Econ. Hist. 76 (01), 41–75.

Berendes, D., Kirby, A., Clennon, J.A., Raj, S., Yakubu, H., Leon, J., Robb, K., Kartikeyan, A., Hemavathy, P., Gunasekaran, A., Ghale, B., Kumar, J.S., Mohan, V.R., Kang, G., Moe, C., 2017. The influence of household- and community-level sanitation and fecal sludge management on urban fecal contamination in households and drains and enteric infection in children. Am. J. Trop. Med. Hyg. 96, 1404–1414.

Bostian, M., Daraio, C., Grosskopf, S., Ruocco, G., Weber, W.L., 2019. Sources and uses of knowledge in a dynamic network technology. Int. Trans. Oper. Res. 27 (4), 1821–1844.

Burström, B., Macassa, G., Öberg, L., Bernhardt, E., Smedman, L., 2005. Equitable child health interventions: the impact of improved water and sanitation on inequalities in child mortality in Stockholm, 1878 to 1925. Am. J. Public Health 95 (2), 208–216.

Cairncross, S., Valdmanis, V., 2006. Water supply, sanitation, and hygiene promotion. In: Jamison, D.T., Breman, J.G., Measham, A.R., Alleyne, G., Claeson, M., Evans, D.B., Jha, P., Mills, A., Musgrove, P. (Eds.), Disease Control Priorities in Developing Countries. The International Bank for Reconstruction and Development/The World Bank. Oxford University Press, New York.

Caravati, K.C., Seymour, Z.A., Hughes, J.B., 2009. Civil infrastructure for water, sanitation, and improved health: existing technology, barriers, and need for innovation. In: Choffnes, E.R., Mack, A. (Eds.), Global Issues in Water, Sanitation, and Health: Workshop Summary. Forum on Microbial Threats. Institute of Medicine.

Cesa, M., Fongaro, G., Barardi, C.R.M., 2016. Waterborne diseases classification and relationship with social-environmental factors in Florianópolis city – Southern Brazil. J. Water Health 14 (2), 340–348.

Cetrulo, T., Marques, R., Cetrulo, N., Malheiros, T., 2020. Monitoring inequality in water access: challenges for the 2030 agenda for sustainable development. Sci. Total Environ. 727, 138746.

CEVS, 2020. Centro Estadual de Vigilância em Saúde: Informativo epidemiológico de arboviroses: Semana epidemiológica 02. https://www.cevs.rs.gov.br/upload/arquivos/202003/02140822-informativo-epidemiologico-dengue-chik-zika-e-fa-se-09-2020.pdf [accessed: October 11, 2019].

Chen, Y.C., Chiu, Y.H., Chiu, C.J., 2017. The performance evaluation of banks considering risk: an application of undesirable relation network DEA. Int. Trans. Oper. Res. 27 (2), 1101–1120.

Cutler, D., Miller, G., 2005. The role of public health improvements in health advances: the twentieth-century United States. Demography 42 (1), 1–22.

Ercumen, A., Gruber, J.S., Colford Jr., J.M., 2014. Water distribution system deficiencies and gastrointestinal illness: a systematic review and meta-analysis. Environ. Health Perspect. 122 (7), 651–660.

Färe, R., Grosskopf, S., 1996. Productivity and intermediate products: a frontier approach. Econ. Lett. 50 (1), 65–70.

Färe, R., Grosskopf, S., 2000. Network DEA. Socio Econ. Plan. Sci. 34 (1), 35–49.

Ferreira, D.C., Marques, R.C., Pedro, M.I., 2018. Explanatory variables driving the technical efficiency of European seaports: an order-α approach dealing with imperfect knowledge. Transport. Res. Pt. E: Log. Transport. Rev. 119, 41–62.

Ferreira, D.C., Marques, R.C., Pedro, M.I., Amaral, C., 2020. On analyzing the economic inefficiency levels of Portuguese municipalities in urban solid waste treatment. Sustainability 12 (10), 4170.

Ferrie, J.P., Troesken, W., 2008. Water and Chicago's mortality transition, 1850–1925. Explor. Econ. Hist. 45 (1), 1–16.

Fontoura, V.M., Graepp-Fontoura, I., Santos, F.S., Neto, M.S., de Almeida Tavares, H.S., Bezerra, M.O.L., et al., 2018. Socio-environmental factors and diarrheal diseases in under five-year old children in the State of Tocantins, Brazil. PLoS One 13 (5), e0196702.

Freeman, M.C., Garn, J.V., Sclar, G.D., Boisson, S., Medlicott, K., Alexander, K.T., Penakalapati, G., Anderson, D., Mahtani, A.G., Grimes, J.E.T., Rehfuess, E.A., Clasen, T.F., 2017. The impact of sanitation on infectious disease and nutritional status: a systematic review and meta-analysis. Int. J. Hyg. Environ. Health 220, 928–949.

Fuller, J.A., Eisenberg, J.N., 2016. Herd protection from drinking water, sanitation, and hygiene interventions. Am. J. Trop. Med. Hyg. 95 (5), 1201–1210.

Gleick, P.H., 2000. The changing water paradigm: a look at twenty-first century water resources development. Water Int. 25 (1), 127–138.

Gonçalves, S., 2014. The effects of participatory budgeting on municipal expenditures and infant mortality in Brazil. World Dev. 53, 94–110.

Guerrant, R.L., DeBoer, M.D., Moore, S.R., Scharf, R.J., Lima, A.A.M., 2013. The impoverished gut — a triple burden of diarrhoea, stunting and chronic disease. Nat. Rev. Gastroenterol. Hepatol. 10 (4), 220–229.

Guerrini, A., Romano, G., Campedelli, B., 2011. Factors affecting the performance of water utility companies. Int. J. Public Sect. Manag. 24 (6), 543–566.

Helgertz, J., Önnerfors, M., 2019. Public water and sewerage investments and the urban mortality decline in Sweden 1875–1930. Hist. Fam. 24 (2), 307–338.

Heller, L. (2009). Water and sanitation policies in Brazil: historical inequalities and institutional change. In Water and Sanitation Services, vol. 321, pp. 321-337.

Herrera, V., 2019. Reconciling global aspirations and local realities: challenges facing the Sustainable Development Goals for water and sanitation. World Dev. 118, 106–117.

Hsiao, B., Shu, L., Chou, F.Y., 2017. Assessing the efficiency of the accounting industry using multiactivity network DEA: evidence from Taiwan. Int. Trans. Oper. Res. 26 (6), 2362–2386.

Ibrahim, M., Ferreira, D., Daneshvar, S., Marques, R., 2019. Transnational resource generativity: efficiency analysis and target setting of water, energy, land, and food nexus for OECD countries. Sci. Total Environ. 697, 134017.

Jaitman, L., 2015. Urban infrastructure in Latin America and the Caribbean: public policy priorities. Latin Am. Econ. Rev. 24 (1), 13.

Juntunen, J., Meriläinen, P., Simola, A., 2017. Public health and economic risk assessment of waterborne contaminants and pathogens in Finland. Sci. Total Environ. 599, 873–882.

Kao, C., 2014. Network data envelopment analysis: a review. Eur. J. Oper. Res. 239 (1), 1–16.

Kao, C., 2017. Network Data Envelopment Analysis: Foundations and Extensions. Springer International Publishing, Switzerland.

Kao, C., Hwang, S.-N., 2008. Efficiency decomposition in two-stage data envelopment analysis: an application to non-life insurance companies in Taiwan. Eur. J. Oper. Res. 185 (1), 418–429.

Kao, C., Hwang, S.-N., 2011. Decomposition of technical and scale efficiencies in two-stage production systems. Eur. J. Oper. Res. 211 (3), 515–519.

Kawaguchi, H., Tone, K., Tsutsui, M., 2014. Estimation of the efficiency of Japanese hospitals using a dynamic and network data envelopment analysis model. Health Care Manage. Sci. 17 (2), 101–112.

Kesztenbaum, L., Rosenthal, J.-L., 2017. Sewers' diffusion and the decline of mortality: the case of Paris, 1880–1914. J. Urban Econ. 98, 174–186.

Khushalani, J., Ozcan, Y., 2017. Are hospitals producing quality care efficiently? An analysis using Dynamic Network Data Envelopment Analysis (DEA). Socio Econ. Plan. Sci. 60, 15–23.

Kotsila, P., Saravanan, V.S., 2017. Biopolitics Ggone to shit? State narratives versus everyday realities of water and sanitation in the Mekong Delta. World Dev. 93, 374–388.

Kumar, S., Vollmer, S., 2013. Does access to improved sanitation reduce childhood diarrhea in rural India? Health Econ. 22 (4), 410–427.

Lai, H., Hales, S., Woodward, A., Walker, C., Marks, E., Pillai, A., Chen, R.X., Morton, S.M., 2020. Effects of heavy rainfall on waterborne disease hospitalizations among young children in wet and dry areas of New Zealand. Environ. Int. 145, 106136.

Lee, B.L., Worthington, A.C., 2016. A network DEA quantity and quality-orientated production model: an application to Australian university research services. Omega 60, 26–33.

Lee, C.Y., Johnson, A.L., 2012. Two-dimensional efficiency decomposition to measure the demand effect in productivity analysis. Eur. J. Oper. Res. 216 (3), 584–593.

Levy, K., Smith, S.M., Carlton, E.J., 2018. Climate change impacts on waterborne diseases: moving toward designing interventions. Curr. Environ. Health Rep. 5 (2), 272–282.

Liu, L., Johnson, H.L., Cousens, S., Perin, J., Scott, S., Lawn, J.E., Rudan, I., Campbell, H., Cibulskis, R., Li, M., Mathers, C., Black, R.E., 2012. Global, regional, and national causes of child mortality: an updated systematic analysis for 2010 with time trends since 2000. Lancet 389 (9832), 9–15.

Lozano, R., Naghavi, M., Foreman, K., Lim, S., Shibuya, K., Aboyans, V., et al., 2012. Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: A systematic analysis for the Global Burden of Disease Study 2010. Lancet 380, 2095–2128.

Marques, R., Da Cruz, N., Pires, J., 2015. Measuring the sustainability of urban water services. Environ. Sci. Pol. 54, 142–151.

Marques, R.C., 2010. Regulation of Water and Wastewater Services: An International Comparison. International Water Association (IWA), London, UK.

Matthews, K., 2013. Risk management and managerial efficiency in Chinese banks: a network DEA framework. Omega 41, 207–215.

Medeiros, V., Ribeiro, R.S.M., Amaral, P.V.M., 2021. Infrastructure and household poverty in Brazil: a regional approach using multilevel models. World Dev. 137, 105118.

Ministry of Health, 2018. Situação epidemiológica da malária. https://portalarquivos2.saude.gov.br/images/pdf/2018/agosto/30/3.%20c%20-%20malaria_CIT_30_ago_2018_cassiopeterka.pdf.

Ministry of Health, 2019. Quase mil cidades podem ter surto de dengue, zika e chikungunya no país. https://agenciabrasil.ebc.com.br/saude/noticia/2019-04/quase-mil-cidades-podem-ter-surto-de-dengue-zika-e-chikungunya.

Mitropoulos, P., 2019. Production and quality performance of healthcare services in EU countries during the economic crisis. Oper. Res. https://doi.org/10.1007/s12351-019-00483-3.

Mor, S.M., DeMaria Jr., A., Naumova, E.N., 2014. Hospitalization records as a tool for evaluating performance of food- and water-borne disease surveillance systems: a Massachusetts case study. PLoS One 9 (4), e93744.

Moreno, P., Lozano, S., 2016. Super SBI Dynamic Network DEA approach to measuring efficiency in the provision of public services. Int. Trans. Oper. Res. 25 (2), 715–735.

Nouri, J., Lofti, F.H., Borgheipour, H., Atabi, F., Sadeghzadeh, S.M., Moghaddas, Z., 2013. An analysis of the implementation of energy efficiency measures in the vegetable oil industry of Iran: a data envelopment analysis approach. J. Clean. Prod. 52, 84–93.

Otaki, Y., Otaki, M., Chaminda, T., Kishimoto, Y., Nakazawa, Y., Gimhana, K., 2021. Hygiene risk of waterborne pathogenic viruses in rural communities using onsite sanitation systems and shallow dug wells. Sci. Total Environ. 752, 141775.

Ouyang, Z., Song, C., Zheng, H., Polasky, S., Xiao, Y., Bateman, I.J., Liu, J., Ruckelshaus, M., Shi, F., Xiao, Y., Xu, W., Zou, Z., Daily, G.C., 2020. Using gross ecosystem product

(GEP) to value nature in decision making. Proc. Natl. Acad. Sci. https://doi.org/10.1073/pnas.1911439117.

Ozcan, Y., Khushalani, J., 2017. Assessing efficiency of public health and medical care provision in OECD countries after a decade of reform. Cent. Eur. J. Oper. Res. 25, 325–343.

Paiva, R.F.P.S., Souza, M.F.P., 2018. Associação entre condições socioeconômicas, sanitárias e de atenção básica e a morbidade hospitalar por doenças de veiculação hídrica no Brasil. Cad. Saúde Públ. 34 (1), 1–11.

PLANSAB, 2019. Plano Nacional de Saneamento Básico. https://ondasbrasil.org/wp-content/uploads/2020/09/Plansab-revisado-2019.pdf [accessed: June 11, 2020].

Prüss-Ustün, A., Bartram, J., Clasen, T., Colford Jr., J.M., Cumming, O., Curtis, V., et al., 2014. Burden of disease from inadequate water, sanitation and hygiene in low- and middle-income settings: a retrospective analysis of data from 145 countries. Trop. Med. Int. Health 19 (8), 894–905.

Raso, G., Vounatsou, P., McManus, D.P., N'Goran, E.K., Utzinger, J., 2007. A Bayesian approach to estimate the age-specific prevalence of Schistosoma mansoni and implications for schistosomiasis control. Int. J. Parasitol. 37, 1491–1500.

Romano, G., Ferreira, D., Marques, R., Carosi, L., 2020. Waste services' performance assessment: the case of Tuscany, Italy. Waste Manag. 118, 573–584.

Sclar, G.D., Garn, J.V., Penakalapati, G., Alexander, K.T., Krauss, J., Freeman, M.C., et al., 2017. Effects of sanitation on cognitive development and school absence: a systematic review. Int. J. Hyg. Environ. Health 220, 917–927.

Siqueira, M.S., Rosa, R.S., Bordin, R., Nugem, R.C., 2017. Hospitalizations due to diseases associated with poor sanitation in the public health care network of the metropolitan region of Porto Alegre, Rio Grande do Sul State, Brazil, 2010–2014. Epidemiol. Serv. Saúde 26 (4), 1–11.

SNIS, 2017. Diagnóstico dos Serviços de Água e Esgotos — 2017. http://www.snis.gov.br/diagnostico-anual-agua-e-esgotos/diagnostico-ae-2017 [accessed: June 10, 2020].

Stenberg, K., Axelson, H., Sheehan, P., Anderson, I., Gülmezoglu, A.M., Temmerman, M., et al., 2014. Advancing social and economic development by investing in women's and children's health: a new Global Investment Framework. Lancet 383 (9925), 1333–1354.

Sueyoshi, T., 2003. DEA implications of congestion. Asia Pacific Manag. Rev. 8 (1), 59–70.

Sueyoshi, T., Sekitani, K., 2009. DEA congestion and returns to scale under an occurrence of multiple optimal projections. Eur. J. Oper. Res. 194 (2), 592–607.

Tsutsui, M., Goto, M., 2009. A multi-division efficiency evaluation of US electric power companies using a weighted slacks-based measure. Socio Econ. Plan. Sci. 43, 201–208.

UN, 2017. Resolution adopted by the General Assembly on July 06, 2017. Work of the Statistical Commission Pertaining to the 2030 Agenda for Sustainable Development.

UN, 2018. Sustainable Development Goal 6: Synthesis Report 2018 on Water and Sanitation.

UNICEF, 2015. Progress on sanitation and drinking water — 2015 update and MDG assessment. https://www.unicef.org/publications/index_82419.html [accessed: October 02, 2020].

Vaz, C.B., Camanho, A., Guimarães, R.C., 2010. The assessment of retailing efficiency using network data envelopment analysis. Ann. Oper. Res. 173, 5–24.

Vos, T., Barber, R.M., Bell, B., Bertozzi-Villa, A., Biryukov, S., Bolliger, I., et al., 2015. Global, regional, and national incidence, prevalence, and years lived with disability for 301 acute and chronic diseases and injuries in 188 countries, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. Lancet 386 (9995), 743–800.

Wei, Q.L., Yan, H., Pang, L.Y., 2011. Composite network data envelopment analysis model. Int. J. Inf. Technol. Decis. Mak. 10, 613–633.

WHO, 2019. Health Statistics and Information Services. Disease burden and mortality estimates. www.who.int/healthinfo/global_burden_disease/estimates/en/index1.html.

Wolf, J., Hunter, P.R., Freeman, M.C., Cumming, O., Clasen, T., Bartram, J., et al., 2018. Impact of drinking water, sanitation and handwashing with soap on childhood diarrhoeal disease: updated meta-analysis and meta-regression. Trop. Med. Int. Health 23 (5), 508–525.

Yin, P., Chu, J., Wu, J., Ding, J., Yang, M., Wang, Y., 2020. A DEA-based two-stage network approach for hotel performance analysis: an internal cooperation perspective. Omega 93, 102035.