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Reuse-oriented decentralized wastewater and sewage sludge treatment for rural settlements in Brazil: a cost–benefit analysis

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ABSTRACT

Decentralized sanitation and reuse (DESAR) solutions can contribute significantly to the improvement of wastewater treatment in small urbanized rural settlements (SURUS). Amongst the advantages of DESAR solutions for SURUS is a reduction in final treatment costs because they allow for water reclamation and sewage sludge reuse; predominantly for agriculture. In the present work, a cost–benefit analysis on a DESAR system installed into a rural community in Rio de Janeiro State, Brazil, was conducted. The net present value (NPV) method was applied to assign a monetary value to the economical and environmental benefits associated with water reclamation, sewage sludge reuse and the avoided cost of 5-d biological oxygen demand (BOD_5) discharges. The NPV results of this case study revealed that the proposed DESAR solution could recover up to 73% of the total operating and maintenance costs. These findings suggest that DESAR solutions can respond to the need to reduce costs and improve the nutrient recovery capabilities of sanitation interventions in rural communities.

Keywords: Decentralized sanitation and reuse solutions; Sewage sludge reuse; Rural development; Nutrient recovery; INTECRAL

1. Introduction

Worldwide, there is a need for integrated and sustainable wastewater and sewage sludge treatment solutions (WASTES) for small urbanized rural settlements (SURUS) in low-to-middle income countries. However, nations implementing WASTES in SURUS face technological, social, economical and institutional challenges, such as limited payment capability of resident communities, new investment

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failing to create economies of scale and weak local governments; all of which curb investment in effluent treatment systems [1]. These restrictions are generally more evident in small populations (below 20,000 inhabitants), where water resource management programs do not have sufficient funds and institutions lack the management capacity to guarantee investment into water infrastructure [2,3]. Moreover, SURUS usually have population densities for which conventional on-site sanitation facilities prove less cost-effective than collecting wastewater using sewer networks and treating the effluent in treatment plants [4,5]. A SURUS constitutes a "grey zone" in which sanitation projects are commonly postponed due to the absence of an economy of scale and a high per capita treatment cost as compared with an urbanized area [3,6]. This situation has produced significant asymmetries in investment between rural and urban areas; especially in developing nations [2].

Decentralized wastewater management (DWM) concepts are gaining popularity in small communities with low-to-middle population densities [7,8]. Decentralization refers to the treatment of wastewater either close to or at the point of generation and the potential it provides for the reuse of wastewater, as well as other by-products (e.g., reclaimed water, sewage sludge), in agriculture are considered amongst the most important benefits [9–11]. In fact, several authors consider the reuse capabilities of decentralized wastewater treatment solutions as the primary advantage for their implementation in small, rural communities [7,8,12,13]. The use of DWM systems – broadly categorized by some authors as decentralized sanitation and reuse (DESAR) solutions – in an urban setting in China is addressed by Wang et al. [14]. Although the study is area specific, the recommendations could be generalized and applied to a broader selection of settings.

Growing interest in DESAR approaches has introduced the need to evaluate the economical feasibility of implementing DWM strategies. Several contributions in the field of the economic valuation of DESAR solutions have been presented [8,12,15,16]. However, there remains a need to develop empirical assessments and to establish methodologies for conducting detailed assessments of DWM interventions, in terms of fundamental characteristics and difficulties. DESAR solutions are highly dependent on local social, environmental, geographical, economical and technological conditions [17]. Consequently, technoeconomic studies are required to demonstrate the feasibility of DESAR systems in SURUS from a systematic perspective. It is important that the economic valuation component of any such study account for all potential benefits derived from the reuse practices.

In Brazil, around 75% of the rural population (equivalent to approximately 23 million inhabitants) does not have access to wastewater treatment facilities [18]. The IBGE census of 2010 reported that 75% of the total rural population receives inadequate sanitation services [19]. Moreover, in Brazil, 73% of the population have a population not more than 20,000 inhabitants it has been estimated that communities under 20,000 inhabitants [19] and only 55% of them have a sewage system, and 52% used septic tanks [20]. None of these systems comply with Brazilian legislation for wastewater treatment and disposal and they have the potential to cause a multitude of environmental and social problems (e.g., groundwater pollution, waterborne diseases, etc.) [12]. Although domestic wastewater pollutants account for only 0.1% of the contaminants present in water, they are responsible for 80% of the reported water related diseases [21]. These data reflect the importance of investment in proper sanitation in SURUS and in general.

In this paper, a cost–benefit analysis (CBA) of a hypothetical DESAR system for a 1,000 population equivalent (PE) rural community located in Rio de Janeiro State, Brazil, was performed. The analysis aimed to identify the cost-recovery capabilities of the WASTE solution, with particular focus on operating and maintenance costs. The CBA assigned a monetary value to the economical and environmental benefits associated with water reclamation and sewage sludge reuse for agriculture as well as to the avoided costs of 5-d biological oxygen demand (BOD_5) discharges. Although, several studies on CBA for DESAR solutions have been published [12,15,16,22,23]; the proposed methodology in this paper provides an innovative and integrative environmental–economical approach for Latin-American contexts. Therefore, the proposed method introduce a more integrative CBA for DESAR projects compared with the conventional economic feasibility procedures used in the country mostly based on Ministerio da Cidades [24]. The conventional procedure tends to focus mainly on internal costs whilst additional environmental–economical benefits are relegate or not considered. The environmental–economical indicator generated in the study can act as justification for the introduction of decentralized wastewater and sewage sludge treatment and management concepts in rural areas and communities across the world with similar sanitations needs.

2. Methodology

The following steps were proposed for the economic valuation of DESAR solutions:

- Socioeconomic survey of the selected community.
- Geographic information system analysis. This procedure can be used to assess the topographical and hydrological conditions of the study area.
- Population density analysis, based on the socioeconomic survey as well as satellite imagery. The densities of buildings and the distances between them can be used to determine the requirements for laying the sewer network.
- Estimation of the required pipe or channel lengths in the sewer network, based on remote sensing.
- Identification of suitable, open areas for the location of wastewater and sewage sludge treatment facilities.
- Selection of the most suitable wastewater and sewage treatment technologies.
- Investigating local/regional wastewater quality standards and sludge quality parameters.
- Estimation of land acquisition, construction, operation and maintenance costs for the proposed wastewater and sewage treatment facilities.
- Estimation of the economic benefits associated with the treatment solutions, for which consideration of the following is proposed (i) avoided penalties for BOD_5 discharges, based on local environmental legislation, (ii) avoided costs associated with sludge management (transportation, drying and final disposal), (iii) avoided

costs related to water uptake for irrigation and (iv) the benefits of sludge reuse as fertilizer.
- Calculation of cost-recovery capabilities, especially in terms of operating and maintenance costs.

In the DESAR solution considered in this study, the CBA was performed based on Eq. (1):

$$\text{NPV} = \sum_{t=0}^{n} \frac{(B_i - C_i)_t}{(1+r)^t} \quad (1)$$

where NPV is the net present value, B_i is the value of the benefit of item i, C_i is the value of the cost of item i, r is the discount rate, t is the time (year) and n is analytical time horizon (year). The NPV measures the economic value of a project. The CBA takes NPV as the main financial indicator to guide decision making. A project with a positive NPV (NPV > 0) is economically viable. If the NPV is negative (NPV < 0), the project should be rejected. The best option will offer the highest CBA [25]. The costs and benefits to be considered in a CBA for the DESAR system are described in Fig. 1.

2.1. Case study

2.1.1. Background

The "Integrated Eco Technologies and Services for a Sustainable Rural Rio de Janeiro (INTECRAL)" project, initiated by the German Ministry for Education and Research (BMBF), sets out to promote sustainable sanitation solutions for rural areas. One key aspect of the project is the development of integrated wastewater treatment solutions for rural areas in Rio de Janeiro State. This integrated approach will greatly improve the sanitation situation in rural areas of the country, whilst providing direct environmental–economical benefits because the sludge by-product is a chemical fertilizer substitute. This is an important consideration, given that agriculture is the primary economic activity in the target communities.

For this case study, the Brazilian community of Barracão dos Mendes was chosen. It is located in the municipality of Nova Friburgo (22°16′54.98″S/42°41′00.25″W) and is 136 km from the state capital of Rio de Janeiro. At the time of the study, cesspits were used for collecting wastewater, but they had neither any form of drainage facility nor treatment capability. Cesspit tanks are normally installed for each household, but in rural areas, such as Barracão dos Mendes, it is common for a single tank to be shared by several families. Cesspit systems present problems such as foul odour emission and a propensity to overflow, particularly during the rainy season [26]. They often leak or sink into the ground, both of which pose serious problems in terms of elevating levels of groundwater pollution. Less than 10% of total volume of wastewater in the Nova Friburgo municipality is collected; highlighting the inadequacy of the current sewer network in the region (Fig. 2).

The population of the study area was estimated at 528 residents in 2014, with an average of 3.85 inhabitants per household. The population is expected to grow to 1,000 inhabitants by 2034. This projection is based on a local survey and satellite imagery.

2.1.2. Population density

According to the set of recommendations from the European Economic and Social Committee, installed sewerage networks should be less than 5–10 m drain length/capita. This is equivalent to 100–200 inhabitants/km of the sewage network. In the selected area, satellite imagery was used and digital elevation models were developed to estimate

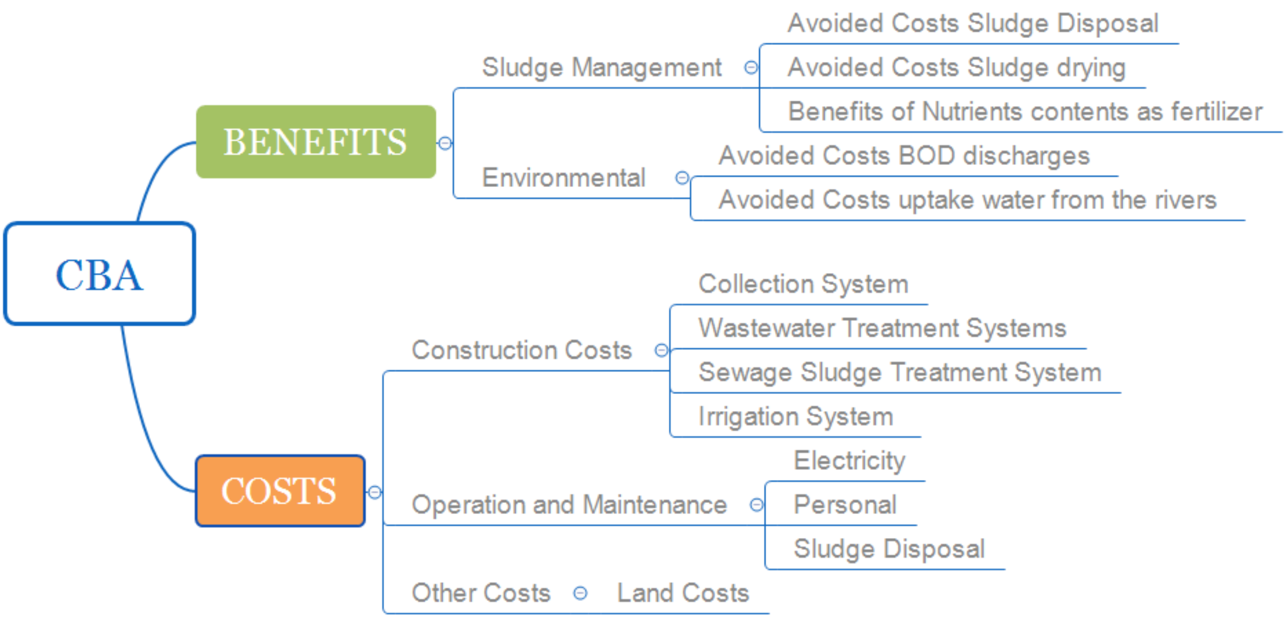

Fig. 1. Costs and benefits considered for the DESAR system (own elaboration).

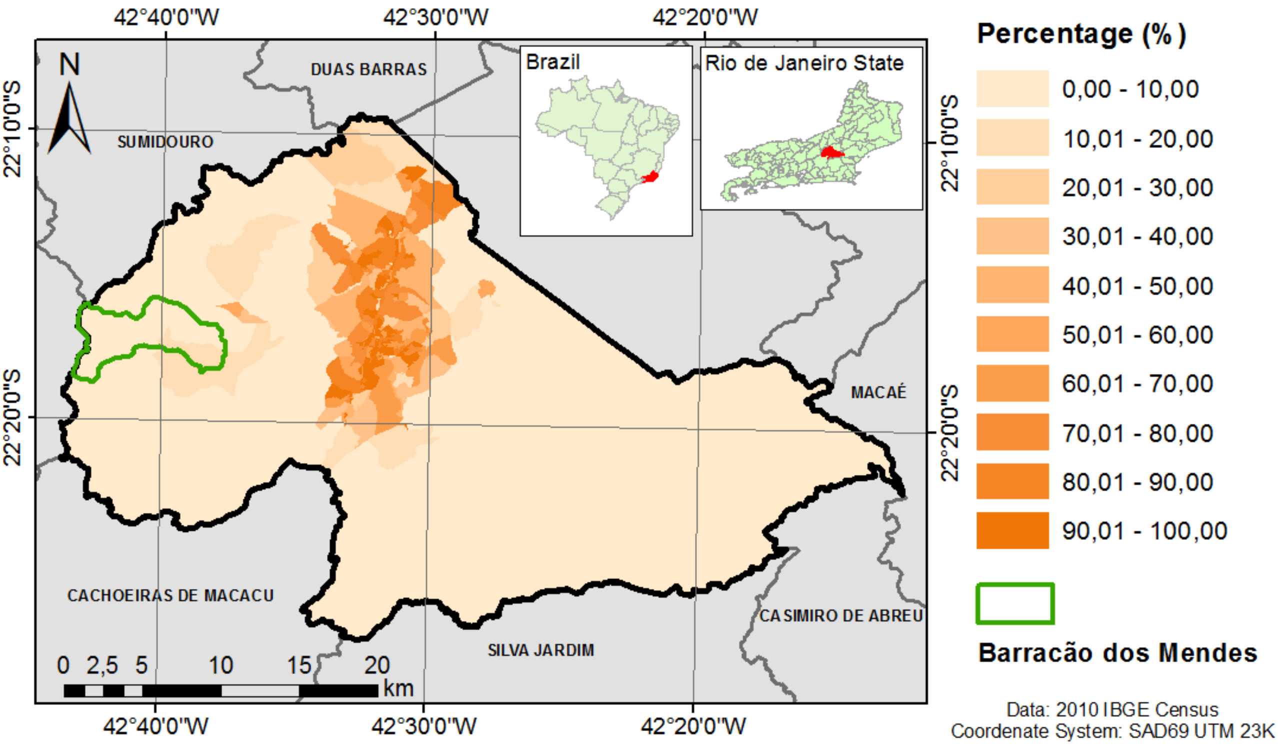

Fig. 2. The percentage of the population in the municipality of Nova Friburgo connected to wastewater collection systems, based on the 2010 census [19]. In the focused study area of Barracão dos Mendes, 0% of the households were connected to a sewer system [26].

a total sewer length of 2,575 m; equivalent to 2.5 m/capita. This value justifies the construction of a sewage network that caters for population densities similar to those of urban areas in the city of Rio de Janeiro (population density of 6,200 inhabitants/km^2) [27]. Based on satellite imagery (Fig. 3), a population density in excess of 5,000 inhabitants/km^2 was found in Barracão dos Mendes. For this reason, the proposed wastewater treatment solution requires the installation of a wastewater collection system.

2.1.3. Selected technologies for wastewater and sewage sludge treatment

The field of decentralized wastewater treatment encompasses a variety of technologies. For this case study, the most suitable wastewater treatment solution was deemed to be an upflow anaerobic sludge blanket (UASB) combined with a vertical flow constructed wetland (VFCW). The selected treatment train is a low-cost solution for rural sanitation that supports reuse practices [28–31]. In addition, an on-site sludge treatment facility using sludge drying reed beds (SDRBs) was evaluated [32]. Fig. 4 shows the proposed treatment train for the DESAR solution within the case study area. An additional benefit of this study was the opportunity to test and evaluate the performance of anaerobic systems in Brazil and highlight their importance. The use of UASB systems in combination with VFCWs (which have proven to be successful in decentralized solutions) was also investigated [33].

SDRBs or sludge treatment wetlands (STWs) were developed more recently and are based on the operation of constructed wetland systems. SDRBs consist of shallow tanks filled with layers of gravel and emergent vegetation, such as *Phragmites australis* [34,35]. Sludge is spread over the surface of the bed and its water content is gradually lost by drainage through the gravel filter layer and plant uptake and evapotranspiration. This leaves behind a concentrated sludge residue. When the maximum storage capacity of the system is reached, after a resting period, the biosolids are withdrawn before a new operating cycle commences. The concentrated sludge product is immediately suitable for land applications [32] and improves both the physicochemical properties and fertility of the soil due to its high content of organic matter and nutrients [36,37]. In some cases, the sludge product may be post-treated for stabilization and hygiene purposes [37].

2.1.4. Legal framework

According to its 1988 constitution, the Brazilian government is responsible for the restoration and preservation of natural ecological infrastructure. To this end, the government passed Federal Law no. 9433 on the management of water resources in 1997. Also known as the "Water Law", this legislation established the National Policy of Water Resources (PNRH) and created the National System of Water Resources Management (SINGREH). State Law no. 3239, introduced 1 year later in Rio de Janeiro, had a similar purpose. More recent federal laws on sanitation, such as Federal Law no. 11445 of 2007, established the national policy guidelines for Basic Sanitation. The National Environment Council (CONAMA), the Brazilian Association for Technical Standards (ABNT) and the State Environment Institute (INEA) of Rio de Janeiro are responsible for regulating the technical and environmental

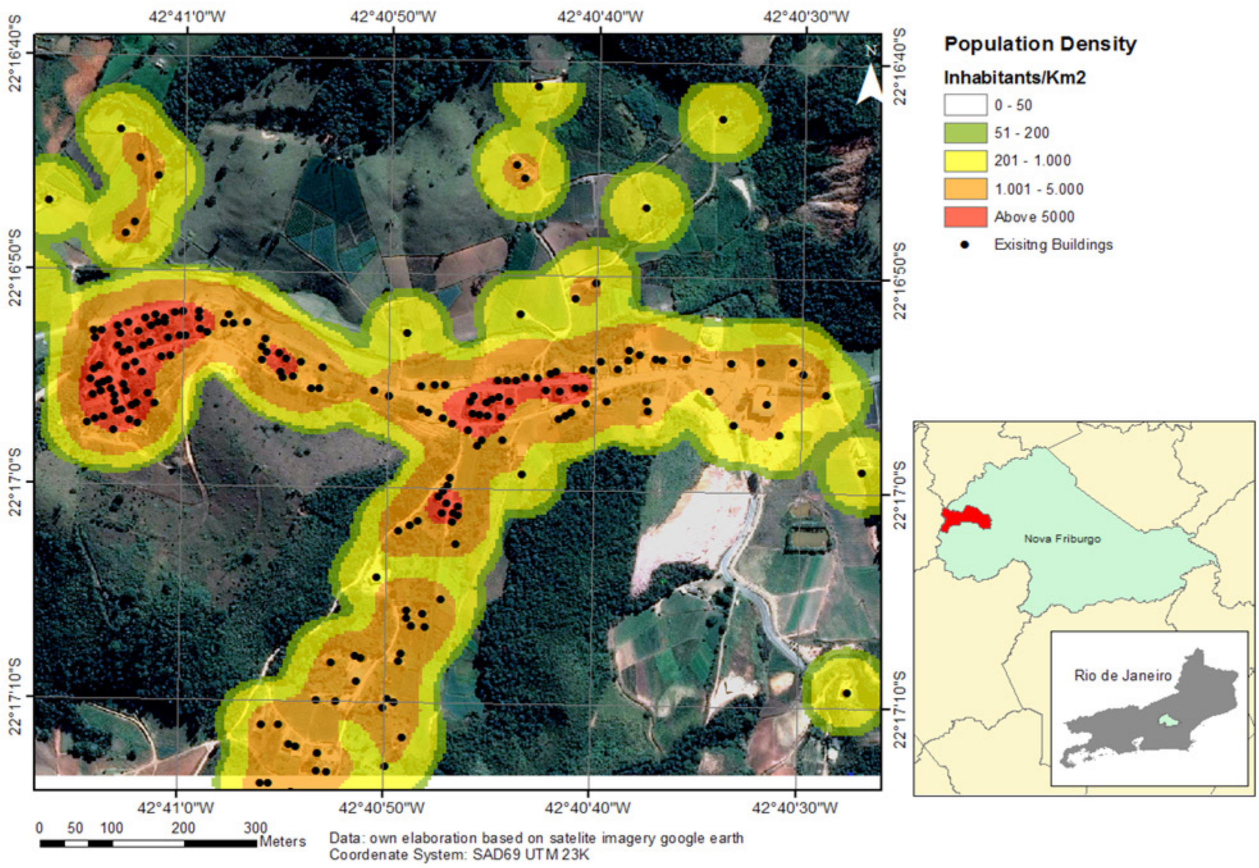

Fig. 3. Population density at the community of Barracão dos Mendes (own elaboration).

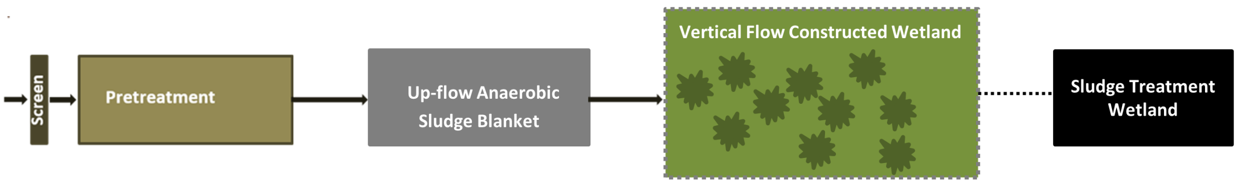

Fig. 4. Selected treatment train for the DESAR solution within the case study area. Source: Cardona et al. [38].

structures and bodies so as to ensure compliance with the legislation.

2.1.5. *Expected effluent quality by wastewater treatment plant*

The current Brazilian legislation (resolution 357 of 2005) was consulted to determine the maximum legal levels of contaminants for safe discharge. Resolution 357 (2005) was enacted by the National Environmental Council (Conselho Nacional do Meio Ambiente or CONAMA). In this case, the applicable standard is DZ 215.R4 of 2007 with respect to biochemical oxygen demand (BOD). In this particular case study area, containing 201–1,000 inhabitants, the treatment system must achieve at least 65% reduction of BOD and total suspended soils. Hence, the BOD load rate should be established so as not to overload the treatment system and expose the residents to poor quality water.

2.1.6. *Expected sludge quality by sewage sludge treatment plant*

The DESAR solution complies with the Brazilian legal requirements for sludge use and disposal, including restrictions and precautionary measures. Resolution 375 of 2006, which was issued by the Brazilian National Environment Council [39], regulates only the concentrations of heavy metals and some pathogens [33]. Table 1 shows the most important sludge quality parameters to ensure compliance with CONAMA standards. It also includes parameters cited in literature after treatment with various technologies; namely SDRB or STW, centrifuge and composting. Although there are no standard values for the parameters specified in Table 1 for these types of systems, there are some suggestions reported in the literature [35,40,41]. The removal efficiencies that can be achieved with SDRBs, in terms of percentage total solids (TS) and percentage volatile solids/total solids (VS/TS), are comparable with those obtained with centrifugation and composting [41].

3. Results

3.1. Cost-calculation for wastewater treatment and reuse system

The costs associated with sanitation projects, in monetary terms, are important for justifying investment. Concerning the wastewater treatment facility, three principal costs have been considered to estimate the total cost: (i) initial investment costs, which include city network, house connection and wastewater treatment system installation costs, (ii) land costs and (iii) system operating and maintenance costs, for example, personnel and energy costs. The costs related to wastewater infrastructure were estimated based on fieldwork carried out, local prices, empirical values determined by wastewater engineering companies and a literature review. Eq. (2) shows the calculation of the total cost wastewater treatment systems.

$$\sum C_i = C_{\mathrm{IW}} + C_{\mathrm{L}} + C_{\mathrm{O\&MW}} \quad (2)$$

where C_{IW} represents the initial investment cost of wastewater treatment plant, C_{L} represents the land cost and $C_{\mathrm{O\&MW}}$ represents the operating and maintenance costs of wastewater treatment plants.

For reuse purposes a storage tank and pipelines for irrigation have to be installed and maintained. Eq. (3) shows the calculation of total costs for the irrigation system.

$$\sum C_i = C_{\mathrm{IT}} + C_{\mathrm{L}} + C_{\mathrm{O\&MT}} \quad (3)$$

where C_{IT} represents the initial investment cost of storage tank, C_{L} represents the land cost and $C_{\mathrm{O\&MT}}$ represents the operating and maintenance costs of storage tank. Considering that, within the study area the reported precipitation is 1.372 mm/year [42], the potential benefits of direct wastewater reuse were not considered. Therefore, the associated cost regarding water reuse such as pipeline and water storage tank and their respective operation and maintenance cost were not included in the cost-estimation section. Table 2 summarized the total estimated costs.

3.2. Calculation of economic benefits

Wastewater treatment projects provide environmental and social benefits (e.g., health improvements, water

Table 2
Costs associated with DESAR infrastructure, presented in terms of NPV for a project life span of 20 years and a discount rate of 12% [24]

Item	Value in R$
Total capital costs[a]	660,000
Total land costs[b]	25,000
Total O&M costs[c]	111,000

Costs are given Brazilian Reals (R$) as of October 2014 (1R$ = 0.4073 USD). Design data: PE = 1,000; flow rate = 130 m^3/d; BOD_5 = 350 mg/L.
[a]For the treatment train UASB + VFCW + SDRB: construction costs (CC) of UASB [43]; CC of VFCW and SDRBs based on $C = 1{,}650.4Q^{0.697}$ [44]; sewer network costs based on own calculations using satellite images and digital elevation models.
[b]Land requirements: UASB = 0.05 m^2/c [45]; VFCW = 1 m^2/c [46,47]; SDRM = 0.3 m^2/c [35]; land costs assumed to be 20 R$/$m^2$ based on local survey.
[c]Operating and maintenance costs: UASB = 15 R$/c.a. [46]; VFCW and SDRB assuming 0.5 US$/c.a. [48].

Table 1
Characteristic quality parameters of treated sewage sludge or biosolids generated by different treatments as well as those established by CONAMA

Parameter	Uggetti et al. [35,41]			CONAMA [39]
	SDRB or SWT	Centrifuge	Composting	
TS (%)	20–24	18	83	–
VS (%TS)	38–39	73.4	62	–
TNK (%TS)	2.6–3.4	6.4	2.5	–
P_{total} (%TS)	0.08	1.84	2.3	–
Cu (mg/kg)	48–55	518	388	1,500
Zn (mg/kg)	533–551	807	1,087	2,800
Pb (mg/kg)	43–52	60	110	300
Cd (mg/kg)	0.6	2	1.5	39
Ni (mg/kg)	29–36	15	54	420
Cr (mg/kg)	49–55	40	95	1,000
Hg (mg/kg)	3.5–5.3	4	–	17
Faecal bacteria indicators				
Salmonella	Absence in 25 g	–	–	Absence in 10 g
Faecal coliforms	<3	–	–	<1,000 MPN/g TS
Viable helminthic eggs	–	–	–	<0.25 eggs/g TS

Note: SWT = Sludge wetland treatment; TKN = Total Kjeldhal nitrogen.

polishing, opportunities for recreation, water reuse, etc.) [49]. These wastewater treatment benefits should be included in economic feasibility studies, but their quantification in monetary terms suffers a high level of complexity; predominantly because they are not registered directly by the market and, thus, must be calculated based on non-market values [50]. In this study, the potential environmental–economical benefits associated with local reuse of treated sewage sludge were maximized. Additionally, the avoided costs associated with transport and disposal of sludge and discharge of BOD into water bodies were evaluated as additional benefits.

The data used for the economic benefit estimation is summarized in Table 3.

3.3. Avoided cost for BOD discharge

Implementation of the DESAR system will lead to a reduction in the quantities of BOD_5 discharged into local water bodies. This will curtail water pollution and can be considered a benefit. In order to evaluate the benefit associated with this reduction in BOD_5 discharge, we considered the amount of BOD_5, in kilograms, generated by the system on a yearly basis and multiplied the result by the unit price per kilograms of BOD_5 discharged (0.0763 R$/kg), as established by CEIVAP (Committee for the Integration of the Paraíba do Su River Basin) directives for the Paraiba do Sul basin [55]. The avoided cost is discounted for each year. Eq. (4) shows the calculation of this benefit.

$$AC_{BOD_5} = 365\sum_{i=1}^{n} Q_{BOD_5}\, P_{BOD_5} \tag{4}$$

Table 3
Assumptions considered for CBA estimations

Parameter units	Value	Source
Design parameters		
Water consumption (L/(c·d))	250	[51]
Biological oxygen demand (mg/L)	463	[51]
Chemical oxygen demand (mg/L)	947	[51]
Inhabitants per household	3.5	[26]
Costs parameters UASB + VFCW		
Sewer line requirements per capita (m)	2.5	
Land prices ($R/m)	16	[26]
Costs parameter sludge transportation and disposition		
Transport costs = (Pf/Cap) × 2D		[52]
where Pf (assumed price per km = R$3.79/km), Cap = cargo capacity of the truck assumed in 16 tonnes. Two times distance for collecting and disposition (2D)	3.79	
Land fill disposal (R$/tonne)	120	[53]
Benefits of nutrient recovery: best case (R$/tonne)	164.32	[54]

where AC_{BOD_5} is the avoided cost due to BOD_5 discharge, Q_{BOD_5} is the quantity of BOD_5 generated and P_{BOD_5} represents the public unit price of BOD_5 organic discharge.

3.4. Avoided cost of water uptake for irrigation

The DESAR system also considers water reuse for irrigation purposes. This presents an economic benefit in terms of avoided pumping costs and an environmental benefit in terms of preserving natural bodies of water. Irrigation costs imposed on the community were calculated based on the CEIVAP water directives [55]. The calculation of this benefit is shown in Eq. (5). This value is discounted for each year.

$$AC_{UWI} = 365\sum_{i=1}^{n} Q_{WW}\, P_{WC} \tag{5}$$

where AC_{UWI} represents the avoided cost of water uptake for irrigation, Q_{WW} is the quantity of wastewater treated per day and P_{WC} is the fee of water uptake for irrigation as established for the region [55].

3.5. Avoided cost of sludge transportation and disposal

This aspect considers local reuse of sludge for agricultural purposes. As such, the cost incurred for the transportation and disposal of sludge produced in a conventional treatment plant at a sanitary landfill would be eliminated. The benefit associated with avoiding this cost factor was calculated from Eq. (6). This value is discounted for each year.

$$AC_{SIT\&D} = QSl_i \times (PSl_T + PSl_D) \tag{6}$$

where $AC_{SIT\&D}$ is the avoided cost of sludge transportation and disposal, QSl_i is the annual sludge production in the DESAR system (metric tonnes per year), PSl_T is the cost of sludge transportation to the sanitary landfill (R$11.84/tonne) and PSl_D is the cost of sludge disposal. The transportation cost was based on previous estimates and calculated assuming that the sludge had to be transferred over a distance of 25 km [52].

3.6. Benefit of sludge as fertilizer substitute

Wastewater contains a variety of nutrients that can enrich the soil and be taken up by crops. The sludge produced by the DESAR system is a concentrated source of these nutrients. Hence, this study focused on the local reuse of this sludge by-product, which will benefit local farmers by saving on the costs of chemical fertilizers and benefit the environment by reducing the release of agrotoxins. This study assumed that sludge can be obtained every 5 years and calculations considered only the volumes of nitrogen, phosphorus and potassium (NPK). Sludge production (kg/d) was estimated based on a population of 10,000 inhabitants based on Andreoli et al. [51]. The sludge mass production per capita is expressed in grams of suspended solids per inhabitant per day (gSS/inhabitant·d), whilst the volumetric production per capita is expressed as litres of sludge per inhabitant per day (L/inhabitant·d).

The quantities of nutrients were estimated based on typical values reported for commercial fertilizers [56] and biosolids from wastewater treatment plants in Brazil [51]. The nutrient benefits, BN, were calculated as shown in Eq. (7):

$$BN = \sum (Q_{Ni} \times P_{Ni}) \quad (7)$$

where Q_{Ni} is the quantity of nutrients (NPK) in the sludge and P_{Ni} is the updated market price of each nutrient in Brazil. It was assumed that 42 tonne/year of sludge was generated in the wastewater treatment plant, according to the flow rate and typical values for UASB + aerobic post-treatment [51]. Therefore, nutrient production was calculated as N = 1,390 kg/year; P = 970 kg/year; K = 128,970 kg/year.

The total benefits (ΣB_i) for the implementation of a DESAR solution were estimated using Eq. (8).

$$\Sigma B_i = AC_{BOD_5} + AC_{UWI} + AC_{SIT\&D} + BN \quad (8)$$

The total benefits considered a time frame of 20 years. Based on the European Commission guidelines, the construction phase, in which the initial investment costs and land costs will be incurred, is defined as Year 0. The operating and maintenance costs will be incurred annually once the system becomes operational. Benefits will ensue from the commencement of operation in Year 1. Table 4 summarizes the benefits associated with the DESAR system.

The economic benefits associated with the DESAR solution are presented in Fig. 5. Fig. 5 shows the total benefits,

Table 4
Benefits associated with the proposed DESAR solution

Items	Total benefit in R$
Avoided costs of BOD_5 discharges[a]	11,000
Avoided costs of uptake water for irrigation[b]	4,000
Avoided costs of sludge transportation and disposal[c]	26,000
Benefits for nutrients contents as fertilizer[d]	41,000

Infrastructural benefits are presented in terms of NPV for a 20-year project life and 12% discount rate [24]. Values in Brazilian Reals (R$) as of October 2014 (1R$ = 0.4073 USD). Design data: PE = 1,000; flow rate = 130 m^3/d; BOD_5 = 350 mg/L.
[a]Discharge fee for BOD_5 = 0.0763 R$/kg from reference [55].
[b]Cost of water uptake for irrigation = 0.0109 R$/$m^3$ from reference [55] (according to the flow rate and typical values for UASB + aerobic post-treatment from reference [51]).
[c]Sludge transportation costs based on previous estimations of in R$11.84/tonne [52].
[d]Derived from local survey, including prices for mineral fertilizer NPK [26].

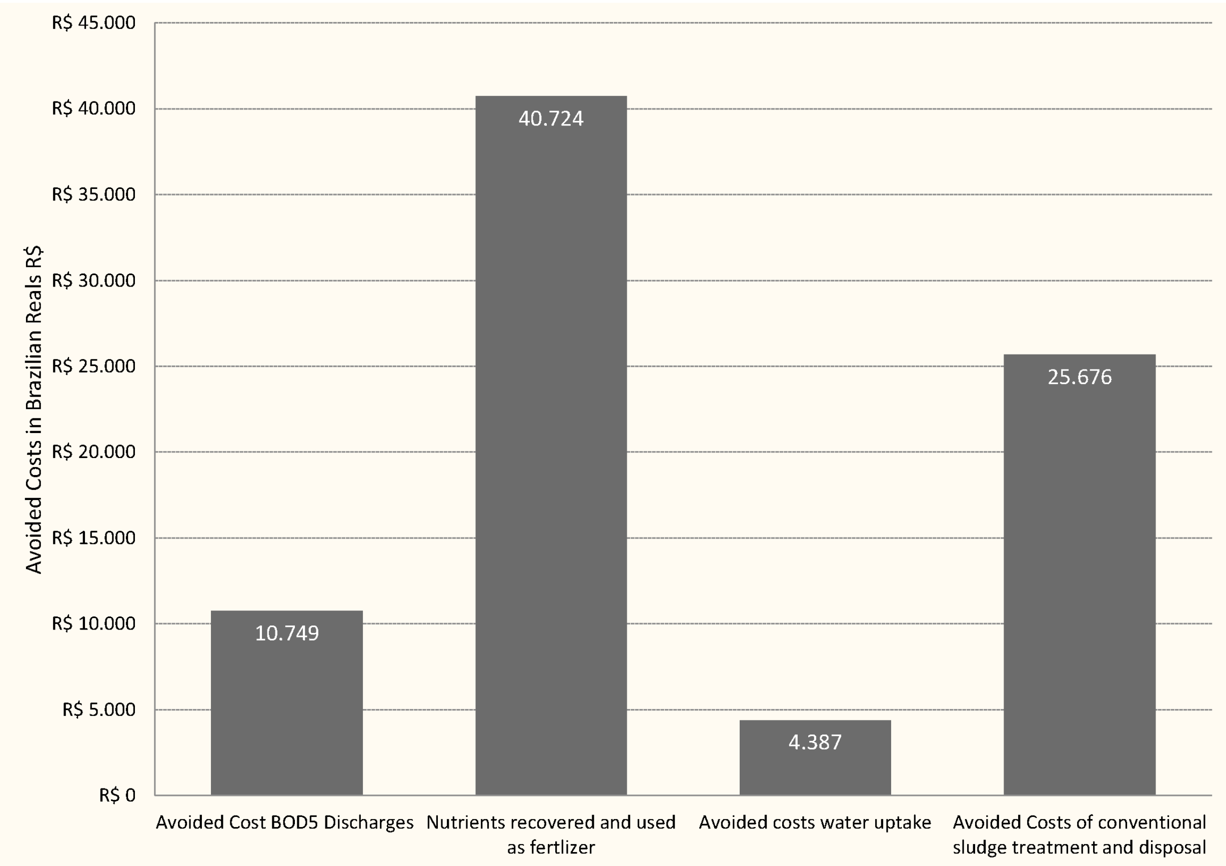

Fig. 5. Distribution of economic benefits after 20 years of operation of the DESAR wastewater and sludge treatment solution applied in the community of Barracão dos Mendes in Rio de Janeiro, Brazil (own elaboration).

Table 5
Cost–benefit analysis considering 20 years of operation of DESAR solution

Costs and benefits	Values in R$
Net present value (NPV)	–713.817
Total O&M costs after 20 years operation	111.031
Total benefits after 20 years operation	81.537
Recovery costs associated to O&M costs	73%

in monetary terms, in terms of the NPV. The largest economic benefit is derived from the recovery of nutrients in the stabilized sludge and use of this by-product as a chemical fertilizer substitute. The next greatest benefit is the avoided costs of sewage sludge transportation, treatment and final disposal at a sanitary landfill site. This result illustrates that a large economic benefit can be derived from in situ treatment of sewage sludge in a decentralized unit because all nutrients can be reutilized directly and locally for agriculture.

4. Discussion

The results of the CBA – considering a 20-year project lifespan and a discount rate of 12% [24] are presented in Table 5. The NPV is a negative value taking into account that all the investments needs were considered. In real projects usually constructions costs for sewer network and wastewater treatment plants are covered by public investments programs. Therefore, operation and maintenance costs have a more significant role for the economic sustainability of the treatment solutions. The results show that the proposed DESAR solution offers high potential for cost-recovery in terms of operation and maintenance costs. It was found that the benefits, in monetary terms, led to the recovery of 74% of the total operating and maintenance costs and nutrient recovery, in terms of local sludge reuse, presented another major benefit. Specifically, it was estimated that R$108 per tonne of treated sludge (SDRB) could be recouped. The benefits acquired through the avoidance of sludge transportation and disposal amounted to 0.026 R$/m^3, whilst the avoided costs of BOD_5 discharge and water uptake for irrigation amounted to 0.0108 and 0.0044 R$/m^3, respectively.

The costs and requirements for suitable sewage sludge management are considerable and often account for 20%–60% of the total operating costs in conventional wastewater treatment facilities [41]. In this study, sewage sludge reuse accounts for a significant proportion of the potential benefits associated with the DESAR system. Several studies have discussed the importance of reutilizing treated wastewater and sludge for agricultural purposes in Brazil [57,58]; highlighting the benefits with regards to improving soil fertility. In addition, there is an urgent need for companies, institutions and governments to share technical and operational information regarding sludge reuse in agriculture, as well as to provide support (training) to farmers who receive the sludge.

5. Conclusion

DESAR solutions are an alternative means of wastewater treatment and provision of nutrients for agricultural production which show great potential for use in rural communities in Brazil. The treatment of sewage sludge on-site for nutrient recovery enables the development of new informal markets associated with agroecological practices. Therefore, DESAR solutions present an opportunity for farmers to save on costs and acquire new income by combining wastewater and sludge treatment with their reuse.

The CBA methodology is a powerful tool which is easily applied to the evaluation of the economic feasibility of DESAR systems. More specifically, it can be used to quantify the total benefits associated with sanitation projects. Assigning monetary value to additional environmental benefits, such as avoided costs related to water uptake for irrigation and BOD_5 discharge penalties. This study makes a methodological contribution towards improving the decision-making process when evaluating new investment into sanitation infrastructure. It focuses specifically on rural settlements with small-to-medium population densities, because these are priority areas for future investment into domestic wastewater and sewage sludge collection, treatment and reuse or disposal systems.

DESAR solutions respond to the need to improve the inadequate sanitation in small, rural communities worldwide. As an additional benefit, DESAR systems can contribute towards the improvement of food security in these regions. For instance, the reuse of nutrient-rich stabilized sludge lends itself towards the development of new, green markets catering for agroecological production. DESAR solutions, thus, provide an integrated approach to wastewater treatment in as much as concentrated nutrient material can be reutilized and, further, present opportunity for new income generation. These decentralized systems can be particularly beneficial in the field of local water and sanitation and green practices in rural areas worldwide.

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