Treated domestic effluents for non-potable reuse: microbial risk assessment and economic viability

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Abstract

Although water quality can be ensured for various pollutant removal processes, concerns regarding microbial pathogens can set very high-quality standards for treated wastewater rendering the practice financially unfeasible. In this study, we applied quantitative microbial risk assessment and net present value methodologies to evaluate the economic viability and safety of wastewater treatment to produce water for reuse. Under the evaluated conditions, even though applying tertiary treatments (such as chlorination, ozonation, or UV radiation) for non-potable reuse purposes presents higher investment costs, it could offer a faster return on investment as a result of the greater income derived from the sale of the treated wastewater, and consequently, reduce the risk of exposure to pathogens. An economic viability analysis revealed payback periods of three to over 15 years for investment in the universalisation of sanitation services in the selected municipalities, wherein the most feasible scenarios were those in which water reuse was carried out at its maximum potential. We evaluated the reuse potential of treated wastewater in terms of reduced concentrations of *Escherichia coli* and observed that effluents treated by six wastewater treatment plant configurations (involving secondary treatment processes) could be used for restricted crop irrigation, with disability-adjusted life years (DALYs) of 9.20E03 ± 4.59E05 related to the risk of infection to the farmers. The application of additional disinfection procedures indicated that treated wastewater could be reused for unrestricted and restricted urban and agricultural uses, with corresponding DALYs of 1.35E05 ± 6.73E08 for the same group.

1. Introduction

The reuse of water has gained prominence in modern society, as it is crucial to reduce the need for water resources (Lofrano and Brown 2010; Wilcox et al. 2016; Chen et al. 2016). Reused water is suitable for a wide range of applications that are usually associated with non-potable purposes, such as the irrigation of crops or urban green areas, industrial applications, environmental purposes, and cleaning of streets (Ait-Mouheb et al. 2018; Deng et al. 2019; Li et al. 2019b). Nevertheless, financial impediments (high-cost treatment for desired water quality and transportation costs), absence of legislation, social constraints such as lack of acceptance from the public and authorities, and knowledge and awareness of associated health risks, specifically for the use of domestic sewage, may limit the adoption of reuse technologies (Woldetsadik et al. 2017; Voulvoulis 2018; Li et al. 2019a).

Some countries, such as Singapore, China, the United States, Turkey, and Israel, have already advanced significantly and continue to invest in water reuse systems (Lyu et al. 2016; Deng et al. 2019; Reznik et al. 2017; Lefebvre 2018; Maryam and Büyükgüngör 2019). The European Union (EU) is also moving forward with new measures to promote the use of reclaimed water for agricultural irrigation. The new EU regulation addresses the risk of drought conditions and increasing pressure on water resources due to new climate patterns fuelled by climate change (European Parliament 2020). Brazil still struggles to overcome barriers to wastewater (WW) collection and treatment; however, the country has great untapped potential for WW reuse (Stepping 2016). One of the main barriers is the lack of a legal framework specifying the required water quality as a function of the use of treated WW (von Sperling 2016).

In the last 20 years, there have been cases of water-supply crises in Brazil, specifically in the northeastern semi-arid region. However, it has now extended to cities with high consumption demand and insufficient water supply, generating a negative impact on the economy and society. The water crisis experienced in the Greater São Paulo between 2014 and 2015 showed the limitations of water resource management system of Brazil, and confirmed the need for the insertion of water security in sectoral agendas (Lima 2018). According to the SNIS database (2018), Mato Grosso do Sul State ranks 11th out of the 27 Brazilian Federation Units in terms of the percentage of sewage collected (SNIS indicator IN015), with 39% coverage. In contrast, both in the Federal District and the State of São Paulo, approximately 80% of sewage was collected. The low connection rate to the public sewerage system is socially problematic and leads to lost revenue for the service provider (Stepping 2016).

Sewage must undergo a degree of treatment compatible with the intended use of the treated WW. Systems can be designed with “flexible” technologies that theoretically allow for closing cycles and resource recovery if plants are properly conceived. For this reason, the WW industry is facing a paradigm shift: WW treatment plants (WWTPs) are no longer designed merely as systems to remove pollutants (end-of-pipe approach) but instead as factories where various value-added products can be recovered (resource-oriented approach) (Papa et al. 2017). Therefore, although there is an additional cost to improve WWTPs (e.g. addition of the tertiary treatment step), a faster return on investment can be obtained from the additional revenue generated from the sale of treated WW. In addition, risk of exposure to pathogens is reduced for operators and users; consequently, there will be less expenditure on public health.

Compared with the huge expenditure already made for establishing the treatment plants, a minimal additional investment should be considered to generate treated WW for non-potable reuse. Such additional revenues can also contribute to the investments needed to increase collection rates, and even improve the quality of the water produced, with the aim of meeting possible discerning demands. Because the degree of treatment has a direct impact on the economic viability and contaminant removal rates of a water reuse project, it is imperative to define appropriate systems for each intended use. In this study, we applied quantitative microbial risk assessment and net present value methodologies to evaluate the financial viability and safety of WW treatment for water reuse in different scenarios related to universalising access to sanitation in five cities in the state of Mato Grosso do Sul (MS), Brazil.

2. Methodology

First, five municipalities were selected to identify the potential for using treated WW. These study sites had the municipal public sewage collection and treatment services that generate reclaimed water for non-potable purposes. In addition, population growth was projected in the selected municipalities until the year 2035 in order to estimate the investment necessary to universalise access to the sewage service. Therefore, it was possible to obtain the period of return of this investment from the collection of the tariff paid by the users. In addition to the income collected by the service provider, in the situation where water reuse was assumed, an additional increase in the income of the service providers was estimated from the sale of recycled WW. Thus, the economic feasibility analysis aims to elucidate whether additional investment to promote a better quality of reclaimed water is feasible in view of the potential return on this investment from the commercialisation of this resource by service providers.

Therefore, variations in the investment required to expand access to sewage treatment services for the population by 2035 were assumed, mainly because of the proposed level of treatment, which can be secondary or tertiary (with disinfection systems). Consequently, along with the variation in the level of sewage treatment, the potential risk of microbiological contamination for users, operators, and the general population during the application and use of reclaimed WW was also important. For this reason, a quantitative microbiological risk assessment methodology was applied to identify the risk associated with contamination in each condition analysed. Therefore, methodologies of quantitative microbiological risk assessment and net present value were applied in a complementary manner to assess financial viability.

2.1 Selected municipalities as a case study and the study boundaries

The five most populous municipalities in MS State were used as study sites (Table 1).

Table 1
The most populous municipalities of Mato Grosso do Sul and their respective rankings in terms of gross value added at competing industry prices

Municipality	Population (inhabitants)[a]	Current ranking in terms of gross value added participation at current industry prices relative to the total state GDP (%)[b]	Sewage collection and treatment index (%)[c]
Campo Grande	885,711	1	73.0
Dourados	215,486	4	51.4
Três Lagoas	119,465	2	37.3
Corumbá	110,806	5	45.0
Ponta Porã	91,082	10	27.6
Source: [a]IBGE (2017), [b]IBGE (2014), [c]ANA (2017).			

The final uses for the treated WWs considered in the study were street cleaning, sewage network unblocking, crop irrigation, and industrial activities. These scenarios were compared with the scenario of discharging treated WW to water bodies. Figure 1 shows the analysis of water reuse from a financial perspective considering the risk associated with microbial contamination.

2.2. Economic feasibility study

The net present value (NPV) methodology was applied to revenues obtained under different investment scenarios from income generated by service user tariffs and the sale of reuse water by local concessionaires. Apart from assuming operation and maintenance costs, the NPV considered the investment required to universalise access to WW treatment services in the selected municipalities, as shown in Eq. 1:

$$NPV = \sum_{y=0}^{n} \frac{CF_y}{(1+i)^y} - C_0 \text{ Eq. 1}$$

where *y* is the year, *CF* is cash flow, *i* is the discount rate, and C_0 is the total initial investment cost. We assume a minimum attractiveness rate of 12%. The costs and benefits of the modelled interventions were calculated in the Brazilian currency Reais (R$), based on the January 2020 exchange rate, assuming an intervention period of 15 years, starting in 2020 and ending in 2035. All costs and benefits incurred after 2020 were converted to 2020-equivalent values using a discount rate of 2.5%.

Four panoramas of investment reflecting variations in WW treatment services were analysed in addition to the variations in the sensitivity analysis. In the first condition (baseline), receipts for the WW treatment were obtained solely from the collection of annual tariffs applied to users of the WW service. In the second, the annual tariff revenue was supplemented by the medium possible increment in annual revenue from the sale of treated WW, based on the demand for medium quality and medium cost water. Finally, in the third and fourth conditions, the annual tariff revenue was supplemented by the minimum and maximum possible revenue from low-to-high-quality water, respectively. The cost of the treated WW was based on the study of Sabesp (2017) and ranged from 1.50–5.08 R$/m^3 depending on the required quality.

The estimated revenue of sewage services was calculated using data on billed sewage volumes from the Brazilian National Sanitation Information System (SNIS) from 2012–2017, considering projection trends up to 2035 including the revenue from the reuse of water, as shown in Eq. 2:

$$RT = (WTR) + (VR \times TR) \text{ Eq. 2}$$

where *RT* is the total revenue from sanitary sewage, *WTR* is the WW treatment service revenue, *VR* is the volume of reused water billed, and *TR* is the average water reuse rate. Increases in the projected population served by the sanitation service over the duration of the project and readjustments to tariffs led to variations in the total annual receipts collected by the service provider. In the Online Resource 1, it is possible to verify all data considered in each municipality from 2013–2035, including estimated population, increase in WW treatment coverage by WWTPs (not including septic tanks), tariffs of WW treatment, operating revenue from WW treatment, operating expenditure from WW treatment, and water reuse volume according to different applications.

2.3. Recycled WW demand and supply

We estimated the water reuse demand in each municipality and conducted a sensitivity analysis considering a variation of ± 20% in the estimated average amount of water (Khan and Jain 2018; Hernandez-Sancho and Molinos-Senante 2015).

2.3.1. Street cleaning

We assumed that only 20% of the total streets paved per municipality would be cleaned using treated WW, as this practice is carried out in addition to simple sweeping and is only necessary on streets with high flows of people or economic activity, producing an excess of dirtiness. To estimate the volume of recycled water in each municipality necessary to meet this demand, SNIS data were used to determine the number of households supplied with the water distribution network. Data on the per-link extent of the water network from SNIS were also considered to obtain an estimate of the total length of the paved streets. It was assumed that the average width of the streets was 8 m, with a cleaning efficiency of approximately 100 m/m^3, and a weekly street washing frequency.

Street cleaning was assumed to be performed by a team of four employees, including three workers and a driver, who wore all the necessary individual protection equipment (gloves, boots, proper clothing, and helmets). Materials, such as brooms and liquid detergents, were also used in the washing process. It was assumed that the treated WW was transported by tank trucks. Street cleanings should be scheduled at times when movements of people were minimal.

2.3.2. Sewage network cleaning

The need for unblocking the sewage network was assessed using information obtained from the United States Environmental Protection Agency (EPA 1999). This study adopted a method of simply discharging treated WW into the network at pressure under the control of a water truck (at a pump head of approximately 60 mca). The procedures adopted for clearing sewage networks are similar to those adopted for street cleaning, in which a tanker truck is used with employees wearing personal protective equipment.

Considering that the frequency of unblocking can vary from twice a month to once every six months, we assumed an average frequency of sewage network unblocking of once a month, over only 5% of the network length in each municipality. Based on the fact that for diameters of up to 500 mm, the average demand volume of treated WW is equivalent to three times the linear volume of the pipe, we assumed a required volume to remove obstructions of 2.4 m^3 for each linear meter of sewage network, with a useful volume of approximately 0.8 m^3. Note that these figures consider the growth of the sewage network of each municipality over time, and therefore show increases in the proportion of the demand for treated WW for cleaning the network.

2.3.3. Industrial activities

The system model used in this study considered a closed circuit for industrial water reuse. The model starts with the final effluent of an existing municipal WWTP, and the endpoint is the industry that receives this effluent from a water tanker. When the water tanker enters the facility, it is connected to a storage reservoir to supply the recycled water, which is later pumped to its final site of use. The pump is operated and maintained to ensure minimal risks for the workers.

We estimated the demand for treated WW in industry in the selected municipalities using data from SNIS on volumes of produced water, assuming that approximately 17% of the water consumed in Brazil is allotted to industry (FAO 2019), and that an average of 30% of this water supply could be replaced by treated WW. It is worth mentioning that SNIS data refer to water produced and distributed by public water supplies, and do not include other routes through which water can be supplied to the industry.

2.3.4. Crop irrigation

The agricultural sector is the largest water consumer globally, and consumes approximately 60% of the freshwater in Brazil (FAO 2019). We estimated the demand for treated WW in agriculture in the selected municipalities using data from SNIS on volumes of produced water, assuming that approximately 60% of the water consumed in Brazil is allotted to agriculture (FAO 2019), and that 30% of this amount could be used from treated WW.

2.4. Projection of sewage treatment demand

We analysed the demand for WW treatment in selected municipalities in MS State (Campo Grande, Dourados, Três Lagoas, Corumbá, and Ponta Porã) based on the population growth of each municipality for the year 2035. Therefore, we developed several investment conditions under the assumption that the entire urban population will be served by sewage treatment systems by 2035, with 90% of the population served by a centralised system and 10% served by individual solutions, such as septic tanks.

We applied mathematical and statistical methods to identify growth trends in the sanitation service industry. We estimated parameters such as tariffs, as well as operational and maintenance costs through 2035 by extrapolating historical data (covering 2012–2017) from the SNIS database. Appropriate parameters were obtained by applying the linear regression tool in Excel (Microsoft Corporation 2018) directly to data values (for linear growth) or to their logarithms (for exponential growth). Exponential growth curves were appropriate for the economic parameters, as tariffs and costs tend to keep pace with inflation, and therefore exhibit geometric growth. To calculate operational expenses for WW collection and treatment services, the total expenditure on both sewage and water supply services in the SNIS database was considered, as well as the percentage of participation of each service (water and sewage) in relation to the total operating revenue. Because the population growth rate in the state is currently decreasing, an exponential model of population growth would have been inappropriate. Instead, a linear model was applied and calibrated to match data from the last IBGE (2010) census with the 2035 population predictions produced by ANA (2017) as the starting and ending points, respectively.

The linear and exponential representations of the parameter growth are given in Equations 3 and 4, respectively:

$$Value = (Cst + rate) \times A(lineargrowth) \text{ Eq. 3}$$

$$Value = e^{(Cst + rate)A}(exponentialgrowth) \text{ Eq. 4}$$

where *Value* is the projected parameter, *Cst* is the historical value of the parameter, *rate* is the function-determined linear or exponential growth rate, and *A* is the year. These equations were used to model the costs of tariffs, operation, and maintenance, as well as the growth of population and sewage production for each year from 2020–2035.

2.5. Expansion of access to sanitation services

Costs for the expansion of access to WW collection and treatment were obtained from ANA (2017). These costs are related to conventional sewage systems, where raw effluent is collected separately from rainwater/drainage, and its treatment must achieve the standards for discharge into water bodies.

Tertiary treatment of WW for reuse is a common treatment level where close contact with the water is considered a possibility (Vojtěchovská Šrámková et al. 2018; Voulvoulis 2018). Thus, to guarantee the required quality, additional costs of 30% (based on the estimates by von Sperling 2016) were considered when introducing disinfection systems to decrease microbial contamination. It should be noted that some systems have lower investment and operating costs than others, with higher treatment levels generally corresponding to higher costs. In addition, per capita costs will decrease with increasing installed capacity, as a result of economies of scale. Finally, several local factors can influence system costs, including the quality of the materials used in construction, local personnel costs, energy costs, and potential land acquisition costs (depending on whether the land is owned by the government).

As the accuracy of the cost estimates in each locality was difficult to access, an additional variation of ± 20% in the cost of treatment for reuse was assumed in our sensitivity analysis (in addition to 30%). Table 2 lists the treatment systems used in each municipality and their respective characteristics (Sanesul 2017; Águas Guariroba 2017).

Table 2
Technologies used for the treatment systems in each selected municipality and their current respective characteristics

Wastewater treatment plant	Population project (inhab.)	Expected flow[b] (l/s)	Treatment process
Três Lagoas WWTP 1 Planalto	72,000	100	UASB + physico-chemical
Três Lagoas WWTP 2 Jupiá	28,800	80	UASB + Biodrum[a] + Secondary decanter
Corumbá WWTP 1 Olaria	57,600	80	UASB + Trickling filter + Secondary decanter
Corumbá WWTP 2 Maria Leite	57,600	80	UASB + Trickling filter + Secondary decanter
Dourados WWTP 1 Guaxini	86,400	120	UASB + Trickling filter + Secondary decanter
Dourados WWTP 2 Água Boa	79,200	110	UASB + Trickling filter + Secondary decanter
Dourados WWTP 3 Laranja Doce	28,800	40	UASB + Trickling filter + Secondary decanter
Dourados WWTP 4 Harry Amorim	28,800	40	UASB + Facultative pond
Ponta Porã WWTP 1 Estoril	57,600	80	UASB + Trickling filter + Secondary decanter
Ponta Porã WWTP 2 São Thomaz	28,800	40	UASB + Trickling filter + Secondary decanter
Campo Grande WWTP 1 Imbirussú	67,000	120	Compact aerobic system + Unitank
Campo Grande WWTP 2 Los Angeles	500,000	900	UASB + contact tank for disinfection

[a]Consisting of an anaerobic system, followed by an aerobic system with rotating microbial support type Tubular Reel; [b]Design parameter: maximum expected flow when the system is in full operation.

2.6. Microbial risk assessment

The risks associated with the use of treated WW for the aforementioned purposes were assessed using the quantitative microbial risk assessment (QMRA) approach. This involves the following four key steps.

2.6.1. Hazard identification

Escherichia coli 0157 was chosen as the pathogen for the QMRA. Infection with this pathogen from exposure to WW has been extensively reported (Forslund et al. 2012; Akiba et al. 2015; Tripathi et al. 2019). Data on *E. coli* concentrations in different scenarios can be found in the Online Resource 1. Data were collected monthly for a monitoring period of 18 months. Data from WWTPs in Campo Grande were obtained from Aristimunho (2019). The concentrations of *E. coli* in the final effluent from all the selected WWTPs ranged from 10^4 to 10^6. This was assumed to be the concentration before tertiary treatment, as observed in the treatment plants (see Online Resource 1).

2.6.2. Exposure assessment

Exposure to WW was considered based on the different uses of WW, currently or projected, within the various municipalities considered for this study. Exposure to treated WW was considered in six scenarios (Fig. 1). The main routes through which the exposed populations could ingest pathogens in treated WW are described in Table 3. For instance, during WW collection, risks were assessed for workers in the major exposure group. The routes of exposure were through inhalation of aerosols generated during collection, direct ingestion of aerosol droplets, and hand-to-mouth exposure (from contaminated hands). The duration of exposure was assumed to be 30 min during this stage. Similar to effluent collection, workers were the major exposed group during the transport of the treated WW. The exposure routes and durations were the same as those during the WW collection stage.

During the application of the treated WW for the different uses mentioned above (Fig. 1), two population groups were considered: the workers involved in the practice, and the public, who may be exposed during these practices. For the workers, the main routes of exposure considered were the same as mentioned above, with a duration of an hour. However, the exposure of the public was mainly through the route of inhalation of droplets for a maximum of 1 min. Application of WW for crop irrigation was also considered, with farmers as the main exposed population. Additionally, the risks of infection with the pathogen for consumers of farm produce were also considered. In this assessment, lettuce consumption was used to model the risk of infection for consumers. Table 3 presents the volume of water ingested used in the risk assessment.

Table 3
Volume of water ingested under different exposure scenarios

Exposure Scenario	Route of Exposure	Volume of effluent exposure
Scenario I: Discharge into rivers	Direct ingestion during recreation (swimming)	1–5 mL[a]
Scenario II: Exposure to effluents during collection	Aerosol inhalation	Calculated using Equations 6–8 and input data from Table 6
	Ingestion of droplets	
	Hand-to-mouth ingestion	
Scenario III: Exposure during transport of effluents	Ingestion of droplets	Calculated using Equations 6–7 and input data from Table 6
	Hand-to-mouth ingestion	
Scenario IV: Street and sewer network cleaning	Aerosol Inhalation for workers	Calculated using Equations 6–8 and input data from Table 6
	Ingestion of droplets for workers	
	Hand-to-mouth ingestion for workers	
	Aerosol inhalation by the general public (street cleaning)	Calculated using Equations 6–8 and input data from Table 6
Scenario V: Use of effluents for industrial activities	Aerosol inhalation	Calculated using Equations 6–8 and input data from Table 6
	Droplet ingestion	
	Hand-to-mouth ingestion	
	Aerosol inhalation (irrigation of green spaces)	
	Direct ingestion during irrigation (farmers)	1–5 mL[b]
	Consumption of vegetables (consumers)	Calculated using Equations 9 and input data from Table 7

[a]Based on assumptions; [b]WHO (2006).

To determine the dose of pathogenic *E. coli* ingested during these different scenarios, Eq. 5 was used, as follows:

$D = Craw \times V$ Eq. 5

Where "*D*" is the dose ingested, "*Craw*" the concentration of pathogenic *E. coli* per milliliter and "*V*" the volume (mL/day) ingested.

Equations 6–8 were used to determine the volume of WW ingested per person under each of the exposure scenarios.

Hand-to-mouth ingestion from wet hands:

$QHM = h \times A \times fHM$ Eq. 6

where h is the thickness of the water film on the hands (mm), A is the skin surface area in contact with the mouth (mm^2), and f_{HM} is the frequency of the hand-to-mouth contact (n/min).

Ingestion of droplets of water:

$QD = VD \times fD$ Eq. 7

where V_D is the water droplet volume (μL) and f_D is the frequency at which droplets splash into the mouth (n/min).

Inhaled volume of water per minute:

$QI = IR \times VIWS$ Eq. 8

where IR is the air inhalation rate (m^3/min) and $VIWS$ is the fraction of inhalable water spray (μL water/m^3 air). The values of the parameters used in Equations 7–9 are listed in Table 4.

Table 4
Additional data for QMRA calculations

Parameter	Value or distribution of values	Source
Inhalation rate (m^3/min)		
Children	Uniform (1.11E-02, 4.36E-02)	
Adults	Uniform (1.03E-02, 7.77E-02)	USEPA 2011
VIWS, volume of inhalable water spray (μL/m^3)	Average: 10.8 95% confidence interval: 1.76–36.3	de Man et al. 2014
H, film thickness of water on hands (mm)	Uniform (1.97E-02, 2.34E-02)	USEPA 2011
A, surface area of hand that is mouthed (mm^2)	Uniform (100, 2,000)	USEPA 2011
F_{hm} frequency of hand-to-mouth contact, (n/min)	Gamma (2, 0.5)	Freeman et al. 2001
F_d, frequency of water droplets landing in mouth (n/min)	Gamma (2.1, 0.17)	de Man et al. 2014
$V_{d,}$ volume of a droplet (μL)	Uniform (0.5, 524)	de Man et al. 2014

The risk of infection from the indirect use of water, due to the consumption of vegetables irrigated with this water, was determined based on the dose of pathogenic *E. coli* ingested by consumers. This was modelled with lettuce as a surrogate vegetable, using the following formula:

$$DC = V \times I \times c \quad \text{Eq. 9}$$

Where "*V*" is the volume of water caught on the lettuce in mL/g of lettuce, "*I*" the mean per capita intake of lettuce in grams per person per day, and "*c*" the concentration of pathogenic *E. coli* in the water used for irrigation. The different exposure scenarios and ingested volumes are listed in Table 5.

Table 5
Assumptions used in estimation of risks of consuming vegetables irrigated with recycled WW

Exposure scenario /Assumptions for dosage	**Volume of water ingested (mL or g)**	**Frequency (days)**	**Reference**
Consumption of lettuce		Uniform distribution (156,160)	
Volume of water caught on lettuce	Normal distribution (0.108, 0.019)		Hamilton et al. (2006)
Per capita intake of lettuce	Pert distribution (25, 50, 75)		Sant'Ana et al. (2014)

To model the risk of infection from the discharge of the treated sewage into rivers, a baseline *E. coli* concentration of 1 colony forming unit/100 mL was assumed for the river water quality prior to discharge. Based on the assumption that workflow discharge was carried out at a fixed point, the reduction in the rate of auto-depurification was calculated as a function of time to determine the risk of infection in individuals swimming in the river between zero and five days after the release of the effluent (Eq. 10).

$Nt = N_0 \times e^{(-kt)}$ Eq. 10

where Nt is the coliform density at time t in running water (most probable number 100 mL^{-1}), N_0 is the initial density of coliforms after dilution, and k is the first-order activation constant (d^{-1}).

2.6.3. Dose response assessment

Similarities in exposure risk arose from the fact that each type of activity assumed the same route of exposure and pathogen (pathogenic *E. coli*) concentration. The volumes of water ingested by direct contact were obtained from the 2006 WHO publication on WW reuse, and were assumed to be uniformly distributed over a range of 1–5 mL. Most of the *E. coli* load was disregarded, with only 8% assumed pathogenic. The dose of pathogenic *E. coli* ingested under each scenario considered in this study was calculated based on the volume of water consumed during these activities. We also assessed the potential reduction in the risk of infection when tertiary WW treatment was implemented. We modelled the risks with a 3 Log (99.9%) reduction in *E. coli* concentration after possible tertiary treatment (disinfection) with chlorination, ozonation, or UV radiation (von Sperling 2005). Thus, we assessed the risks of exposure to secondary-and tertiary-treated WW separately. The beta Poisson dose-response model was used for risk assessment (Haas et al. 2014), represented by the following equation:

$$p(d) = 1 - \left(1 + \left(\frac{d}{N_{50}}\right)\left(2^{\frac{1}{\alpha}} - 1\right)\right)^{-\alpha}$$ Eq. 11

where *"p(d)"* is the probability of infection, *"d"* is the median infection dose representing the number of organisms that will infect 50% of the exposed population (N_{50}), and α is the dimensionless infectivity constant. For this assessment, the risks were modelled for *E. coli* 0157 with an N_{50} value of 2.11×10^6, and α was set equal to 1.55×10^{-1} (DuPont et al. 1971; Girardi et al. 2019).

2.6.4. Risk characterisation

Risks of infection from multiple exposures were determined using Eq. 12:

$$\mathrm{P1(A)}=1\text{-}(1-\mathrm{P1}(d))^{n} \quad \text{Eq. 12}$$

where '*P1(d)*' is the risk of infection from a single exposure to a dose '*d*' of the bacteria; and '*n*' is the number of days of exposure to the single dose '*d*'(Sakaji and Funamizu 1998). The duration of exposure (n) for all scenarios was considered to be 30 min, except for the exposure to aerosols by the general public, which was modelled for 1 min.

Determination of harm by using the disability-adjusted life year (DALY) metric

The DALY metric can be used to widely compare different illnesses and other risks from daily life (Havelaar et al. 2000). The DALY aims to estimate the overall environmental burden of disease (Knol et al. 2009) and measures population health (Vocht et al. 2011) by estimating the loss of healthy life years of the population (Havelaar et al. 2000; Murray 1994). DALYs are calculated by considering the years of life lost due to premature death or mortality and years of life lived with a disability (Timm et al. 2016). In this study, the DALYs per year were calculated using Eq. 13:

$$DALY = \sum_{i=1}^{n} P(ill\backslash inf) \times P(outcome_i\backslash ill) \times Duration_i \times Severity_i \quad \text{Eq. 13}$$

where "n" refers to the total number of outcomes considered. Three outcomes were considered in this study, and all of them were considered to be consequences of diarrhoea. P(ill\inf) is the probability of illness given an infection, as we assessed the risks for *E. coli* 0157 to be 1. P(outcome\ill) provides the probability of an outcome given an illness. $Duration_i$ is the duration (years) of outcome i, and $Severity_i$ is the severity weight for outcome i. The severity, weight, and duration of the disability or disease used in this assessment were adjusted to developing country conditions (Katukiza et al. 2014). The severity weight scale ranged from 0 (healthy) to 1 (death) (Havelaar and Melse 2003; Katukiza et al. 2014). For each pathogen, the disease outcomes, duration, severity, and disease burden per case of infection were obtained from literature. An average life expectancy of 61 years was used for this study, and the years lost were based on death occurring at the age of 1 year (Howard and Pedley 2004). All input data taken from the literature for the DALY estimation are presented in Table 6. All the microbial risk (QMRA) and burden of disease (DALY) assessments were performed with Monte Carlo simulations with 10,000 iterations using the @Risk (Palisade, USA) add-on to Excel (Microsoft Corporation 2018).

Table 6
Health outcomes and the related probability inputs used in the DALY assessment

Relevant Health outcome	Probability of outcome (P(outcome\ill))	Severity weight	Duration (Years)
Watery diarrhoea	0.53	0.067	0.009
Bloody diarrhoea	0.47	0.39	0.015
Death	0.007	1	60
*Input values taken from Havelaar and Melse (2003), Machdar et al. (2013), Katukiza et al. (2014), and Howard and Pedley (2004).			

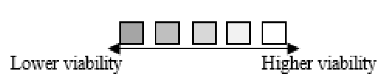
3. Results And Discussion

3.1. Economic study - Net present value

Table 7 lists the years in which the NPV exceeded zero in each municipality under each treatment condition (with and without the application of treated WW).

Table 7 Year of positive NPV for panoramas of investment with and without the use of treated WW, considering variations on costs of improving access to the population by secondary treatment processes or systems, including a disinfection step allowing water reuse, as well as assuming ±20% variations on the amount of water reuse, characterising conditions of maximum and minimum potential of water reuse, with a discount rate of 12%

			Campo Grande	Corumbá	Dourados	Ponta Porã	Três Lagoas
Panorama of investment 1: without water reuse (baseline)			5	>15	>15	>15	>15
Panorama of investment 2: reuse of water increasing 30% of investment due to disinfection step	sensitivity analysis of water reuse demand volume	minimum	5	>15	>15	>15	>15
		Medium	4	>15	>15	>15	>15
		maximum	3	>15	8	11	13
Panorama of investment 3: reuse of water increasing 10% of investment due to disinfection step	sensitivity analysis of water reuse demand volume	minimum	4	>15	>15	>15	>15
		Medium	4	>15	>15	>15	>15
		maximum	3	>15	7	9	10
Panorama of investment 4: reuse of water increasing 50% of investment due to disinfection step	sensitivity analysis of water reuse demand volume	minimum	5	>15	>15	>15	>15
		Medium	5	>15	>15	>15	>15
		maximum	4	>15	10	13	>15



The period of payback of investment in WW treatment systems in the municipalities of MS State ranged from three to more than 15 years. Municipalities with higher service indices had shorter payback periods because they required less investment than municipalities with less developed service infrastructure. Under the maximum water reuse demand volume (20% more than the average condition) and assuming an addition of only 10% on investment costs due to disinfection of WW (most optimistic condition), water reuse improved the NPV by an average of 33.2% in the selected municipalities, compared to the baseline panorama of investment. In contrast, under the most pessimistic condition, which assumed a minimum demand volume potential for water reuse and high investment costs for improving the systems, the NPV did not improve, compared to the baseline situation.

The conditions that presented an expressive improvement in the financial performance of the systems, promoted by the reuse of treated WW, were those in which the maximum demand volume of water reuse was assumed. This means that the more water reuse that is stimulated for non-potable purposes, the better the economic balance of sanitation companies. The municipality that presented the best return period in all assumed conditions was Campo Grande, the most populous municipality in the state of MS, with the highest percentage of sanitation services provided to the population. In contrast, the municipality that presented the worst return period was Corumbá, with none of the proposed conditions presenting a positive NPV in less than 15 years, mainly due to high projected operating costs.

Improving the financial viability of sewage treatment systems to ensure a healthy cash surplus for service providers can guarantee an improvement in the quality of services and in the performance toward universal access to sanitation in Brazil.

3.2. Assessment of the risk from exposure during reuse

3.2.1. Discharge into rivers

Risk estimates showed that within the first day of discharge, the risks were high (1.30E-02 ± 0.0), with a corresponding high DALY of 2.60E-04 ± 1.90E-05. However, five days after discharge, the risks were drastically reduced (Table 8). The risks of infection and DALYs after accounting for tertiary treatment of WW were notably reduced. For instance, on day zero after discharge of tertiary treated WW, the risks of infection were 1.64E-05 ± 1.20E-03, against risks of 1.30E-02 ± 0.0 when secondary treated WW was discharged.

Table 8
Risks of infection with pathogenic *E. coli* and the associated DALYs from exposure to rivers receiving treated WW at different days

	Effluents after secondary treatment		**Effluents after tertiary treatment**	
Day	Median risks (90%CI)	DALY pppy (± 90%CI)	Median risks (90%CI)	DALY pppy (± 90%CI)
Day 0	1.30E-02 ± 0.0	2.60E-04 ± 1.90E-05	1.64E-05 ± 1.20E-03	3.37E-07 ± 2.51E-05
Day 1	4.30E-03 ± 2.40E-03	8.50E-05 ± 4.63E-05	5.40E-06 ± 1.00E-03	1.06E-07 ± 2.05E-05
Day 2	1.50E-03 ± 2.00E-03	2.90E-05 ± 4.01E-05	1.86E-06 ± 8.90E-04	3.67E-08 ± 1.74E-05
Day 3	5.10E-04 ± 1.70E-02	1.00E-05 ± 3.40E-05	6.42E-07 ± 7.60E-04	1.26E-08 ± 1.50E-05
Day 4	1.80E-04 ± 1.80E-04	3.56E-06 ± 3.56E-06	2.31E-07 ± 6.50E-04	4.54E-09 ± 1.27E-05
Day 5	6,64E-05 ± 1.20E-03	1.31E-06 ± 2.46E-05	7.97E-08 ± 5.40E-04	1.57E-09 ± 1.07E-05

As shown in Table 8, direct exposure to WW (Day 0) may result in a major risk of infection. However, the risk estimates are much lower than the acceptable risk of illness recommended by the Commission of the European Communities (3–5%) (Georgiou and Bateman 2005), and the US EPA (3.6%) (Wiedeman et al. 2006). Based on the risk of infections from bathing or recreational use of surface water receiving secondary treated effluents, the use of a tertiary treatment or disinfection process is not required. For instance, exposure to WW-contaminated surface water after one day of discharge results in a significant reduction in risk by approximately 1 Log; therefore, further reduction achievable with tertiary treatment will not be necessary.

3.2.2. Risk of infection during reuse for street cleaning and declogging of sewers

The use of treated WW for street cleaning and declogging of sewers had similar exposure patterns; therefore, the risk estimates were the same for these reuse scenarios, with the highest risks to both the workers and the general community. Under these exposure scenarios, approximately two out of 100 workers will be infected during this practice, mainly from the ingestion of WW droplets. Aerosol inhalation may also lead to infections; however, this is much lower than estimates from direct contact. The risks to the general public were generally lower than those to the workers, with children at a higher risk (1.72E-05 ± 1.80E-03) than adults (3.72E-07 ± 5.30E-04). However, a significant reduction in infection risk was observed after the incorporation of a possible pathogen reduction during tertiary treatment. For instance, the risk of infection for droplet ingestion was reduced from 2.40E-03 ± 3.80E-03 to 2.81E-06 ± 1.70E-03 after the incorporation of a tertiary treatment step. Similar risks and DALY reduction trends were observed for all the exposure scenarios (Table 9).

Table 9
Risks of infection for exposed populations during reuse of the treated WW for street cleaning and sewer declogging

			Effluents after secondary treatment		**Effluents after tertiary treatment**	
Exposure scenario	Exposure group	Exposure route	Median risks (90% CI)	DALY pppy (± 90% CI)	Median risks (90% CI)	DALY pppy (± 90% CI)
Effluent collection truck loading	Workers	Aerosol Inhalation	1.09E-05 ± 1.60E-03	2.19E-02 ± 1.10E-04	1.38E-08 ± 7.50E-04	2.67E-10 ± 2.38E-12
		Ingestion of droplets	2.40E-03 ± 3.80E-03	5.68E-05 ± 2.97E-07	2.81E-06 ± 1.70E-03	6.75E-08 ± 3.53E-10
		Hand-to-mouth (wet hands)	5.70E-04 ± 3.10E-03	1.44E-05 ± 7.49E-08	7.11E-07 ± 1.30E-03	1.81E-08 ± 9.36E-11
Effluent transportation	Workers	Ingestion of droplets	2.40E-03 ± 3.80E-03	5.27E-07 ± 2.80E-04	2.81E-06 ± 1.70E-03	6.76E-08 ± 3.53E-10
		Hand-to-mouth (wet hands)	5.70E-04 ± 3.10E-03	9.43E-09 ± 4.90E-11	7.11E-07 ± 1.30E-03	1.80E-08 ± 9.36E-11
Effluent application	Workers	Aerosol inhalation	2.19E-05 ± 1.90E-03	1.44E-05 ± 7.45E-06	2.78E-08 ± 8.20E-04	9.25E-10 ± 4.79E-12
	General Public (Adults)	Aerosol inhalation	3.72E-07 ± 5.30E-04	2.44E-07 ± 1.18E-09	4.71E-10 ± 2.60E-04	3.09E-10 ± 8.66E-13
	General Public (Children)	Aerosol inhalation	1.72E-05 ± 1.80E-03	1.13E-05 ± 5.48E-08	2.19E-08 ± 7.90E-04	1.43E-08 ± 6.94E-11

3.2.3. Industrial activities

The risks of infection during the industrial reuse of WW were similar to those observed during street cleaning and sewer declogging. The difference between these two reuse scenarios is the discharge of WW into storage tanks or containers in the industry. For this exposure scenario (discharge of effluents into storage tanks), the considered exposure routes were the same during effluent collection; therefore, the risk and DALY estimates were the same (Table 10).

An additional exposure scenario was the reuse of treated WW for the irrigation of green spaces within the industry. This may result in risks of infection for exposed populations within the industry, with estimated risks of 1.24E-07 ± 2.80E-03 for the reuse of secondary treated WW, and 2.17E-10 ± 3.80E-04 for tertiary treated WW. The DALYs figures also show a similar trend (Table 10).

Table 10
Risks of infection for exposed populations during reuse of the treated WW in industry

		Effluents after secondary treatment		**Effluents after tertiary treatment**	
Exposure scenario	Exposure route	Median risks (90% CI)	DALY pppy (± 90% CI)	Median risks (90% CI)	DALY pppy (± 90% CI)
Discharge into storage tank	Aerosol inhalation	1.09E-05 ± 1.60E-03	2.19E-02 ± 1.10E-04	1,38E-08 ± 7.50E-04	2.67E-10 ± 2.38E-12
	Ingestion of droplets	2.40E-03 ± 3.80E-03	5.68E-05 ± 2.97E-07	2.81E-06 ± 1.70E-03	6.75E-08 ± 3.53E-10
	Hand-to-mouth (wet hands)	5.70E-04 ± 3.10E-03	1.44E-05 ± 7.49E-08	7.11E-07 ± 1.30E-03	1.81E-08 ± 9.36E-11
Irrigation of green spaces	Aerosol inhalation	1.24E-07 ± 2.80E-03	3.08E-05 ± 3.20E-04	2.17E-10 ± 3.80E-04	3.12E-11 ± 3.12E-12

The industrial reuse of the secondary treated WW did not pose any high risk of infection beyond the recommended tolerable risk figures alluded to previously. However, there is an exception for the droplet ingestion as route of exposure. Therefore, to protect workers who are the major exposure group for this route, the use of face masks and gloves could potentially reduce or eliminate these risks. This simple risk-reduction intervention reduces the need for a tertiary treatment process.

3.2.4. Crop irrigation

Farmers who use WW after secondary treatment for crop irrigation have a high risk of infection. For instance, approximately 35 out of 100 farmers were at risk of infection (Table 11), with corresponding DALYs of 9.20E-03 ± 4.59E-05. The incorporation of tertiary treatment of WW before reuse resulted in lower estimated risks of infection.

The risk of infection for consumers of farm produce is also high. For instance, the consumption of vegetables irrigated with secondary treated WW may result in risks of infection of 5.80E-02 ± 3.30E-03, and DALYs of 1.80E-02 ± 9.30E-05. However, significantly lower risks were estimated when tertiary-treated WW was used (Table 11).

Table 11
Risks of infection for exposed populations during reuse of the treated WW for crop irrigation

	Effluents after secondary treatment		**Effluents after tertiary treatment**	
Exposure group	Median risks (90% CI)	DALY pppy (± 90% CI)	Median risks (90% CI)	DALY pppy (± 90% CI)
Farmers	3.50E-02 ± 3.10E-03	9.20E-03 ± 4.59E-05	5.06E-05 ± 1.40E-03	1.35E-05 ± 6.73E-08
Consumers	5.80E-02 ± 3.30E-03	1.80E-02 ± 9.30E-05	9.33E-05 ± 1.60E-03	2.82E-05 ± 1.38E-07

Despite the associated benefits of agricultural reuse of treated WW, the risks of infections for the two exposed populations were high. For instance, consumption of vegetables irrigated with secondary-treated WW could result in approximately six out of a hundred consumers infected. These risk estimates are higher than the tolerable risk of one infection per 10,000 exposed people, as recommended by the WHO for WW reuse (WHO 2006). Our estimates are similar to those reported in other studies (Deepnarian et al. 2020; Van Vu et al. 2018; Moazeni et al. 2017). However, we observed a significant reduction in the risk estimates when a tertiary treatment step or process was incorporated. The risks were reduced by almost 3 Log and were lower than the tolerable risk figures recommended by the WHO. Therefore, our results show that for direct reuse of the treated WW in agriculture, further treatment is necessary. Therefore, incorporation of these tertiary treatment steps should consider their intended use. To eliminate the additional cost of tertiary treatment, different options can be applied to reduce the risks of agricultural reuse. These include cessation of irrigation before harvest, washing of produce under running water, washing with bleach, disinfection with a hypochlorite solution, and cooking of vegetables (where possible) (Amoah et al. 2007).

4. Conclusion

The economic analysis highlighted that payback periods varied from three to more than 15 years for investment in the universalisation of sanitation services in the municipalities of Mato Grosso do Sul State, influenced by the sum of the revenue from sewage tariffs and the sale of recycled water. This finding indicates that financial viability is directly related to the current situation regarding the access of population to the service. Hence, in smaller municipalities, a high investment in the sanitation service is still necessary to reach universalisation, since these municipalities have low percentages of sewage coverage to the population when compared, for example, to the capital Campo Grande. Thus, the implementation of water reuse procedures was found to markedly reduce the return period in optimistic panoramas of investment, consisting of the maximum potential use of recycled water, which was estimated to be 20% more than the average use in each municipality, through an investment in disinfection systems that do not exceed 30% of the WWTP capital costs.

The risk estimates showed that discharging secondary treated effluent into rivers, which is the most common practice in Brazil, presents a high risk of infection from bathing or recreational use of surface water only within the first day of discharge (DALY 2.60E-04 ± 1.90E-05). After this period the risk decreases, making the tertiary level of treatment unnecessary. Similarly, regarding the reuse for street cleaning and declogging of sewers, as well as for industrial purposes, even though a significant reduction in the risk of infection would be observed after possible pathogen reduction during tertiary treatment, the water treated without a tertiary step did not pose any high risks beyond the recommended tolerable risk figures, except for the droplet ingestion route of exposure (2.40E-03 ± 3.80E-03). Therefore, to protect the exposed workers, the use of face masks and gloves could potentially reduce or even eliminate these risks, thereby reducing the need for a tertiary treatment process. In contrast, tertiary treatments are highly recommended for crop irrigation. Despite the associated benefits of agricultural reuse of treated WW, the risks of infections (considering only secondary treatment) for the two exposed populations, were high. For instance, consumption of vegetables irrigated under this condition may result in the risk of infection of 5.80E-02 ± 3.30E-03, and DALYs of 1.80E-02 ± 9.30E-05.

Considering the risk of infection estimates from our study and depending on the intended reuse, the secondary treated WW meets the standard for health protection. Therefore, the cost of adding a tertiary treatment process could be avoided in municipalities where treated water is not used for irrigation purposes, and the discharge or reuse of secondary-treated WW is adequate. To increase the use of recycled water and its feasibility, the government efforts are necessary through the elaboration of public policies encouraging this practice, as well as greater acceptance by the population, farmers, and industry. Microbial risk assessments should be carried out to determine the real risk of contamination from recycled water, which may help in overcoming the barriers that hinder the extensive use of this valuable resource.

Declarations

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Figures

Figure 1

System boundaries of microbiological risk assessment and economic feasibility methodologies

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