Wastewater collection system failures in a capital city: analysis and sustainable prevention

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ABSTRACT

An analysis of failures in a capital city's wastewater collection system was carried out and recommendations were made for sustainable preventive measures based on a risk of failure assessment. Most failures in sewer lines were associated with blockage caused by sediment accumulation and clogging from fats, oils and/or grease dumped by restaurants along several streets, combined with poor or nonexistent maintenance of the lines. Sewer lines in streets with higher risk levels due to multiple food establishments along those streets experienced most of the failures. Sustainability of the proposed maintenance was evidenced since it reduces costs and exposure to harmful substances and hazardous conditions as well as minimizing environmental impacts.

Key words | fats, oils and/or grease, risk of failure assessment, sediment accumulation, sewer lines, sustainable preventive maintenance, wastewater collection system failures

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HIGHLIGHTS

- Wastewater collection system failures.
- Sustainable preventive measures.
- Sediment accumulation and clogging from dumped fats, oils and/or grease.
- Sewer lines in streets with higher risk levels due to multiple food establishments along those streets experienced most of the failures.
- Sustainability: reduces costs, exposure to harmful substances and hazardous conditions, and minimizes environmental impacts.

LIST OF ABBREVIATIONS

CoF	Consequence of failure
FOG	Fats, oils, and/or grease
LCC	Life cycle cost
LoF	Likelihood of failure
RoF	Risk of failure
SSO	Sanitary sewer overflow or sewer system overflow
WASA	Water and Sewerage Authority of Trinidad and Tobago
WWCS	Wastewater collection system

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INTRODUCTION

Having a reliable and continuous water service system for domestic potable water or industrial cooling water (Ambrose *et al.* 2008; Khurana 2017; Lee *et al.* 2017; Marquez *et al.* 2020a) is as important as being able to count on a wastewater collection system (WWCS) that is reliable and operates round the clock. Both domestically and in a manufacturing facility there is a need to minimize disruptions due to WWCS failures that can affect everyday life, have health effects and cause costly plant shutdowns.

In WWCSs, several failure modes can take place. Sewer system overflows or sanitary sewer overflows (SSOs), in which raw sewage spills from sewer lines, are extremely common and of great concern in many places (Selvakumar *et al.* 2014; Wastewater Collection Systems Best Management

Practices 2016; Wastewater Collection System Toolbox 2017; Sanitary Sewage Collection System Study Guide 2018). Some of the reasons SSOs are blockages caused by the accumulation of sediments, the generation of large amounts of untreated waste ending up in the collection points and the dumping of fats, oils and/or grease (FOG) into the sanitary drains by food establishments that end up in sewer lines. SSOs can create many undesirable effects, including traffic disruptions, build up of volatile/flammable/toxic gases, public exposure to harmful substances (liquids/solids), and health-related illnesses (skin and eyesight irritations/allergies, respiratory tract affections, dizziness, acute headaches, loss of sense of smell, disorientation, fever).

Similar to a risk-based inspection method (Roberge 2000; Marquez *et al.* 2021), where plant equipment can be prioritized for inspection, preventive maintenance based on risk of failure (RoF) assessment can be implemented to ensure the continuous operation of a WWCS. The assessment can identify the components of a WWCS that can be focused on for inspection and/or maintenance, as well as the places a WWCS runs higher risks (e.g., streets, avenues, roads, highways, neighborhoods, industrial estates). Numerous studies have dealt with WWCS failures (Selvakumar *et al.* 2014; Operation and Maintenance of Sewer and Drainage System 2016; Laakso *et al.* 2018a; Balacco *et al.* 2020; Maximize Sewer System Lifespan 2020). Some works, events and studies have dealt specifically with the risk-based assessment of WWCSs. (Rita *et al.* 2007; Salman & Salem 2012; Rossi 2015; Bhasar Dasari 2016; Snyder & Associates 2020)

It is definitely advantageous to pursue the sustainable operation of a WWCS, since ensuring sustainability is extremely important in several technologies and processes in numerous applications for industrial estates and for domestic purposes (Marquez *et al.* 2020b). This work presents an analysis of systemic failures that occurred at several locations in a WWCS in a capital city over a 3-year period, and a recommendation for sustainable preventive measures based on RoF assessment. Some pictures of the failures in main sewer lines along several streets of the WWCS are shown. In addition, the most relevant results of the RoF analysis on several streets are reported, along with a cost analysis to compare preventive and emergency maintenance strategies.

METHODOLOGY

Port of Spain, the capital city of Trinidad and Tobago, where the study was carried out, has a downtown area population of about 49,000 (The World Bank 2019; Central Statistical Office 2020). The area has many restaurants/fast food places as well as mobile food stands or food cars, numerous street vendors, businesses (commercial, retailers, hardware, appliances, clothing stores), government offices, large buildings, some hotels and heavy traffic during rush hours. Figure 1 shows a map of Port of Spain on which the zone under study (downtown and part of the surroundings) is outlined. Several streets, avenues, and roads, including Ariapita Avenue, Tragarete Road, Park Street, Maraval Road, Independence Square Street, and a popular park, Queen's Park Savannah, can be distinguished.

All the failures of the WWCSs reported in this work for a 3-year period are restricted to the delimited area. The Water and Sewerage Authority of Trinidad and Tobago (WASA) is the official institution authorized to handle all domestic water servicing distribution and WWCSs in the country. For this study, the Wastewater north west section was the specific branch of WASA from which all data and failure information was gathered. This WWCS section was designed to handle around 30,000 m^3 of sewage on a daily basis. It has a total sewer line length of about 270 km, with diameters ranging from 12.5 cm to 170.0 cm. The sewers are buried at about 2–4 m (up to 7 m depth in some cases) (WASA).

The WWCSs in Trinidad and Tobago carry only sanitary waste. Therefore, for illustration purposes, in Figure 2 a schematic of typical independent sanitary sewer collection and distribution system components (a WWCS without rain drainage lines) is shown (Department of Public Works). It can be seen that the main components of an uncombined WWCS (Department of Public Works; Wastewater Treatment Plant 2002; State of Technology for Rehabilitation of Wastewater Collection Systems 2010) are private service laterals (Department of Public Works) from the points of origin, a local (Department of Public Works) main sewer line, manholes, and regional trunk sewer lines (Department of Public Works). Usually, the main sewer lines that suffer a number of failures are installed under streets (discussed later). The manholes allow the entry of maintenance personnel and can be also used to change the direction of the wastewater flow and to interconnect main sewer lines to other main sewer lines and/or to trunk sewer lines. These lines are also prone to different kinds of failures. All sewer lines analyzed in this work are referred to as *gravity sewer pipes* (Department of Public Works; Wastewater Treatment Plant 2002; State of Technology for Rehabilitation of Wastewater Collection Systems 2010; R. Tanaka Mark Thomas and Company Inc. 2014; Laakso *et al.* 2018a; Wastewater Snyder & Associates 2020).

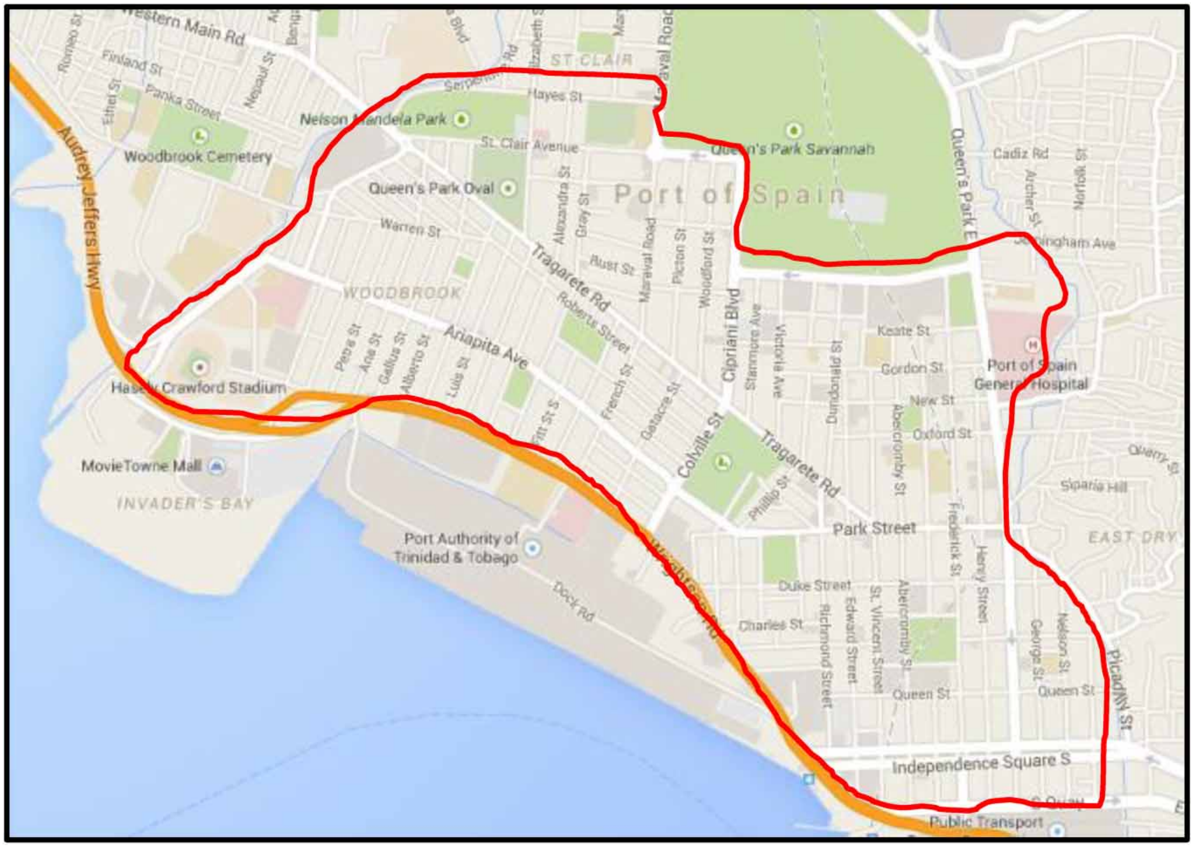


Figure 1 | A map view of downtown Port of Spain (Google Maps). The area under study is outlined.

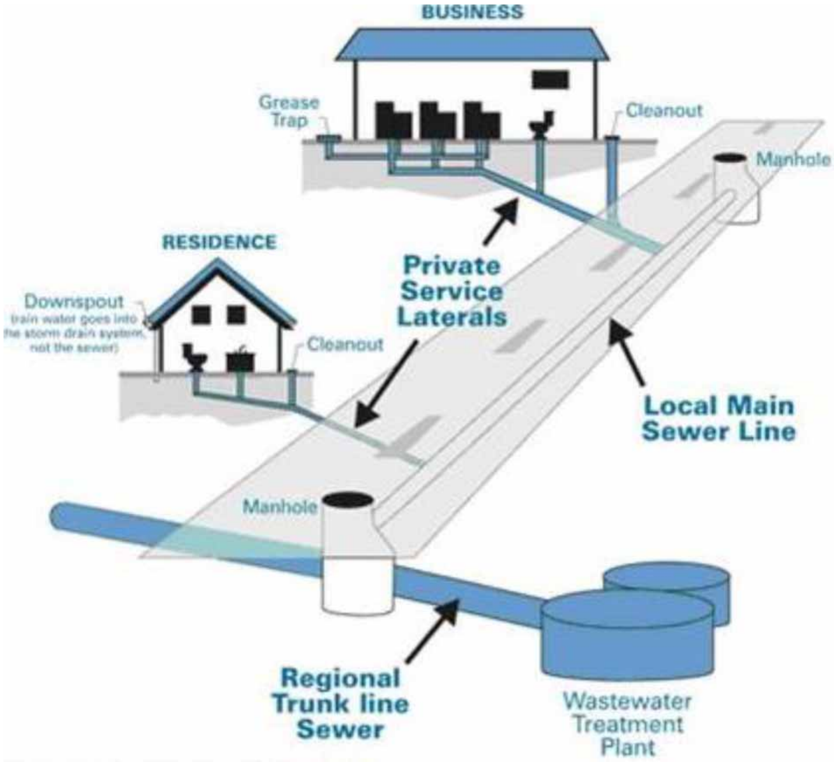


Figure 2 | Sanitary sewer collection and distribution system components (Department of Public Works).

Numerous failures in different components of the WWCS have been encountered in the area under study. About 520 of these failures were well documented. The vast majority (around 450 failures) occurred on main sewer lines under different streets in downtown Port of Spain. These failures are analyzed in more detail in this study.

Failure determination/identification

The root cause of each failure is determined by WASA maintenance personnel (Water & Sewerage Authority of Trinidad and Tobago (WASA) during the corrective/emergency activities to remediate failures on sewer lines and during occasional visual inspection using closed circuit television (CCTV) equipment. Different types of root causes (Nelson *et al.*; Chughtai & Zayed 2008; Laakso *et al.* 2018a; Mohammadi 2019; Balacco *et al.* 2020) are reported in this study. The more common and repeated failures occurring in main sewer lines include sediment accumulation, dumping of FOG by food establishments, and dumping of foreign objects. Other less frequent root causes that took place in main sewer lines during the same 3-year period were pipe sag, leaking sewer joints, and root intrusion. In terms of failures in manholes, environmental conditions, temperature, and unprotected surfaces were the most common root causes.

Each root cause induced several sewer line failure categories (Nelson *et al.*; Chughtai & Zayed 2008; Laakso *et al.* 2018a; Mohammadi 2019; Balacco *et al.* 2020). In this study, three failure categories are considered: hydraulic restrictions (blockages), reduction of hydraulic capacity, and structural failure. These failure categories created different kinds of failure modes or end results (Nelson *et al.*; Chughtai & Zayed 2008; Laakso *et al.* 2018a; Mohammadi 2019; Balacco *et al.* 2020), ranging from the well-known and most common failure, SSO, to manhole-related failures and cavities on roadways. Each failure mode can produce undesirable effects for the public, infrastructure and other effects. The specific effects of each failure mode are addressed in the Results and Discussion section.

All data collected for the failures reported in this work was provided by the personnel of WASA north west section. Video footage and stills, using CCTV equipment where a camera is inserted into the sewer pipe and remotely operated by a technician inside a truck, was obtained for part of the WWCS north west section (mostly for the streets/areas with more frequent failures) (WASA).

Risk of failure assessment

To identify the streets in the downtown area of Port of Spain (refer to Figure 1) where sewer lines are more susceptible to failure, a risk-based approach was used. Furthermore, similar to a previous study (Marquez *et al.* 2021), risk is defined as 'a combination of probability and consequence. Probability is the likelihood of a failure occurring, and consequence is a measure of the damage that could occur as a result of the failure (in terms of injury, fatalities, and property damage' (Roberge 2000)*, as well as environmental and social impacts)*. Thus the RoF, the likelihood of failure (LoF) and the consequence of failure (CoF) were estimated by using the procedures detailed below. For both LoF and CoF five values/categories from 1 to 5 were assigned to quantify the degree of severity/priority (Stewart 2016; Risk-Based Structural Integrity Management of Offshore Jacket Structures 2017; Marquez *et al.* 2021).

Likelihood of failure

In this study five factors related to physical parameters and environmental impacts: pipe material and age, pipe depth, vehicular traffic, distance from restaurants, and soil type (Nelson *et al.*; Chughtai & Zayed 2008; Rossi 2015; Laakso *et al.* 2018a) were used to calculate the LoF. Each factor was subdivided into six values/categories ranging from 0 to 5, depending on the degree of severity/priority considered. In addition, for each factor a weight fraction was applied to account for the influence of each factor on the estimation of the LoF (Nelson *et al.*; Chughtai & Zayed 2008; Rossi 2015; Laakso *et al.* 2018a). The ranges for the factors were determined and tailored according to their characteristics and values, the nature of the variables and the criteria for the priority of risk if a WWCS failure occurred. The details involved in the determination of each LoF factor, with the respective weight fraction indicated in parentheses, are summarized below.

i. *Pipe material and age (0.3):* More than 50% (WASA) of the sewer lines in Port of Spain (and throughout the country) are made of concrete. A small percentage are made of clay (WASA). Therefore, in this study it is reasonably considered that the WWCSs in downtown Port of Spain are made of concrete. The WWCSs in Trinidad and Tobago are reported to have been constructed/installed between 35 and 60 years ago (with an average age of around 48 years) (WASA). Considering that concrete sewer lines have an estimated average lifespan of 65 years (American Concrete Pipe Association n.d.; Life Cycle

Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials 2017), within a range between 42 and 52.5 years with an average age of 48 a value of 4 was assigned for this factor. Some examples of other values for this factor are: for 0–10.5 years a value of 0 would be assigned, while a value of 5 would be assigned for concrete sewer lines between 52.5 and 65 years old (Nelson *et al.*; Chughtai & Zayed 2008; Rossi 2015; Laakso *et al.* 2018a). Consequently, all streets in the downtown Port of Spain area in this study will have a value of 4 based on the pipe material and age factor (see Table 1).

ii. *Pipe depth (0.2):* For this factor there is a combination of probabilities of failure. Both sewer pipes that are buried a few metres underground and those that are deeper can have high probabilities of failure. Sewer lines buried (along streets) at shallow depths are subjected to dynamic loading, mainly due to traffic. On the other hand, those buried at greater depths are under higher pressure exerted by the soil/land/construction above, which may weaken the structure and cause breakages leading to failures. For this study, shallow lines will be those buried between less than 1.0 m to 3.5 m underground, with pipe depth factor values of 0 for depths within 3.0 m to 3.5 m and 5 for those at less than 1.0 m of depth. Deeper sewer lines will refer to those buried 3.5 m down or more, with assigned factor values of 0 for depths less than 3.5 m and 5 for depths greater than 5.5 m. Table 1 indicates a factor value of 5 for the pipe depth for Wrightson Road, which is buried at about 7.0 m (WASA), with a factor value of 1 for Ariapita Avenue, with pipes buried at about 2.5–3.0 m (WASA), and a factor value of 1 for pipes at Woodford, which are buried at about 2.5–3.0 m (WASA).

iii. *Vehicular traffic (0.1):* For this factor, an average traffic count was obtained from the Ministry of Works and Transport (http://www.mowt.gov.tt). The Ministry regularly measures vehicular traffic along several streets during rush/peak hours (6:00 a.m. to 9:00 a.m. and 3:00 p.m. to 5:00 p.m.), using standard devices employed worldwide in which every vehicle driving over a wire triggers a count, with no distinction between the type/weight of vehicles. Vehicular traffic causes vibrations on the streets, and combined with the pressure exerted on the pipes based on the depth factor, increases the probability of sewer line failures. For traffic averaging more than 2,500 vehicles per day at peak rush hour, a value of 5 is assigned for this factor. For traffic counts averaging fewer than 500 per day, a factor value of 0 is assigned. Table 1 shows the values for the three representative downtown Port of Spain streets in this study. For instance, Ariapita Avenue was assigned a value of 3 from an average vehicular count of about 1,822 a day, corresponding to peak rush-hour traffic of between 1,500 and 2,000 per day.

iv. *Distance from restaurants (0.3):* It is expected that the proximity to restaurants increases the probability of failure in any sewer line. The majority of food establishments discharge significant amounts of FOG into the sewage if they do not have any kind of FOG removal or pretreatment device installed and/or operating adequately. Moreover, other types of organic leftovers and dirt from washing supplies also enter the sewer lines if not separated and/or treated properly, which is the case for most food establishments in many cities. In this study a factor a value of 5 is assigned for any sewer line buried under a street closer than 120 m to a restaurant, perhaps meaning that one or more food places are located on that street. A factor value of 0 is given if a sewer pipe is located more than 600 m away from a food establishment. Table 1 indicates that Wrightson Road has a value of 4 since it is located approximately 120–240 m to the nearest restaurant(s). Woodford Street has a value of 2 for being within 360–480 m from any food place.

v. *Soil type (0.1):* soil type also has an influence on the LoF of a (buried) sewer line. Soil particles that are more unstable and/or less compacting to act as supports for sewer lines present a higher threat to the destabilization

Table 1 | Lof and CoF (Nelson *et al.*; Chughtai & Zayed 2008; Rossi 2015; Laakso *et al.* 2018a) estimation for main sewer lines along three representative streets in downtown Port of Spain

Factor (weight fraction)[a]/LoF, CoF	Wrightson Road[b]	Ariapita Avenue	Woodford Street
Pipe material and age (0.3) *(LoF)*	4	4	4
Pipe depth (0.2) *(LoF)*	5	1	1
Vehicular traffic (0.1) *(LoF)*	5	3	0
Distance from restaurants (0.3) *(LoF)*	4	5	2
Soil type (0.1) *(LoF)*	3	3	3
LoF	**4.2**	**3.5**	**2.3**
Distance from commercial areas (0.4) *(CoF)*	5	5	5
Vehicular traffic (0.2) *(CoF)*	5	3	0
Distance from watercourses (0.4) *(CoF)*	5	3	1
CoF	**5.0**	**3.8**	**2.4**

[a] The weight fraction values assigned for each factor are explained in the text.
[b] Wrightson Road contains a (buried) trunk sewer line (refer to Figure 2).

and movement of sewer pipes. Common soil types encountered and considered in this study in decreasing order of support for sewer lines (McDonald & Zhao 2001; MultiQuip 2011) with respective factor level indicated in parentheses are: sand (5), gravel (4), alluvium (3), loam (2), silt (1), and clay (0). Within the northern range of Trinidad and Tobago in which the city of Port of Spain falls, the predominant soil type is alluvium (Brown & Bally 1966). Alluvial soils or river estate soils are derivatives of river alluvium and consist of a combination of fine sandy loams mixed with sandy clay loams (Faizool 2002). All sewer lines (streets) in this study have therefore been assigned a factor value of 3 (Table 1).

Consequence of failure

The CoF was obtained by considering three factors, related to environmental and social impacts: distance from commercial areas, vehicular traffic and distance from water sources. Similar to the estimation of LoF, each factor is subdivided into six values/categories, ranging from 0 to 5, which depend on the degree of severity/priority considered. Also, for each CoF factor a weight fraction is applied to represent the influence that each factor has on the estimation of the CoF (Nelson *et al.*; Chughtai & Zayed 2008; Rossi 2015; Laakso *et al.* 2018a). Similar to the LoF, the ranges for the factors were determined and tailored according to the characteristics and values for each factor, the nature of the variables, the consequences and the criteria for priority of risk if a WWCS failure occurred. The determination of each CoF factor with the respective weight fraction indicated in parentheses is summarized next.

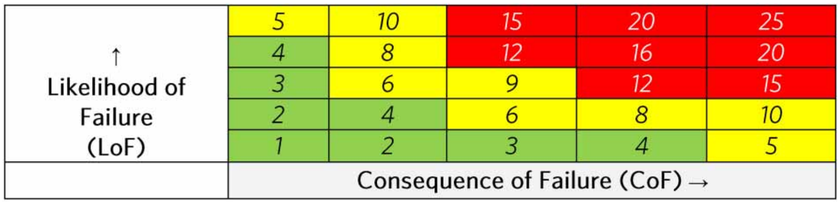
i. *Distance from commercial areas (0.4):* As mentioned in the first part of the methodology, the downtown Port of Spain area has many businesses of several kinds which will be significantly impacted if a sewer line fails. Thus the pipes buried along streets located more than 500 m away from the nearest commercial places are assigned a factor value of 0. Those located less than 100 m from any business will have the highest factor value of 5. The three representative streets were assigned a value of 5 for this factor (Table 1).

ii. *Vehicular traffic (0.2):* For the estimation of this factor in the CoF, the approach previously described in the determination of vehicular traffic for the LoF is used. Thus, the same value (3) for this factor for the three streets in this study is shown in Table 1. The only difference is the weight fraction (0.2) (Nelson *et al.*; Chughtai & Zayed 2008; Rossi 2015) assigned for this factor in the calculation and the consequences for the CoF. A failure in a sewer line along a street with heavy traffic will definitely cause severe traffic disruption and congestion in addition to inconvenience to the public.

iii. *Distance from water sources or watercourses (0.4):* It is also expected that bodies of water of any kind (rivers, lakes, creeks, sea coast, lagoons) will be severely impacted if a sewer line fails and the raw sewage enters such waters. Maraval River to the west, St. Ann's River on the east, and the Caribbean Sea to the south are the three bodies of water that are close to Port of Spain. Therefore, in this study a sewer line located more than 1,700 m away from any of those bodies of water will have a factor value of 0, whereas a (sewer line) street located closer to 340 m will be assigned a value of 5. Table 1 shows the respective values for Wrightson Road (5, closer to the Caribbean Sea), Ariapita Avenue (3, located between 680 m and 1,020 m from the nearest body of water), and Woodford Street (1, which is between 1,360 m and 1,700 m away from the nearest body of water).

Risk of failure

Finally, the RoF was determined from the 5 × 5 matrix in Figure 3 by using the LoF and CoF values. Each institution/organization establishes the priorities and levels of risk according to their criteria addressed in a previous work (Marquez *et al.* 2021) and other studies (Stewart 2016; Risk-Based Structural Integrity Management of Offshore Jacket Structures 2017). In this study, an RoF level higher than 10 is considered as major/severe and needs to be



↑ Likelihood of Failure (LoF)	5	10	15	20	25
	4	8	12	16	20
	3	6	9	12	15
	2	4	6	8	10
	1	2	3	4	5
	Consequence of Failure (CoF) →				

Figure 3 | LoF vs. CoF 5 × 5 risk matrix used to obtain the risk levels for the sewer lines along several streets in downtown Port of Spain.

prioritized (major level values are indicated in the top right-hand corner, Figure 3). This is reasonable as a WWCS failure tremendously affects people's routines, public health, and infrastructure. It also causes major traffic disruptions and other undesirable consequences. A level of risk between 5 and 10 (>5 and ≤10) is considered as having medium priority (pale squares in Figure 3), while and RoF less than 5 will have low priority of risk (bottom left-hand corner, Figure 3).

The RoF results for some of the sewer lines/streets are presented in the Results and Discussion section. It is worth mentioning that for other sewer lines (buried along streets) in downtown Port of Spain, the same procedure for estimating the LoF, CoF and then calculating the RoF was followed step by step.

RESULTS AND DISCUSSION

Failure analysis

Table 2 shows the failures reported for a 3-year period in main sewer lines at several streets located in downtown Port of Spain. About 520 failures of the north west section WWCS were reported (an average of about 173 failures per year), undoubtedly a high number. Most were SSOs,

Table 2 | Main sewer lines failures at several streets in downtown Port of Spain

Failure root cause[a]	**Quantity**	**Failure category**[b]	**Failure mode**[c]
Sediment accumulation	200	Hydraulic restriction[d]	SSO
Dumping of FOG by restaurants	113	Hydraulic restriction	SSO
Several[e]	63[f]	Several[g]	Offensive odor
several[h]	45	Reduction in hydraulic capacity	SSO
Dumping of foreign objects	39	Hydraulic restriction	SSO
Environmental conditions/temperature/unprotected surface[f]	20	N/A[i]	Manhole seating corroded
Environmental conditions/temperature/unprotected surface[f]	16	N/A[i]	Manhole cylinders corroded
Several[j]	15	Structural failure	Cavity on roadway
Pipe sags	12	Hydraulic restriction	SSO
Environmental conditions/temperature/unprotected surface[f]	11	N/A[i]	Manhole rungs corroded
Environmental conditions/temperature/unprotected surface[f]	11	N/A[i]	Manhole invert corroded
Leaking sewer joint	07	Hydraulic restriction	SSO
Several[k]	07	N/A[i]	Manhole invert poorly constructed
Root intrusion	04	Hydraulic restriction	SSO
Theft	04	N/A[i]	Manhole frame and cover absent

[a] The origin/primary failure cause.

[b] The failure that a root cause provokes.

[c] The end result/consequence of a (category) failure.

[d] Hydraulic restrictions are more commonly referred to as blockages.

[e] May include sediment accumulation and dumping of FOG, among others.

[f] 49 failures categorized hydraulic restrictions; the rest (14) categorized as either absence of ventilation or improper or insufficient ventilation. Thus, in this table, the 49 hydraulic restrictions for offensive odor are subtracted from the total number of failures during the 3-year period (about 520).

[g] May include hydraulic restrictions, absence of ventilation, or improper/insufficient ventilation.

[h] May be due to excessive inflow or infiltration, pipe deformation or inadequate slope.

[i] Not applicable.

[j] May include cracks or fractures along the wall of the sewer main, misaligned or offset sewer joints, poorly constructed WWCS, deterioration of sewer main due to internal/external surface material loss.

[k] May include absence of standardized design and construction specifications, inadequate training of wastewater personnel.

with about 420 failures (or around 80%). These were mostly caused by sediment accumulation (200 failures or about 38% of the total 520 failures), and dumping of FOG by food establishments (113 failures or about 22% of the total failures reported). All failures triggered emergency interventions and repairs. Figures 4, 5(a) and 5(b) depict three SSO-related failures that took place in main sewer lines along three streets in downtown Port of Spain. These were due to dumping of FOG by food places and by sediment accumulation, respectively. Moreover, in sewer lines along five streets in downtown Port of Spain, among them Frederick Street, Ariapita Avenue, and Maraval Road (Figure 1) about 142 failures were reported for the 3-year period, most of them caused by dumping of FOG by restaurants.

Sewer system overflows

Having SSOs too often (which is unfortunately the case in this study) can cause dramatic/severe and even catastrophic effects. Some of those effects might be as follows.

Raw sewage entering homes and/or businesses and/or bodies of water, and/or sewage flooding roadways. The risk to citizens are of developing respiratory and skin illnesses, having nausea and headache symptoms, and even vomiting. The damage caused to bodies of water may be long lasting or permanent, affecting not only aquatic life but consumers of water if the affected body of water is a reservoir.

Figure 4 | Hydraulic restriction (blockage) failure along Henry Street, downtown Port of Spain, caused by the solidification of FOG; it caused an SSO, needing an emergency intervention to be cleared (still from CCTV footage WASA).

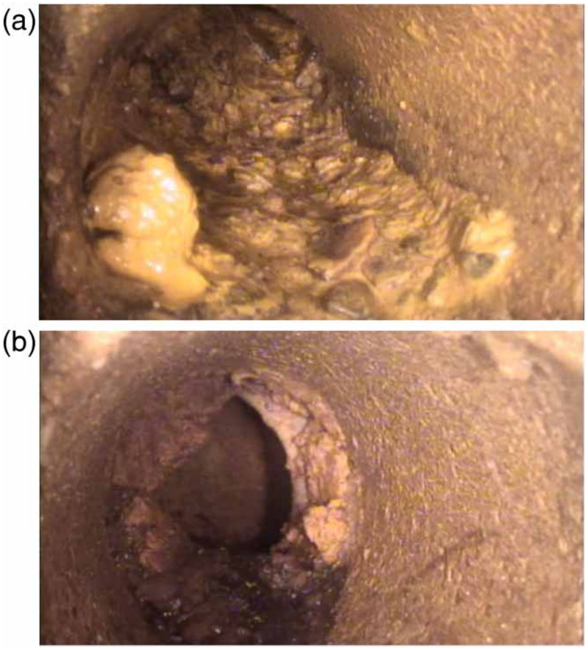


Figure 5 | (a) Sediment accumulation failure within a main sewer line in Independence Square Street, downtown Port of Spain; (still from CCTV footage WASA). (b) Another main sewer line failure due to sediment accumulation, this time along Duke Street, Port-of-Spain (still from CCTV footage WASA). In both cases, the sediment accumulation caused SSOs that needed to be cleared by emergency interventions. Sediment accumulation may solidify inside sewer lines in some instances, aggravating the failure and increasing the time needed for removal/clearing.

It has to be pointed out that the specific effects caused by the SSO failures and the other failure modes reported in this study for the 3-year period were not disclosed by the authorities.

There were around 45 reported failures due to either excessive inflow/infiltration (Wastewater Treatment Plant 2002; Damvergis 2014; Wastewater Collection System Toolbox 2017; Mohammadi 2019; Balacco *et al.* 2020), pipe deformation and inadequate slope causing a reduction of hydraulic capacity failure (Mohammadi 2019) triggering SSOs (Table 2). Figure 6 shows an example of this type of failure in a street in downtown Port of Spain. Infiltration in a sewer line may originate, for example, from the pipe breaking, or defects/deformations in the pipe, or from a manhole cover having defects or being absent, which, in combination with excess flow (during the rainy season) might induce SSOs. This failure mode can be exacerbated if the main sewer line diameter is too narrow.

Figure 6 | CCTV still showing excessive infiltration in the sewer line along Park Street, Port-of-Spain (still from CCTV footage WASA). It eventually caused an SSO, leading to an emergency intervention as well.

As was mentioned in the methodology, sewer lines throughout Trinidad and Tobago have diameters between 12.5 cm to 170.0 cm, and the specific pipe diameters of main sewer lines installed in downtown Port of Spain are uncertain. WASA has not evaluated the hydraulic capacity of the WWCS in downtown Port of Spain and possibly the whole country. The WWCSs is between 35 years and 60 years old (the case in many places/countries Selvakumar *et al.* 2014; Rossi 2015; Gong *et al.* 2016; Laakso *et al.* 2018b; Balacco *et al.* 2020; Maximize Sewer System Lifespan 2020). Since the population has steadily grown it is very likely that the WWCS of the north west section under study does not meet the current expectations/capacity requirements of the sewage flow (it will tend to worsen if it is not expanded or overhauled). The designed capacity of 30,000 m^3 is probably being overwhelmed.

Offensive odor failure modes

There were about 63 failures of this type. They can be triggered by either blockages (hydraulic restrictions), or absence of ventilation, or improper/insufficient ventilation (Table 2). Their root causes may involve, as for SSOs, sediment accumulation and FOG clogging. The effects may include exposure to harmful/toxic/nauseous gases, release of flammable gases which may in turn be fire hazards, respiratory illnesses, nausea, vomiting, dizziness, headaches, and even death if the gas (or one of the gases) happens to be hydrogen sulfide (H_2S), even at low concentrations (a few ppm) and during a few minutes of exposure.

Manhole-related failure modes

There are an estimated 1,694 manholes within the area under study (WASA). Table 2 shows that around 69 failures (or about 13%) associated with manholes were reported for the 3-year period of the study. About 57 failures were related to corrosion in different parts of manholes for sewer lines along several streets in downtown Port of Spain. Corrosion-type failures were expected due to the severe environmental conditions in the country established in a previous study (Marquez *et al.* 2020a). Some manhole covers and frames were not in place due to theft, which is unfortunately, fairly common in many places. These are sold mainly for the scrap value of cast iron. These manhole failures may cause damage to vehicles as well as injury to pedestrians (people could fall in). Manhole failures can also be a source of infiltration, allowing foreign objects into the sewer line and triggering other failures e.g., reduction in hydraulic capacity.

Cavity on roadway failure mode

There were few (15 failures, about 3%) related to cavities on roadways (Table 2). These can have several causes: cracks or fractures along the wall of the sewer main, misaligned or offset sewer joints, poorly constructed WWCS, or deterioration of sewer mains due to the loss of internal/external surface material. In turn, these create weakening that eventually compromise the integrity of the pipe, causing structural failures, e.g., breaking/collapse of a sewer line. These can cause damage to infrastructure and vehicles and injury to pedestrians.

Preventive measures

The very nature of such repetitive failures in Port of Spain's WWCS over the 3 years of study convincingly indicated that too often the public as well maintenance workers/labourers were exposed to some extent to harmful substances/conditions, traffic disruptions were created (added to the interference in other daily activities) and that such failures involved emergency interventions that proved to be costly (see Cost analysis section below).

From the most common types of failures, it is completely clear that human activities, regular sewage discharge, restaurant effluents, combined with poor maintenance (or perhaps lack thereof in most instances) are the main cause of the WWCS failures in downtown Port of Spain. Since population growth and development is unstoppable all over the world (Trinidad and Tobago's capital city is definitely not an exception), it can be inferred that a preventive, aggressively active and sustainable maintenance practice at WASA needs to be implemented to successfully minimize repeated and undesirable WWCS failures in the capital city. Public education and awareness must also be implemented for important issues such as installing and operating some kind of FOG removal or pretreatment device at restaurants that may help in the foundation of a reduction-oriented FOG program. That will enhance the sustainability of the maintenance practice and will make it more effective as there will be less waste ending up in sewer lines.

A comprehensive plan for encouraging the use of FOG removal or pretreatment devices must be implemented. Currently, WASA does not enforce the use of any FOG removal or pretreatment device for owners of food restaurants and most of the food places that have such devices do not have them properly installed or operating. The cases of other cities such as Sacramento and Davis in California USA, with downtown populations of 66,622 and 75,000 respectively (Department of Utilities 2014; City of Davis 2017) must serve as examples for applying a reduction-oriented FOG program.

Risk of failure analysis

Table 3 contains the results of the RoF analysis performed at several sewer lines along some streets in downtown Port of Spain. It must be pointed out that, to limit the study because there was plenty of data collected, failures associated with *trunk* sewer lines were not addressed. The LoF, CoF and then RoF for one road containing a trunk line, Wrightson Road (Tables 1 and 3) is included to emphasize the importance of keeping such sewer lines operative with preventive and sustainable maintenance. Wrightson Road has an RoF score of 21 since it is located in close proximity to the Caribbean Sea and to commercial areas, has heavy traffic (it is sort of a highway) and it is relatively close to restaurants (Table 1). Main sewer lines discharge into trunk sewer lines, which then transport the sewage to the wastewater treatment plants (see Figure 2). Any failure in trunk sewer lines, especially SSO-related, will therefore be catastrophic.

Other streets in downtown Port of Spain, such as Independence Square Street, Ariapita Avenue, Frederick Street, and Maraval Road, were assigned scores higher than 11, which also makes these of higher priority. All of the main sewer lines in those streets are located close to food establishments (or, multiple food places are located on the streets). Most of these streets presented a high number of failures due to dumping of FOG in the sewer lines, as it was the case for Frederick Street, Ariapita Avenue, and Maraval Road.

A preventive maintenance practice focused on the streets with higher risk levels can certainly be implemented every 2 months (Table 2). Some of the maintenance activities that can be carried out and that are already being performed sporadically and without real organization and planning by WASA's north west section are: inspection of manholes, servicing of manholes, raising of manholes and inspection of the WWCS with the use of CCTV equipment (preventive servicing on a sewer line was reported to be rarely performed) (WASA).

Table 3 | RoF and maintenance for main sewer lines along several streets in downtown Port of Spain

Main sewer line/street	RoF level[a]	Preventive maintenance interval[b] (months)
Wrightson Road[c]	21	2
South Quay	14	2
Independence Square Street	14	2
Charlotte Street	14	2
Ariapita Avenue	13	2
Tragarete Road	12	2
Mucurapo Road	12	2
Cipriani Boulevard	11	2
Frederick Street	11	2
Maraval Road	11	2
Woodford Street	6	18

[a] Determined from Figure 3, rounded to the nearest integer (some LoF and CoF values are shown in Table I).

[b] The recommended maintenance frequency of 2 months for streets with RoF scores higher than 10 (high priority) has been estimated from the average time that a WWCS failure occurred during the 3-year period considered in this study. From the data available (WASA), it was estimated to be around 1.8 months, therefore 2 months for the minimum interval time would be adequate. The 18-month recommended maintenance interval for streets with RoF scores between 0 and 10 (low and medium priority) was taken from the longest time that it took an (SSO-related) failure to occur at a street/main sewer line out of all failures considered in this study.

[c] Wrightson Road contains a (buried) trunk sewer Line (refer to Figure 2).

Performing preventive maintenance every 2 months, including flushing of the sewer line (by using sewer jetting equipment noted in the cost analysis section), on those streets with higher risks will ensure a more sustainable maintenance practice. The maintenance personnel are commonly exposed to some harmful/toxic substances and/or hazardous conditions every time they clear an SSO-related sewer line failure during an emergency intervention. Through regular maintenance, the maintenance personnel will be less exposed to hazardous conditions since the amount and possibly the concentration of raw sewage will be lessened (also less waste to manage and dispose of). The public will be less exposed to some extent to those conditions as well, and potential environmental impacts will be significantly reduced because less waste would be flooding the streets.

It is recommended in this study to emphasize the need for practicing strict safety procedures during any maintenance activity. Proper personal protective equipment (PPE), including self-contained air supply equipment, should be used at all times since a sewer line and a manhole can be considered as confined spaces where there could potentially be a reduction in the concentration of oxygen. Measuring the concentration of toxic/lethal gases (such as H_2S and carbon monoxide, which can be fairly common at sewer lines due to sanitary waste decomposition) (Sanitary Sewage Collection System Study Guide 2018) before servicing, and monitoring those gases during the maintenance activity, must be enforced. These steps will make the sustainability of the preventive maintenance servicing even more robust.

Cost analysis

A basic life cycle costs (LCC) analysis (Fuller 2005; 2011; Jules Kere 2017; Kowalski *et al.* 2017; Marquez *et al.* 2020a) was included in this study to compare the economics of the preventive maintenance program and the emergency clearing intervention currently in place when a failure occurs in the WWCSs in downtown Port of Spain. The LCC analysis was performed using a discount rate of 1.80%, a 15-year lifespan and the equation and procedure described in a previous study (Marquez *et al.* 2020a). The sources for the values of all costs, relevant data and other details are indicated in Table 4. In Figure 7 are shown the results of the discounted and normalized cumulative LCC (Marquez *et al.* 2020a) for the most relevant scenarios considered in the analysis involving both alternatives.

Since it was clearly proven that the vast majority (80%) of sewer line failures are associated with SSOs, mostly due to sediment accumulation (38%) and dumping of FOG by food establishments (22%), the recommended preventive practice alternative in the LCC analysis is focused on servicing a sewer line with the use of minimum equipment, including sewer jetting and water tanker equipment as well as the respective labour personnel (craftsman I and supervisory level personnel in Table 4). Even though (WASA) a single craftsman I and supervisory personnel can perform preventive maintenance by operating the minimum equipment (one of the scenarios considered in this study), it is also recommended (in another scenario, Figure 7) that two craftsmen I should be present at all times, to ensure a safer operation and enhance the sustainability of this preventive maintenance alternative.

Table 4 | Costs (US$) associated with both maintenance alternatives for SSO failures

Cost/characteristic	**Preventive servicing**	**Emergency clearing/ remediation**[a]
Equipment 1 (sewer jetting) cost/work day[b]	441	441
Equipment 2 (water tanker) cost/work day	103	103
Equipment 3 (jitney) cost/ work day	–	75
Equipment 4 (trench pump) cost/work day	–	29
Labour cost/work day (craftsman I)[c]	54	54
Labour cost/work day (supervision)[d]	80% labour	80% labour
Labour cost/work day (craftsman II)[e]	–	57
Labour cost/work day (craftsman III)[f]	–	62
Overtime rate/work day[g]	–	116

[a] Emergency intervention to unblock an SSO failure mode.

[b] The work day cost refers to the fact that (as it has been reported by WASA) it may take an entire day or less to perform the maintenance activity. It is similar in all alternatives and scenarios, for ease of comparison.

[c] Craftsman I's rate (https://www.labour.gov.tt).

[d] The supervision cost corresponds to 80% of the total labour cost (WASA; https://www.labour.gov.tt). It may involve in some instances more than one supervisory personnel, depending on the severity and consequences of the WWCS failure (WASA).

[e] Craftsman II's rate (https://www.labour.gov.tt).

[f] Craftsman III's rate (https://www.labour.gov.tt).

[g] An overtime rate (https://www.labour.gov.tt) is applied to the three labour personnel involved in any emergency intervention lasting more than a day. After that, the supervisory costs are determined (the same 80% (WASA; https://www.labour.gov.tt) of the total labour costs).

Moreover, the preventive maintenance being performed currently (inspection of manholes, servicing of manholes, raising of manholes, and inspection of the WWCS with the use of the CCTV equipment) would reasonably be considered to involve a similar cost to the use of the minimum equipment and the respective personnel. Manhole-related failures totaled only around 69 failures (13%), as mentioned earlier. Thus, their contribution to affecting the costs of the recommended preventive maintenance alternative and appreciably altering the results and conclusions inferred in the analysis can be considered negligible.

In this study, from the preventive servicing alternative, the total cost of adding the minimum equipment used as well as the labour cost of one craftsman I and the respective supervisory personnel (Table 4), multiplied by the average of 173 failures per year during the 3-year period amounts to around US$ 111,272 per year. This has been taken as the

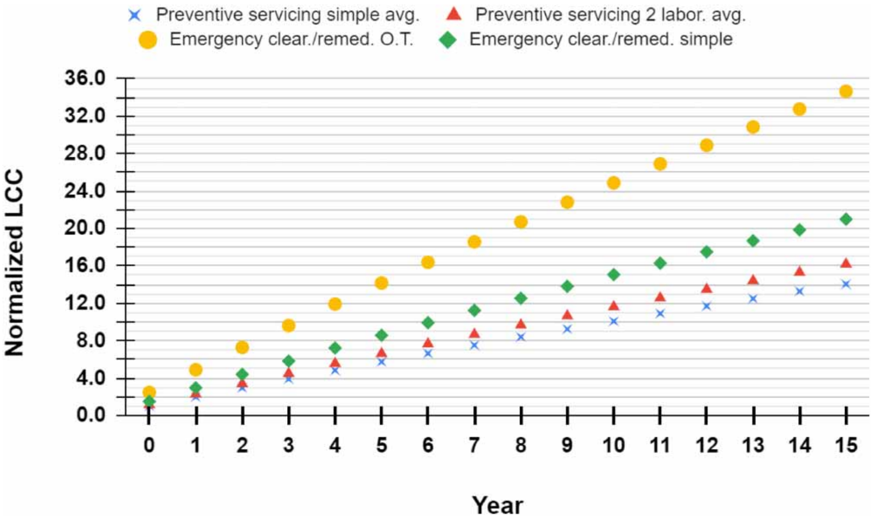


Figure 7 | Cumulative discounted and normalized LCC for four scenarios, two for each maintenance alternative. The 'simple' for the preventive maintenance indicates that one craftsman I is included in the scenario, while 'avg.' stands for the average 173 WWCS failures per year that took place in the 3-year period of this study. The '2 labor. avg.' means that two craftsmen I are included and the same average of 173 failures per year are considered. On the other hand, for the current emergency intervention alternative, the 'clear./remed.' stands for clearing/remediation; while 'simple' means a regular work day cost; and, 'O.T.' indicates overtime costs are included.

cost basis for normalizing all discounted LCC costs. Although not obvious in Figure 7 because of the scale of the graph to cover all data shown, it is the reason for the value of 1.0 for the first year of the LCC scenario 'preventive servicing simple avg.'

Considering the average of 173 failures per year for the preventive maintenance alternative it would be more than sufficient to estimate the cost associated with performing routine maintenance with minimum equipment which would imply the highest cost related to this alternative. The 173 average failures number would imply 173 work days (see Table 4), more than the half (182.5 days, or about 6 months of servicing) of 365 days of a regular year. Servicing most or even all of the streets in downtown Port of Spain with high risk levels every 2 months does not add up to the 173 times of work days of preventive servicing (173 servicing times per year would mean about 28–29 streets being serviced every 2 months). Thus, these costs for the preventive servicing alternatives have been overestimated.

Regarding the cost incurred during the emergency interventions currently in place to unblock sewer lines when and SSO failure mode occurs, it has been reported (WASA) that it involves, in addition to the minimum equipment and personnel involved in the preventive maintenance alternative one craftsman II, one craftsman III and the use of additional equipment such as a jitney and a trench pump (see Table 4). Thus, for the two scenarios of the current emergency interventions (Figure 7) the average of 173 failures per year are definitely considered since those are *real costs that most likely have already been incurred by WASA*. In fact, it has been reported (WASA) that in some cases, due to the severity of the failure, maintenance personnel were repairing the failure for more than a day and overtime costs (another scenario, Figure 7) were even incurred. Therefore, the costs for the emergency interventions have been conservatively underestimated.

It must be pointed out that all the equipment involved in both alternatives is commonly used in these types of activities in sewer line maintenance/remediation elsewhere (Wastewater Treatment Plant 2002; R. Tanaka Mark Thomas and Company Inc. 2014; Wastewater Collection Systems Best Management Practices 2016; Operation and Maintenance of Sewer and Drainage System 2016; Nielsen 2019). Also, the cost of the use of CCTV equipment is not included/considered in this study as it was not disclosed. Nevertheless, it would imply a similar cost for both alternatives.

In Figure 7, it can be *clearly seen that the preventive servicing scenarios will always be more cost effective than any emergency intervention*, even from year 1 (not that noticeable) and including two craftsmen I (for safety purposes). The scenario where the preventive servicing involves two craftsmen I goes from about 1.2 times the cost of the simple average preventive servicing scenario (taken as the cost basis) in year 1 to about 16 times that cost basis in year 15. Furthermore, the emergency intervention scenario involving only regular work day costs starts from being around 1.5 times the cost basis (not noticeable) in year 1 to about 21.0 times in year 15. *For year 3* that emergency scenario with regular work days is about 5.8 times, *which means that WASA's north west section has already cost, at the very least, more than US$ 667,000* (5.8 times US$ 111.272, the cost basis). In year 3, the preventive maintenance with two craftsmen I is 4.5 times the cost basis, which is less (25% lower) than the 5.8 times the cost basis for the emergency scenario with the regular work day. Therefore, still including two labour personnel in the preventive maintenance alternative is more cost effective than the emergency intervention during a regular work day, even from year 1.

The real cost already paid by WASA's north west section to remediate the around 520 total WWCS failures reported for the 3-year period of study in downtown Port of Spain is even more. It has been reported by the same WASA section that due the nature and consequences of the failures which needed to be remediated promptly, most emergency interventions involved overtime for the personnel. Thus, the scenario considering such overtime costs goes from being already high in year 1 (2.5 times the cost basis) to about 35.0 times in year 15 (or around US $4.0 million). That is a very high cost if the failure rate per year continues (around 173 failures/year), extrapolating to the 15-year lifespan in the LCC analysis. In *year 3* the overtime emergency intervention scenario meant about 9.0 times the cost basis *or around US$ 1.0 million that WASA's north west section has most likely already spent in the 3-year period of the study*. It has been clearly demonstrated that preventive servicing will enable much lower costs and a sustainable practice.

CONCLUSIONS

An analysis of the systemic failures in the WWCS of a capital city was carried out. A sustainable preventive maintenance practice was recommended after performing a risk-based assessment in sewer line failures along streets in the area of study. Furthermore, a life cycle cost analysis to compare the economics of the current emergency interventions to remediate failures to the economic feasibility of the proposed preventive maintenance was performed. It was clearly determined that most failures in main sewer lines were associated with SSOs predominantly due to sediment accumulation or clogging by FOG dumped by food establishments located on several streets, combined with lack of regular maintenance of the sewer lines. The sustainability of the proposed preventive maintenance servicing has been substantially proven. It combines cost savings, fewer disruptions to daily life, enhancing the wellbeing of the population, and implies less waste will be generated that will need to be disposed of. It also provides a reduced and better controlled exposure of the workers to harmful substances and hazardous conditions, as well as lessening potential environmental impacts. This work also highlights that encouraging public awareness in the implementation of a reduction-oriented FOG program, including the use of FOG removal or pretreatment devices, is extremely beneficial, making the overall scope of sustainability even more robust. Additionally, the need for periodic maintenance practices executed in WWCSs to guarantee their uninterrupted operation is emphasized.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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