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Operational and structural diagnosis of sewerage and drainage networks in Côte d'Ivoire, West Africa

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In Cote d'Ivoire, the failure of urban sewage systems is a crucial problem for the drainage of wastewater and rainwater. This failure is due to many factors and therefore, calls for diagnostic studies. The present study aimed at analyzing these networks in order to identify the different factors that contribute to the operational and structural degradation in selected sewerage and drainage networks in Abidjan, Cote d'Ivoire. The method used in the study involved semi-structured interviews, video camera inspection and socio-environmental field surveys (geographical survey and household survey), followed by descriptive statistics. The results revealed that many structural, environmental and behavioral practice contribute to the progressive degradation of urban sewage systems. These factors are essentially those that prevent the normal flow of wastewater in the pipes such as the illegal dumping of solid waste, the unauthorized connection of wastewater networks, unsustainable urban agricultural practices, as well as the high concentration of vegetation on both sides of the network and the dilapidated infrastructure of the wastewater and rainwater networks. It was found that these factors are at the origin of the clogging and degradation of the sewers since 85% of the residents used these sewers as a dumping ground for solid waste.

KEYWORDS

urban sewerage systems, malfunction factors, structural factors, anthropogenic factors, drainage systems

1. Introduction

Sewerage systems consist of a set of hydraulic components including pipes, manholes, sumps, pumping stations, retention basins, and various control structures. Their function is the collection and proper disposal of wastewater to a treatment plant or to an appropriate discharge location (Saagi et al., 2016; Raj et al., 2018).

Various studies show that in recent years most urban sewage systems (USS) are in a precarious state (Bengassem, 2001; Ashley et al., 2015), especially in the major Sub-Saharan African cities.

These studies demonstrate that the level of deterioration of these infrastructure, in general, has reached such a critical level that the costs of restructuring and rehabilitation are growing exponentially and that the networks require significant efforts to restore them to working conditions (Mohammadi et al., 2019). The investments needed to rehabilitate and restructure the urban sewage systems in Sub-Saharan Africa, are in the range of billions of US dollars (Sebti et al., 2014). For example, in 2013–2014 period, South Africa invested the amount of 596,121,000.00 Ran or EUR 46,075,561 for the rehabilitation and reconstruction of sewerage systems (Philippe and Pablo, 2014). Different levels of government need to reinvest huge sums, if they are to bring sewage and water systems back to an acceptable level of operation (Rehan et al., 2014). Thus, from the 1st years of operation, preventive maintenance remains one of the most effective means of preserving the integrity of the infrastructure, ensuring their sustainability and thus delaying major rehabilitation and reconstruction works (Bengassem, 2001).

In sub-Saharan Africa, most large cities such as Maroua in Cameroon, Lagos, Accra, and Jonesburg have a real problem with the management of sanitation systems, particularly sewage and drainage systems (Ndongo et al., 2015; Capps et al., 2016). The city of Abidjan (Côte d'Ivoire), like most of the large African metropolises, is not immune to the problems linked to the degradation of urban sanitation networks (Lazare et al., 2017). Already after its independence, in 1969, this megalopolis experienced a terrible flood with its corollary of diseases and various inconveniences (Gnagne et al., 2015). Following this unfortunate event, a sewage network was built between 1975 and 1986 (Anonym, 2012). This network consists of a main sewer and secondary sewers in the different municipalities of the city. The main sewer was designed to carry all the wastewater from the different districts directly into the Atlantic Ocean (Anonym, 2012). In Abidjan, half of the networks are more than 30 years old and their extension rate is < 3% per year since 1980 (Coulibaly et al., 2016). It is evident that a management logic is mainly focused on the need for maintenance and that investments in rehabilitation will occupy a significant part of municipal budgets in the coming years (Kangah and Della, 2015; Ouattara et al., 2021).

There are several causes for the degradation of urban sanitation systems and the most important are age, operational, physical and environmental factors, urbanization, and inefficient management practices, as well as unsustainable practices of the population toward the network (Mohammadi et al., 2019; Tuo et al., 2019; Atambo et al., 2022). With urbanization, for example, the quantity of wastewater (effluents) to be evacuated is increasingly important, causing structural and functional failures (Koffi et al., 2012). These situations, which are responsible for several disorders such as backflow into basements and streets, inflow/infiltration and street collapse, render the network unable to fulfill the functions for which it was designed (Gnagne et al., 2015). Moreover, any postponement of interventions related to the rehabilitation of these networks will have a major impact on their sustainability and the quality of services (Ouattara et al., 2021). In this context and in view of these challenges, developed rehabilitation programmes are needed to maintain sanitation services at an acceptable level of performance. An approach based on planning and sustainable development of resources is therefore essential.

Unfortunately, in the current context, most decisions are still made on the basis of the specific expertise of a few people and on considerations based on the expression of political, economic, social, environmental or other interests (Elachachi et al., 2006). This, sometimes, often leads to objective, in some cases intuitive, decisions as to the best course of action.

However, it should be stressed that the success of a rehabilitation programme relies on a good knowledge of the network and its problems which defines the diagnostic study (Blindu, 2013). The best conditions for an effective rehabilitation programme, both technically and economically, are offered by elaborate diagnostic studies where the performance is thoroughly assessed for each component of the sanitation system (Saagi et al., 2016). It should be noted that the performance of an urban sanitation system generally has two aspects, one operational and the other structural (Mugume and Butler, 2017). Most of the assessment methods used, assign a score based on the severity of the degradation found and the risk of its evolution over time, so that pipe sections with a score below the tolerance threshold will be critical and prioritized for rehabilitation (Anbari et al., 2017). Although many cities around the world have their own rehabilitation management systems, diagnostic studies are often limited to structural and operational aspects based on closed circuit television (CCTV) inspections and do not take into account the poor behavioral practices of residents living on both sides of the network, especially in sub-Saharan African cities (Yang et al., 2017). Some cities systematically investigate infiltration/exfiltration while others with overflow problems turn to hydraulic simulation models so as to correct these situations (Anbari et al., 2017). The analysis of current practices shows that there are structured and fully satisfactory methods capable of making a diagnosis of the sewage system that integrates hydraulic, structural aspects but not including the anthropogenic aspects.

In order to meet the needs of urban sewage system managers in sub-Saharan Africa, particularly in Abidjan, we propose a diagnostic methodology to ensure a better knowledge of these systems. This methodology assigns a structural and operational performance rating to each component. The evaluation of these performance ratings takes into account the state of degradation of the network components, the relative importance of these degradations and the different interactions between the constituent sections of the network, their environment and a set of factors likely to amplify these degradations or their impacts. The parameters characterizing the operational and structural performance of the network are defined. The aim of this work is to make an operational and structural diagnosis of the sewerage and drainage network in the city of Abidjan in order to determine the potential areas of deterioration in the network. The study will equally develop intervention and rehabilitation plans for a better drainage of wastewater. This diagnosis will enable institutions such as the Water Distribution Company in Côte d'Ivoire (SODECI) and the National Office of Sanitation and Drainage (ONAD), which are in charge of wastewater and rainwater management in the Abidjan area, to undertake interventions as quickly as possible to avoid the total destruction of the networks. This intervention will be beneficial and economical for these institutions insofar as it will minimize the costs of rehabilitation.

2. Materials and methods

2.1. Study area

Abidjan is the economic capital of Côte d'Ivoire. It is located in the south of the country between latitudes 5°00' and 5°30' North and longitudes 3°50' and 4°10' West. It covers an area of 577.35 km^2 of which 89.81 km^2 is a lagoon, i.e., 16% of the surface area (Koffi et al., 2012). With an estimated population of 4,693,912 inhabitants (INS, 2014), it comprises 10 municipalities. This city has a 2,000 km separate sewage network.

Yopougon municipality, which is the study area, is bounded to the north by the Banco forest, to the south by the Ebrié lagoon, to the east by the Attécoubé municipality, and to the west by the Songon municipality (Figure 1). More precisely, it lies between latitudes 5°16' and 5°27' North and longitudes 3°21' and 3°32' West. Yopougon covers an area of about 153, 06 km^2 with a population of 1,071,543 inhabitants (INS, 2014).

The base collector, ~25 km long, runs from the municipality of Abobo to the municipality of Port-Bouët where it ends up in the Atlantic Ocean over 1.2 km *via* an outfall. The internal network of

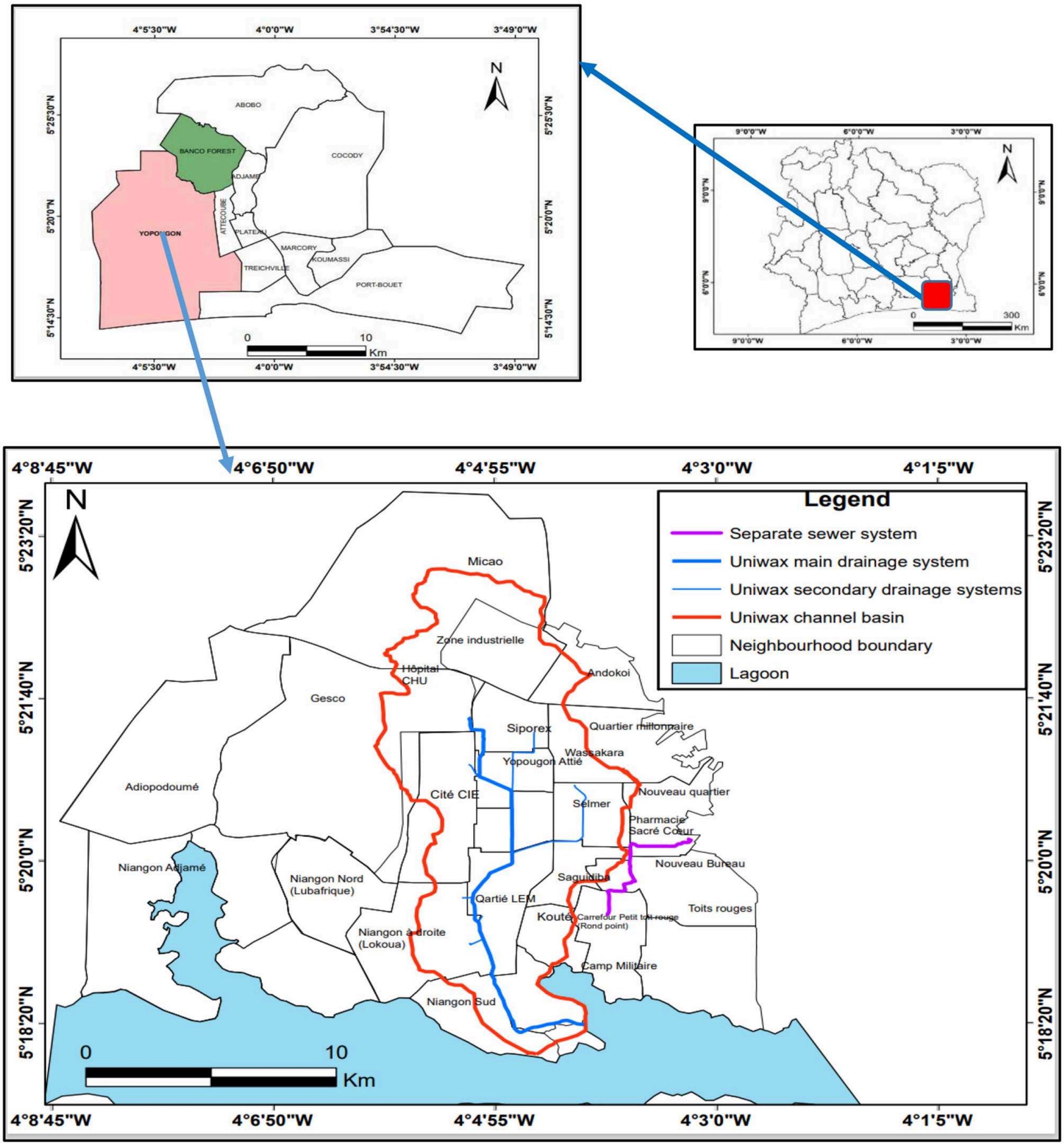

FIGURE 1
Geographical location of Yopougon municipality in Abidjan.

the Yopougon municipality connects the effluents directly into the lagoon and into the environment because it is partially damaged. Except for the Yopougon network, the transport of wastewater in the first two networks is facilitated by the provision of pumping and lifting stations on their route. Figure 2 shows the topography of the land for the installation of pumping stations or lifting stations to

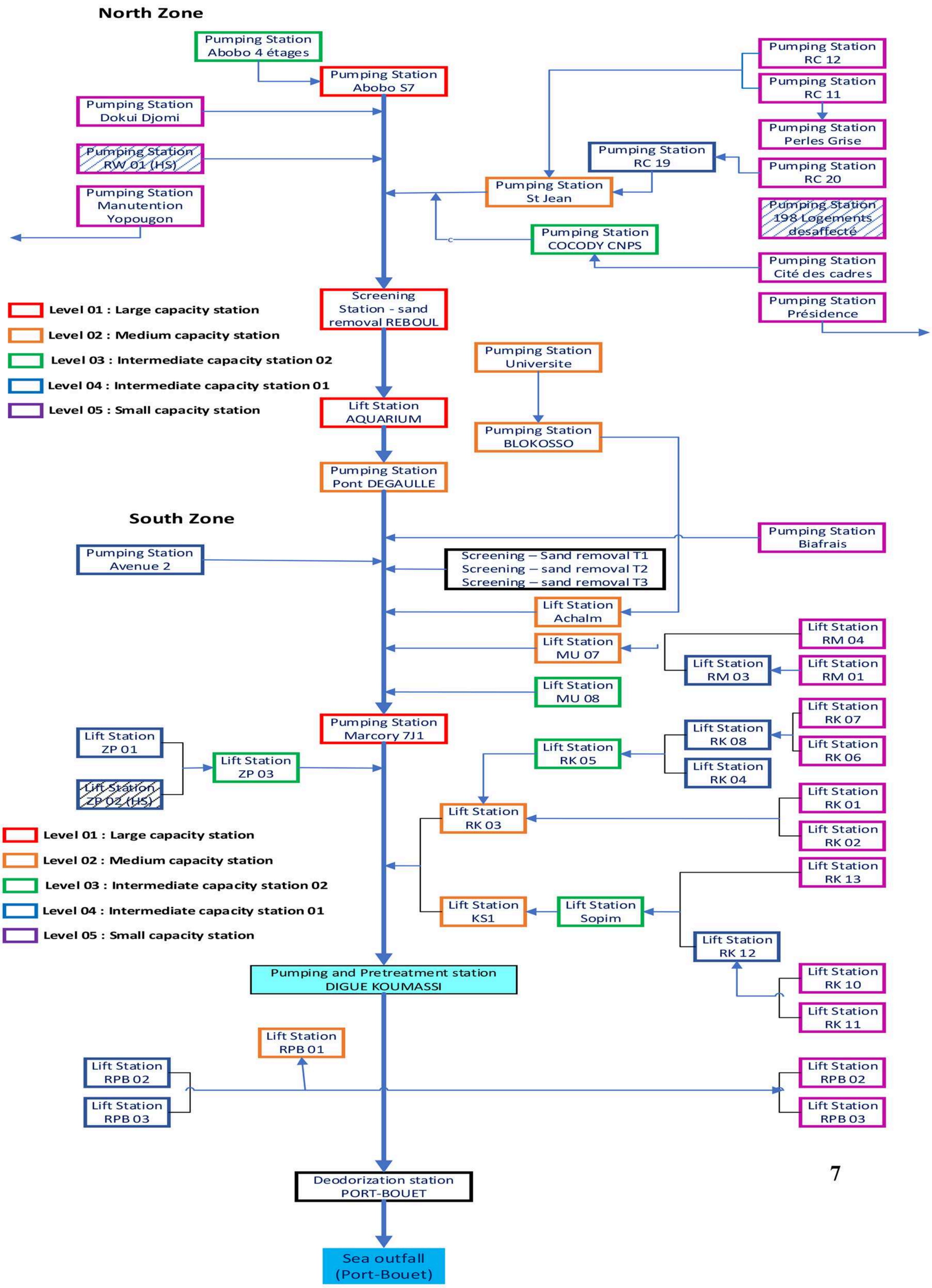

FIGURE 2
Overall operation of the Abidjan city collector.

enable all the effluent to be evacuated to the sea after prior treatment. The first station (station S7) is located upstream in Abobo, and the last station (station 7J1) is located in Port-Bouet; the collection of wastewater is therefore done from Station S7 and routed to station 7J1 where it is discharged into the sea after treatment. Throughout the city, there are 56 stations, 2 of which are not operational. The DeGaulle station allows wastewater to be pumped from Abidjan North to Abidjan South. In Abidjan South, we have a total of 37 stations, 1 of which not operational, and 19 in Abidjan north, 1 of which is also not working. Presently, the number of population connected to the base collector are estimated at 849,300, i.e., 26% of the capacity of the structure. The areas that are connected to the main sewer currently have an estimated wastewater production of 2.19 m^3/s while the current capacity of the treatment plant installed at the outlet of the main sewer is 1.82 m^3 /s, indicating a gap. While the plant should be over-used, it is still operating below its capacity. This indicates a poor connection policy to the main sewer. For the characterization of the urban sewerage networks in the city of Abidjan, the choice was mainly focused on the 21/22 collector and Uniwax drainage system in Yopougon. The number of households connected to the 21/22 collector is 28,460 through connections. As for the Uniwax drainage system, 91,126 households are connected directly to it from upstream to downstream. These two collectors have an important role in the collection of wastewater and rainwater in this area as they represent 28.2% of the volume of liquid waste collected in Yopougon municipality

Collector 21/22 is a 5.65 km long underground sewer network located in the Yopougon Nouveau quartier. It starts from the Lama Fofana district in Sideci Iroko at the Saint François roundabout (Figure 3A). It crosses several districts which are: Lama Fofana, Denver, Sans Loi, Nouveau Bureau, Camp Militaire, and Sideci Iroko. The main sewer has a uniform diameter of 800 mm from upstream to downstream and is constructed with different materials, which are cement, concrete and PVC. The secondary collectors, which are the wastewater inlets, have a diameter of 200 mm. The various secondary sewers are mostly perpendicular to the main sewer. The wastewater flows from Lama Fofana to the Saint François roundabout where it discharges into a large open channel, which then flows into the Ebrié Lagoon. The main sewer comprises a total of 85 manholes. The maximum distance between two consecutive manholes is 50 m.

As for the Uniwax drainage system, it is a combined sewer system that carries both wastewater and stormwater and it is mostly constructed with reinforced concrete. It is also located in the municipality of Yopougon and has a length of 9.79 km with widths varying between 17 and 22 m in different sections (Figure 3B). It has an open network in most of its parts, but some places are however underground; this is the case of the portion going from the Lycée Technique de Yopougon to the Banco 2 bridge. The network starts at the industrial zone of Yopougon toward the BAE Bridge and crosses several districts which are the industrial zone, the cité Abdoulaye Diallo, Banco 2, Siccogi Aimé Cesaire, Siccogi, Yaosehi, Gbinta, Kpimply, Azito, and Beago where the water is discharged directly into the Ebrié lagoon without any treatment. In this channel, wastewater and rainwater flow in the direction of the industrial zone to Beago where the lagoon is located. Several branches are observed on the network and constitute important water inlets as the wastewater increases volume in the network.

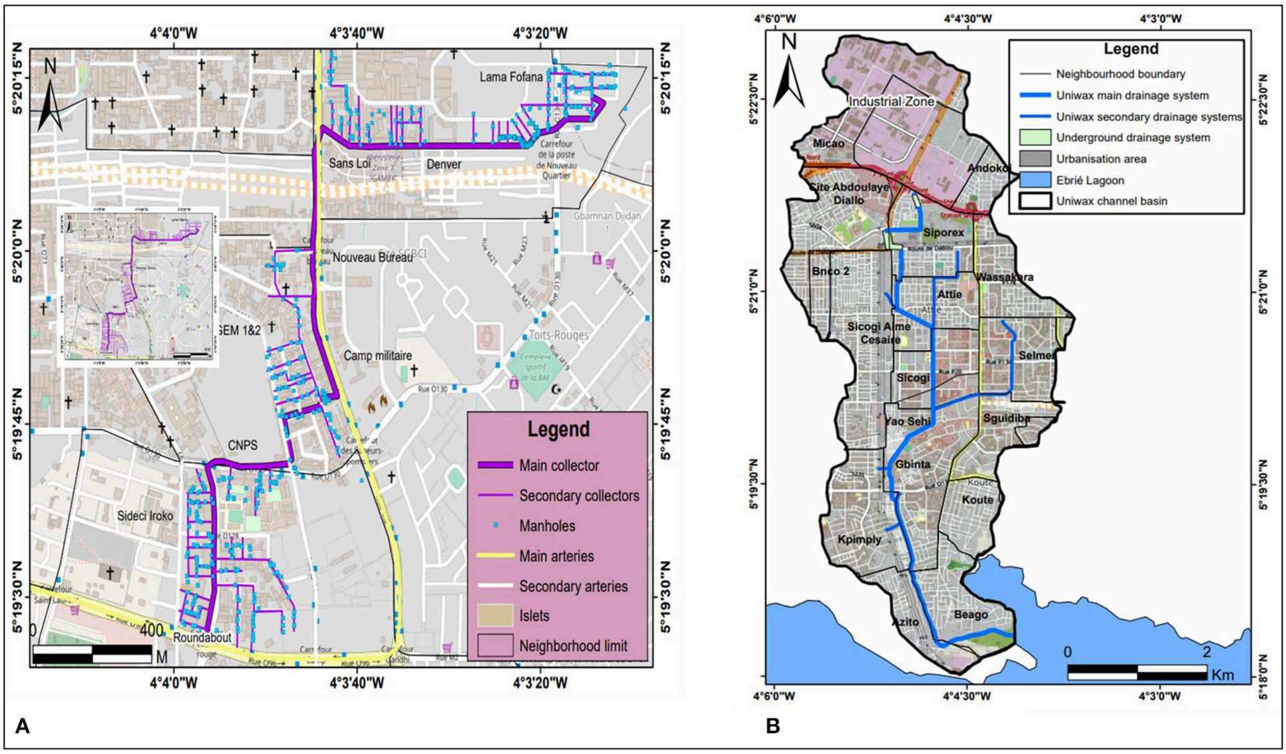

FIGURE 3
Geographic location of the **(A)** 21/22 collector and **(B)** Uniwax drainage system.

2.2. Characterization of the base collector of Abidjan, 21/22 collector and the Uniwax drainage system

In this research work, the 21/22 collector of Nouveau quartier in Yopougon was selected and has not been systematically studied since 1975. As for the Uniwax drainage system, previous studies have been carried out on the system, but these studies were limited to the characterization of the wastewater. The analysis was based mainly on interviews and field surveys, namely: semi-structured interviews, direct field observation of the state of operation of the wastewater and storm drains, geographical survey and a survey of the inhabitants of the district, using a systemic approach to assess the state of the sewage system over the last decades. A video camera survey was also carried out to identify structural factors. The methodology was successfully applied to two sewers in the city of Abidjan, Cote d'Ivoire. Figure 4 below illustrates the methodology used in this work.

2.2.1. Semi-structured interviews

The different semi-structured interviews took place from 24 November 2020 to 18 January 2021. The institutions involved were the Ministry of Sanitation, the Water Distribution Company of Cote d'Ivoire (Sodeci), the Directorate of Urban Waste and Drainage (DAUD), the National Office of Sanitation and Drainage (ONAD), the Projet d'Amenagement de la Baie de Cocody (PABC) the Management Unit of the Guru Watershed Development and Integrated Management Programme (UGP), the Priority Works Programme (C2D), the National Office of Technical Studies and Development (BNETD), the sanitation department of the Ministry of Construction and Urban Planning (MCU), the technical services of the District of Abidjan, and the municipality of Yopougon. These interviews were carried out in order to know and understand the global functioning of the sanitation systems in general and in particular, the basic collector of the city of Abidjan as well as the sewage networks of Yopougon and the Uniwax canal. They also helped in the identification of problems related to the functioning and the main role played by each actor. Besides, they assisted in the acquisition of a cartographic database of the various wastewater and stormwater networks in the city of Abidjan, in particular the Yopougon municipality.

2.2.2. Field observation and geographical survey

The field observations was conducted during two different periods of the year. The first phase occurred during the dry season

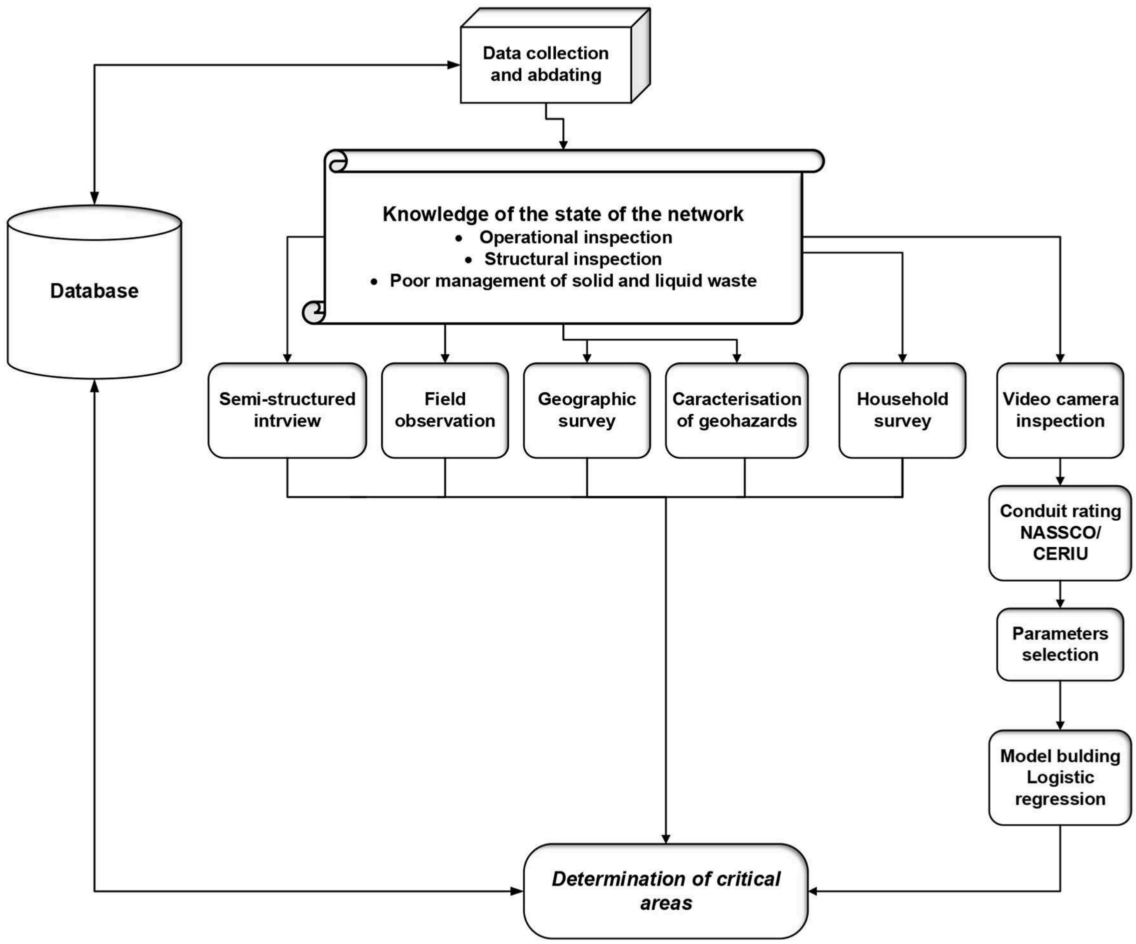

FIGURE 4
Methodological framework used to the diagnosis of Uniwax networks and the 21/21 collector.

in March 2021. The second phase was conducted during the rainy season in June 2021. This process involved exploring all the areas concerned with a digital camera, to capture images of environmental problems found, a notepad to record all the problems observed and a GPS receiver to record the precise positions of the environmental problems found. Also, this step assisted in the observation of the different forms of waste around the sewerage systems, the morphology of the dysfunctional areas, the state of the wastewater and stormwater drainage infrastructures as well as the management of household waste, wastewater and urban activities in the different neighborhoods located along the networks.

This approach aided in the understanding of the environmental problems studied, which were then used for the elaboration of the data sheets of the geographical survey. During this phase, data on the reaction of the population and the representatives of the neighborhoods to the manifestation of the problems linked to the degradation and the failure of the systems was collected.

The geographical survey was carried out after the final definition of the dysfunctional factors to be taken into account in the assessment of the degradation phenomena. It was the main technique used to collect environmental data. It is a precise method for describing the actual situation in a specific location at a given time (Kablan et al., 2019). Like direct field observations, the geographical surveys were carried out in two phases:

The first phase was carried out during the months of February and March 2021 during the main dry season and concerned surveys related to structural and anthropogenic dysfunctions of sewage systems and stormwater networks. For the sewage systems, the survey concerned six neighborhoods of the Yopougon municipality Nouveau quartier (Lama Fofana, Denver, Sans Loi, Nouveau Bureau, Camp Militaire and Sideci Iroko). As for the Uniwax network, which is a rainwater network, nine neighborhoods were investigated (Cité Abdoulaye Diallo, Banco 2, Sicogi Aimé Cesaire, Sicogi, Yao Séhi, Gbinta, Kpimply, Azito, and Beago). On the basis of pre-established technical survey sheets, this particular exercise consisted of assessing the state of degradation of the sanitation systems. Also, using a GPS and a 100 m metric tape, the survey consisted of walking along the entire length of the networks and locating the exact position of all the factors that are at the root of the network's degradation, after which their dimensions (length, width, height, radius, or diameters, etc.) and their volumes were recorded. The second phase of the geographical survey was carried out in June 2021 during the rainy season and after the rainfall. It involved the concepts related to network dysfunction, overflow flooding and sanitation deficits. It, thus, helped in the description of the actual state of the environmental parameters causing network failure and overflow floods which impact on the living conditions of the population.

In order to describe the sanitary situation of the dysfunctional areas along the systems and to assess the behavior of household waste during rainfall and flooding, household waste was selected as the most relevant environmental parameter. The volume of solid wastes as well as its distance to the nearest drainage system was measured. After the household waste surveys, the investigations focused on other parameters such as uncontrolled connections of wastewater networks, urban agriculture, commercial activities on both sides of the networks and the behavior of the residents toward the management of the systems. The last parameter measured was the structural or anthropogenic dysfunction of the drainage system. It was examined in order to determine the presence of domestic waste and to assess its capacity to evacuate wastewater and rainwater. The measurement of environmental parameters was recorded on a pre-established data sheet, which was designed based on information obtained from previous field visits. A GPS receiver was used to take the coordinates of the points concerned and a 100 m metric tape was used either for the estimation of the volume of garbage or for the distance of the garbage to the drainage network. The estimation of the volume was possible by determining the length, width and height of the garbage dump. For the distance of the garbage dump from the drainage system, a simple measurement from the drainage system to the garbage dump was carried out. For the smooth running of the field operations, four surveyors were trained beforehand and explored all the areas concerned in the study so as to fill the survey datasheets. The interviewers were supervised by the principal investigator of the study to ensure that standard procedures were followed.

2.2.3. Household survey

The term "household" means the set of families in a concession that share the same storage and disposal facilities for liquid waste i.e., household wastewater and excreta (Bede and Gilles, 2018). The purpose of the household survey was to collect information on the characteristics of the households, the mode of management of liquid and solid waste by the residents. The questionnaire focused on the perception of the functioning of the different sanitation facilities by the inhabitants of the area.

The method used is the on-site questionnaire at the respondent's residence where the interviewer helps the respondent to fill in the questionnaire. The first phase of the survey was carry out from 25 June to 15 July 2021. The second phase carry out in February 2022. The survey involved all social classes, including modest level of literacy, and this was considered in order to take into account of equity in the choice of households. It involved all persons in the household who were 18 years of age or older in order to obtain reliable information. Thus, the survey form was structured in two (2) main sections: Section 1 was focus on identification and characterization of the household. This part marks the contact with the surveyed household. It assisted in the assessment of the living conditions of the households, some socio-economic characteristics of the households and their link with sanitation. The Section 2 dealt with the situation of sanitation in the household, management of sanitation facilities and their contents. This section of the questionnaire was subdivided into two main parts. The first part helped in highlighting the management mode of liquid and solid waste in relation to the sanitation facilities by the population, while the second part identified the different perceptions of the inhabitants on the functioning of the networks, to have an idea of the content of the facilities and their management mode according to the type of habitat.

The method used to determine the size of the sample to be interviewed was stratified simple random sampling with proportional allocation (Statistics Canada, 2010). It was determined from the following formula.

$$n = \frac{z^2 P\,(1-P)}{\left(\frac{z^2 P(1-P)}{N} + e^2\right)} \quad (1)$$

Where:

n: is the minimum size of the population sample to be interviewed;

Z^2: is the desired confidence level. With a confidence level of 95%, $Z = 1.96$;

P: is the proportion of households assumed to have the desired characteristics. This proportion varies between 0.0 and 1. It is the probability of occurrence of an event. In the case where no value of this proportion is available, it will be fixed at 50% (0.5).

e^2: is the margin of error tolerated which implies the statistical risk (5%);

N: is the population size.

In this study, the population size (N) was based on the population census of the National Institute of Statistics INS (2014) which is 1,071,543 inhabitants (Total population of Yopougon).

For the application of the formula, it was assumed that if $P = 0.5$; at a 95% confidence level, $Z = 1.96$ and the margin of error $e = 0.05$.

Thus, deriving from this formula, a sample of 384 households is representative of the population of the Yopougon municipality. However, the reality of the survey process leads to a readjustment of the sample size in order to compensate for possible refusals from respondents during the survey. In this study, if the response rate is estimated at 80%, then the adjusted sample size will be, according to the formula:

$$n' = \frac{n}{r} \tag{2}$$

Where:

r: the expected percentage of respondents; n': represents the size of the population to be interviewed; n: the minimum size of the population to be interviewed.

The total population to be interviewed is 394. However, a total of 14 households were added to the base sample (394) in order to make the sample more representative.

This results in a sample size of 408 households. The number of households surveyed was distributed across all neighborhoods, using Equation 3:

$$nf = \frac{Xi}{s} n' \tag{3}$$

Where:

nf: is the number of inhabitants to be interviewed per neighborhoods; xi: is the surface area of the different neighborhoods; S: the total surface area of the area likely to apply collective sanitation; n': the total number of people to be interviewed. Table 1 show the distribution of the number of respondents per household in the two study areas.

2.3. Statistical analysis

Descriptive and inferential analytical methods were used to analyze the household survey data with SPHINX software (Ver.5.1) at a statistical significance of 5% error (0.05), i.e., at a 95% confidence level. Descriptive statistics was used to analyze the socio-economic profile, the perceptions of local residents on the operation of the sewers and their liquid and solid waste management methods in relation with the networks. The internal validity of the Likert scale results was tested with Cronbach's alpha reliability ($\alpha = 0.69$). This suggests that the data collection instrument is 69% reliable and will produce the same results if the study was repeated. Percentages, frequencies and means were determined by univariate analysis to understand the behavior of the parameters studied.

TABLE 1 Distribution of the number of respondents along the 21/22 collector and Uniwax drainage system.

n'	S (km^2)	Study area	Xi (km^2)	nf	r
163	22.63	21/22 collector First part	12.6	76	46.62
		Second part	6.2	62	38.03
		Third part	3.83	25	15.35
245	32.30	Uniwax 1	11.83	70	28.57
		Uniwax 1	21.40	91	37.14
		Uniwax 1	19.07	84	34.28

2.4. Characterization of urban geohazard (erosion, landslides, and flooding) in the study area

The characterization of urban geohazard along the Uniwax Canal started with field visits and observations. These different activities took effect from the beginning of the study and were repeated during the study period, taking into account the different seasons. The operation consisted of walking along the drainage network to record the signs of water erosion, followed by slumping and flooding in the study area. This made it possible to follow the Spatio-temporal evolution of the phenomena observed. The equipment used for this purpose is a GPS Garmin eTrex 10 for the spatial positioning of the characteristic element of the phenomenon and a metric tape for measuring distances. Special attention was paid to the runoff circulation corridors (the source of water erosion and landslides), as well as to the depressions where water may stagnate (causing flooding), with regular monitoring.

2.5. Video camera survey (towed camera)

As defined in the BNQ 3680-125 standard, which is used by Sodeci, this inspection method allows the structural and operational state of the sewer system to be checked. This type of inspection requires prior cleaning of the sewer system to be inspected. The towed camera inspection is therefore essential when visualizing the complete structural condition of a pipe, locating anomalies precisely, their extent, locating connections and determining the types of intervention required. It also permits the accurate tracing of the evolution of anomalies over time so as to intervene in a timely manner and to check the quality of new or rehabilitated pipes. Finally, it can also be used in tandem with cleaning, drilling or other equipment to better monitor the process. This inspection method, therefore, consisted of inserting a color video camera either in the main sewer or in the manholes with the following resolutions [(i) IP68 up to 10 m water depth, (ii) High resolution 1920*1080, (iii) Electric rotation, 360° radial limitless rotation, one clink for reset, (iv) Four LED lights, and (v) Sensitivity 0.1 Lux] into the pipe and attaching it to a tractor, skid or raft. The camera is towed and waterproof, and has a lens with a multi-directional control device that rotates 360° radially and 270° laterally, permitting full peripheral view of the sewer pipes and manholes. The inspection was carried out according to the requirements of the Pipeline Assessment Certification Program (PACP® and MACP® of CERIU/NASSCO). The video camera inspection was conducted during the months of January and March 2021 in dry season. The dry season was chosen because it was the best time to debouch the sections of the pipeline that had been held for a video camera inspection and also to allow the mobile camera to move freely in order to visualize the structural defects. The survey was conducted by Sodeci professionals who manage the camera equipment used for structural and operational inspections of the pipelines and have a combined practical experience of 10 years in this field.

2.5.1. Developed operational and hydraulic deterioration model

2.5.1.1. CERIU/NASSCO protocol

The PACP system from NASSCO offers uniformity and consistency in the assessment, coding, and management of sewer lines. Since 2001, the Pipeline Assessment Certification Program (PACP) has been acknowledged as the industry standard in North America. It produces a thorough and trustworthy database of information about the sewer pipe that can be used to organize, plan, and renovate the wastewater collecting system (Tshumuka, 2010). The NASSCO methodology for mains, laterals, and manholes was approved by the Center de Recherche en Infrastructure Urbaine (CERIU) in order to eliminate inconsistencies in the evaluation and inspection of sewer systems in Quebec. This procedure, which was heavily influenced by the Water Research Council, comprises of coding structural defects on one side and operational and maintenance flaws on the other. According to Tables 2, 3 (Tshumuka, 2010; Buss et al., 2012), the general assignment of pipe condition rating (grade) and NASSCO PACP Condition Grading System Code Matrix is as follows. The results can then be utilized in later statistical modeling.

2.5.1.2. Logistic regression model

Bioassay has made substantial use of logistic regression, particularly when it comes to dosage response studies. In some situations, the independent variables can be of any kind, while the dependent variable is a dichotomy, which implies it can only belong to two classes. By indicating the chances of success and failure that strategy seeks to foretell how an event will turn out. Koo and Ariaratnam (2006) and Mohammadi et al. (2019) both use binary logistic regression to model sewer deterioration.

In this study, the transition probabilities of the sewer system are estimated using the ordinal logit model for multinomial answers technique. The created model seeks to define the link between a set of regressor factors and a polytomous response variable (condition grade; age, diameter, length, slope, and material). The probability of that grade and all grades ordered before are taken into account rather than the probability of a single grade, such as one of the binary logistic regressions. The following definition applies to cumulative probabilities: (Agresti, 2002).

TABLE 2 NASSCO PACP condition rating (grade; Tshumuka, 2010).

Grades	Description	Time to failure (year)
Grade 5: Immediate attention	Defects requiring immediate attention	Next 5 years
Grade 4: Poor	Severe defects that will become grade 5 within the near future	5–10
Grade 3: Fair	Moderate defects that will continue to deteriorate	10–20
Grade 2: Good	Defects that have not started deteriorating	≥20
Grade 1: Excellent	Pipe functional with minor defects)	Normal life applicable to the pipe material

$$P\left(Y \le \frac{J}{X}\right) = \pi_1(x) + \ldots + \pi_J(x); \quad j = 1, \ldots, j \tag{4}$$

Then

$$Logit[P(Y \le J/X)] = \ln \frac{P(Y \le J/X)}{1 - P(Y \le J/X)} = \ln \frac{\pi_1(x) + \ldots + \pi_J(x)}{\pi_J(x) + \ldots + \pi_{j+1}(x)}, \quad j = 1, \ldots j-1 \tag{5}$$

A model that simultaneously uses all cumulative logits is

$$Logit\,(Y \le J/X) = \alpha j + \beta' x, \quad j = 1 \ldots j-1. \tag{6}$$

Let Xi denote a p-dimensional vector of explanatory variables or covariates and consider a multinomial response variable Y with categorical outcomes, denoted by 1... J. For the proportional odds model, the dependency of the cumulative probabilities of Y on X's is frequently represented as an Equation 6.

$$\ln \frac{P(Y \le J/X)}{P(Y > J/X)} = \alpha j + x'\beta, \quad j = 1, \ldots, j-1 \tag{7}$$

It can be expressed in the form

$$\ln \frac{\pi_1(x) + \ldots + \pi_J(x)}{\pi_J(x) + \ldots + \pi_{j+1}(x)} = \alpha j + x'\beta, \quad j = 1, \ldots, j-1 \tag{8}$$

2.5.1.3. Application of the logistic regression approach for 21/22 collector data sets

2.5.1.3.1. Data source

The CCTV records from inspections carried out in the Yopougon Nouveau quartier between 2000 and 2021 provide the data for this investigation. Conduits built of various materials, including concrete, reinforced concrete, cement (CA), and PVC, are included in our sample. In the sample, PVC is the material that is most frequently used (52%) whereas reinforced concrete (41%), and cement are underrepresented (only 6%) and combined into one set for analysis. In both investigations, the majority of the sewers were constructed

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TABLE 3 NASSCO PACP Condition Grading System Code Matrix (Buss et al., 2012).

Family	Group	Descriptor	Modifier	Code	Structural grade	O&M grade
Structural	Crack (C)	Circumferential (C)		CC	1	
		Longitudinal (L)		CL	2	
		Multiple (M)		CM	3	
Structural	Fractures (F)	Circumferential (C)		FC	2	
		Longitudinal (L)		FL	3	
		Multiple (M)		FM	4	
Structural	Pipe failures (silent)	Broken (B)		B	1 clock pos – 3.2 clock pos – 4 >=3 clock pos – 5	
		Broken (B)	Soil visible (SV)	BVS	5	
		Broken (B)	Void visible (VV)	BVV	5	
		Hole (H)		H	1 clock pos – 3.2 clock pos – 4, >=3 clock pos – 5	
		Hole (H)	Soil visible (SV)	HSV	5	
		Hole (H)	Void visible (VV)	HVV	5	
O&M	Deposits attached (DA)	Encrustation (E)		DAE		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
		Grease (G)		DAGS		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
		Ragging (R)		DAR		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
		Other (Z)		DAZ		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
	Deposits Settled (DS)	Hard/Compacted (C)		DSC		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
		Fine (F)		DSF		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
		Gravel (G)		DSGV		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
		Other (Z)				≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
	Deposits ingress (DN)	Fines silt/sand (F)		DNF		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
		Gravel (GV)		DNGV		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
		Other (Z)		DNZ		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
O&M	Roots (R)	Fine (F)	Barrel (B)	RFB		2
	Roots (R) at a joint	Tap (T)	Barrel (B	RTB		3
		Medium (M)	Barrel (B)	RMB		4
			Lateral (L)	RML		3
			Connection (C)	RMC		3

(Continued)

TABLE 3 (Continued)

Family	Group	Descriptor	Modifier	Code	Structural grade	O&M grade
		Ball (B)	Barrel (B)	RBB		5
			Lateral (L)	RBL		4
			Connection (C)	RBC		4
O&M	Infiltration (I)	Weeper (W)		IW		2
		Dripper (D)		ID		3
		Runner (R)		IR		4
		Gusher (G)		IB		5
O&M	Obstacles/ obstructions (OB)	Brick or Masonry (B)		OBB		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
		Pipe Material in Invert (M)		OBM		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
		Object Protruding Thru Wall (I)		OBI		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
		Object Thru Connection (C)		OBC		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5
		Construction Debris (N)		OBN		≤10% - 2, ≤20% - 3, ≤30% - 4, >30% - 5

TABLE 4 Variables description.

Variables	Description
Age of the pipe	The installation or repair year is subtracted from the inspection year to get the conduit age. Continuous variable
Diameter of the pipe	Nominal value of conduit diameter in **m**. Continuous variable
Length of the pipe	The length of a pipe segment between two manholes in **m**. Continuous variable
Slope of the pipe	The pipe segment's slope in percentage: (upstream invert elevation—downstream invert elevation)/length. Continuous variable
Material of pipe	Concrete, reinforced concrete, cement, and PVC. Dummy variable.

m, meter.

in 1975, with an average age of 47 years. Defects that alter internal pipes by affecting hydraulic performance. The targets for the total pipe rating were the Manning coefficient (sediment deposition, root incursion, infiltration, corrosion, cracks, etc.). Only 0.01% of the pipe was classified using NASSCO's PACP fast rating technique, while classes 2, 3, and 4 each contained 15, 53, and 31% of the conduit, respectively.

2.5.1.3.2. Model application

Since the entities are primarily residential with a similar soil type and weather pattern, collected data from the many districts along the sewer system were applied. Table 4 lists the considerations that went into developing the degradation model.

3. Results

3.1. Urbanization in Yopougon

A strong trend toward urbanization is observed in Côte d'Ivoire. This urbanization is often very poorly planned in certain areas in Abidjan, such as some houses located along the wastewater and rainwater drainage channels in the Yopougon municipality. It does not take into account wastewater and rainwater drainage systems. This has a considerable impact on the networks, leading to the progressive deterioration of the systems. Supplementary Figure 1 is an illustration of the condensed urbanization in Yopougon.

3.2. Operational and structural defects of 21/22 collector (from Lama Fofana to Saint Francois roundabout)

The dysfunction of the wastewater network in Yopougon Nouveau Quartier is manifested by two different types of factors: structural factors and anthropogenic factors.

The structural dysfunction of the network is largely related to the age of the network (most were built between 1975 and 1986). This manifests itself in four types of functional deficiencies detected during the geographical survey and the video camera survey and is presented here: insufficient hydraulic capacity, infiltration/exfiltration, obstructions, holes, leaks, and breaks.

The estimating model was ran using SPSS with the provided data to determine the best outcome. For class 1, eight iterations were required, whereas classes 2 and 3 only required seven to arrive at the best answer. Table 5 presents the parameter estimation

TABLE 5 Estimation result for ordered logit model.

Terms	Class 1		Class 2		Class 3	
	Estimate	Prob>ChiSq	Estimate	Prob>ChiSq	Estimate	Prob>ChiSq
Intercept1	−0.972	0.1582	4.321	<0.0001*	6.518	<0.0001*
Intercept2	3.728	<0.0001*	7.301	<0.0001*	-	-
Intercept3	7.258	<0.0001*	-	-	-	-
Age	−0.085	<0.0001*	−0.085	<0.0001*	−0.081	<0.0001*
Diameter	0.630	0.0412*	0.502	0.0881	−0.066	0.9321
Concrete	−0.452	0.0345*	−0.319	0.0461*	−0.305	0.0543*
Cement	0.320	0.3051*	0.321	<0.0001*	0.506	0.3133
PVC	0.298	0.1730	0.329	0.1795	0.055	<0.0001*
Length	−0.018	0.1697	−0.018	0.2314	0.013	0.6108
Slope	0.066	0.8001	0.077	0.762	0.115	0.5211

*Significant at 5%.

values for β and α (intercept). While α values depend on the condition under consideration, β values are the same for all condition classes.

From the analysis of Table 5, it appears that age and type of equipment are significant factors in the process of pipe degradation.

The table reveals the age, diameter, concrete, cement, PVC, length, and slope-based wastewater degrading process. Age had an impact on the conditions falling within classes 1, 2, and 3. Age was therefore found to be important across all classes. This indicates that wastewater deterioration worsens over time.

The degradation of wastewater is significantly influenced by age. Consider a root intrusion that occurs through a hole as an example. As the pipe gets older, the root continues to expand, increasing the pipe's roughness. This implies an operational and maintenance decline that may eventually result in a decline in hydraulic performance. As age increases, a reduction from conditions 1 to 2 and 3 to 4 increases for all materials (concrete, cement, and PVC).

However, in class 1, it was discovered that diameter was important. From second grade and up, it has absolutely no impact. When obstructions are present in the conduit, segments with small diameters are more prone than segments with high diameters to experience a decline in hydraulic performance. Due to their hydraulic radius, large diameters may really still transport wastewater, but small diameters may encounter deposits and other barriers.

Concrete was also discovered to have a considerable impact across the three classes. In the elaborate deterioration model for classes 1 and 2, cement plays a key role. Overall, the model still doesn't find it to be significant. In order to build up the dummy variables, reinforced concrete was employed as a reference. Compared to the other materials utilized in this investigation, it proved to be the most degradation resistant. This is to be expected because the conduit is strong enough thanks to the reinforcing steel to prevent structural damage that would otherwise result in hydraulic dysfunction.

Due to a lack of data, the effect of other materials in the degradation processes is not adequately investigated. Nevertheless, they make up <1% of the overall sample.

3.2.1. Insufficient hydraulic capacity

Insufficient hydraulic capacity was observed along the entire length of the main sewer and also in the secondary sewers. This means that the pipe was not able to properly discharge the collected wastewater. It was more evident and heightened in the Lama Fofana, Denver, and Sans Loi districts.

Ultimately, this situation worsens and sewer backups or odors from the sewer are observed in the different neighborhoods in the area. In total, 210 backflow manholes were detected in Lama Fofana representing 34.25% of the backflow manholes observed along with the system, 180 in Denver representing 26.4%, 154 in Sans Loi representing 25.12% of the backflow manholes, 5 in Nouveau Bureau representing 0.9%, 56 in Camp Militaire representing 9.15% and 8 in Sideci Iroko representing 1.40%. Figure 5 presents the number of manholes along the sewer network.

Another indication of insufficient hydraulic capacity observed in the system was a trace of grease at the crown of the pipe; the grease was lighter than water and settled on the pipe wall at the level of the flow. This situation was particularly observed in Lama Fofana near the Sacré Coeur pharmacy.

3.2.2. Infiltration

The infiltration phenomenon in the study area was observed on the main sewer in Lama Fofana after the small football field (beginning of the main sewer) and in Sideci Iroko near the Saint Francois roundabout (see Supplementary Figure 2). It was also observed in Denver and Sans Loi at the level of secondary connections. Thus, five zones were identified in Lama Fofana, four in Denver, three in Sans Loi, and three in Sideci Iroko. The infiltration/exfiltration phenomenon has led to serious problems such as the collapse of some pipes in Lama Fofana, precisely at the Sacré-Coeur pharmacy.

3.2.3. Obstructions

Almost all drains (main and secondary) had blockages. These obstructions were caused by the presence of objects or materials in the pipe, limiting the flow of water by reducing the available space. The

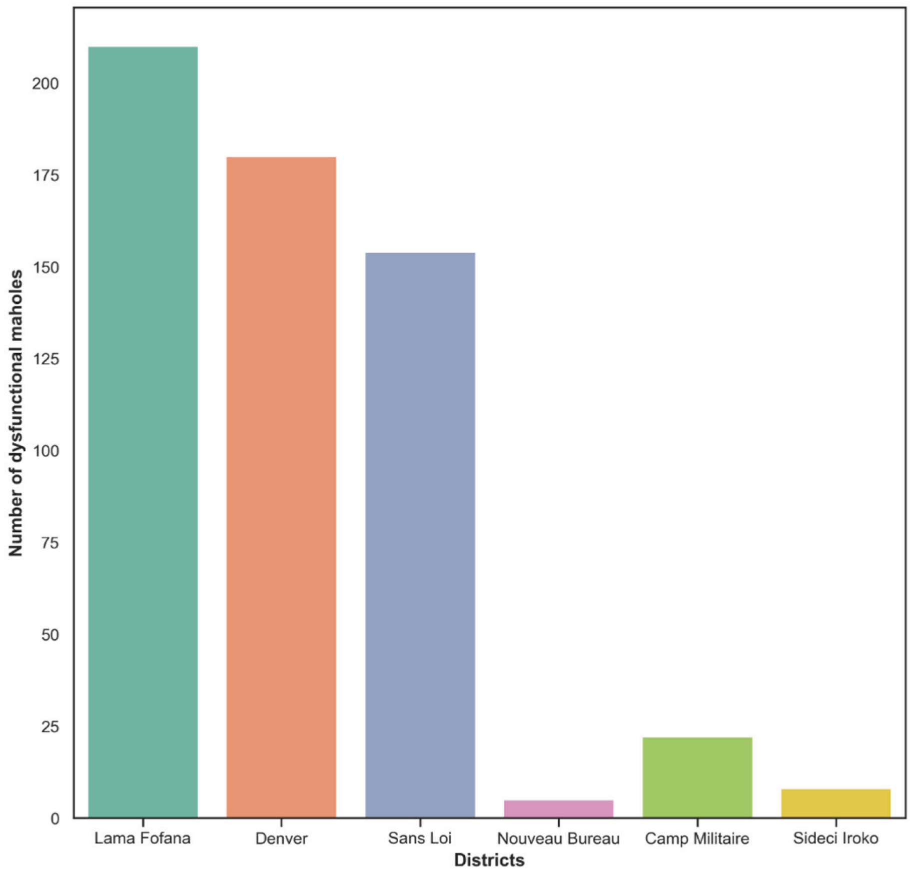

FIGURE 5
Distribution of failed manholes along the sewer system.

obstructions were mostly hard deposits (hardened deposits of long-standing), intrusive objects, or water-borne objects (sand deposits or objects). Field surveys and video camera prospection identified 300 areas (49.5%) of obstructions in Lama Fofana, Denvers. Sans Loi had 220 areas or 36.30% of the obstructed areas. In Nouveau Bureau, Camp Militaire and Sideci Iroko, the frequency of obstructions were low in contrast to the other districts. Thus, 22 zones (3.63%) were identified in the Camp Militaire and 19 zones (3.13%) in the Nouveau Bureau. The last area, Sideci Iroko, had 45 blocked areas or 7.44%.

It should be noted that the obstructions were visualized at the level of the defective manholes and inside the pipe as shown in Supplementary Figures 3A, B.

3.2.4. Cracks/fractures

The video camera survey has identified different types of cracks and fractures in the pipe from upstream to downstream. They were classified into four types: circular, longitudinal, multiple, and holes.

3.2.4.1. Circumferential cracks/fractures

These types of structural dysfunctions have been identified in Lama Fofana in the vicinity of the Sacré Coeur pharmacy. They were observed around the entire circumference of the pipe and were located at the center of the pipe section, at the joint and at the connection to the manhole (see Supplementary Figures 4A, B). They were caused by bending loads that exceed the capacity of the pipe, punching loads (rocks in the bedding), a rigid connection with a structure (manhole), loss of water tightness or the influence of the temperature of the transported effluent.

3.2.4.2. Longitudinal cracks/fractures and holes

These types of cracks and fractures were observed in the pipe at Denver, Sans Loi, and Nouveau Bureau in the vicinity of the Lycée Michel Halaire.

These longitudinal cracks were seen as visible lines on the surface of the pipe in the longitudinal axis. As for the fractures, they were seen as open cracks. As for holes, they were seen as openings in the wall of the pipe. The causes of these malfunctions include: either vertical loads that are more than the design loads; or the effects of wear and tear; or poorly fitted joints; or damage during effluent transport. The following Figure 6 illustrates the positions of longitudinal cracks/fractures and holes in the pipe.

3.2.4.3. Multiple cracks/fractures

Unlike longitudinal and circular cracks which propagate along a single path, multiple cracks propagate in all directions. These types of cracks were also identified throughout the entire network from upstream to downstream. They occur when there are simultaneous vertical loads and uneven support to the pipe, from point loads (e.g., rocks in the backfill) or from the coincidence of cracking with weak paths in the pipe.

FIGURE 6
Longitudinal cracks and holes detected by video camera survey at Lama Fofana district.

3.3. Anthropogenic factors influencing the rate of degradation of the driving condition

The geographical survey identified several anthropogenic factors that contribute to the progressive degradation of the network. These factors mainly involved the dumping of household waste on the manholes, obsolete and defective connections as well as the behavioral phenomenon of residents toward the network. Over the 2.5 km length of the sewer system, a total of 272 illegal and defective connections and 234 refuse deposits were identified. The distance between dumping sites is $\sim$ 2 m at the level of the dysfunctional secondary manholes located between the households. The Figure 7 below shows the spatial distribution of the different anthropogenic factors of degradation of the system in the entire study area. To better understand these factors, the study area was divided into three different parts. The first part contains the districts: Lama Fofana, Denver, and Sans Loi; the second part covers the districts: Nouveau Bureau and Camp Militaire and finally the third part was composed only of the district Sideci Iroko.

3.3.1. Garbage deposits on the manholes

In the first part of the 21/22 collector, the geographical survey identified a total of 136 garbage dumps. These deposits represent 59.11% of the total waste observed in this area. Supplementary Figure 5 shows some of the waste found at the dysfunctional manholes in Lama Fofana, Denver, and Sans Loi districts. This waste is generally composed of tree slices, old mattresses, and municipal solid waste resulting from poorly planned urbanization. These deposits are almost entirely located on sewer manholes. Since most of the manholes are dysfunctional. The waste eventually find their way into the network, creating blockages and backflow. The water can no longer circulate and leave the network. Thus, one can observe the stagnation of wastewater favoring the development of anopheles lava which puts the health of residents at risk. This situation was observed throughout this area. The proportion of waste observed in this first part was as follows: 70 deposits in Lama Fofana, 25 deposits in Denver, and 41 deposits in Sans Loi. Figure 8, Part 1 presents the spatial distribution of anthropogenic factors of dysfunction in the first part.

In contrast to the first part, a few factors were identified in these two areas which constitute the second part. A total of 56 deposits were observed on the manholes and in the network in this section representing 21.88% of the system. Thus, 19 deposits were identified at Nouveau quartier. In Camp Militaire, 37 deposits were identified in GEM1, GEM2, and GEM3. Similarly, the waste was composed of tree slices, old mattresses, pieces of bricks, and several other wastes from the construction of the fourth bridge linking the Yopougon municipality to that of the Plateau. In this part of the city, the sewage system was also totally damaged in some places at the level of Nouveau Bureau, especially the part of the system located in front of the Sodeci office (about 50 m long). At Nouveau Bureau, a high concentration of sand in the pipe was also observed (see Supplementary Figure 6). This situation led to a total blockage of the sewage system. In addition, at Camp Militaire, the deposits were almost entirely located on the sewage manholes.

Forty two waste deposits i.e., 19.01% were identified in the last section. This section extends over a distance of about 500 m from the CNPS roundabout to the Saint Francois roundabout. Most of the waste in this area was also observed in the secondary manholes which were the water inlets. However, the manholes of the main sewer are not spared from these deposits. The waste eventually finds its way into the network and where they drain into the rain water channel at the Saint Francois roundabout.

3.3.2. Illegal and defective wastewater connections

Several uncontrolled and defective connections were identified both on the main and the secondary connections at the level of the houses in the first part of the collector. These connections were mostly made with prefabricated parts, with a saddle, or with a ground. This last method of making a connection was the main source of defects encountered in the networks and the mainline at the latter. The main observations in these defective connections were cracks, fractures, and holes near the connections. In addition, this part of the network had the largest number of unauthorized connections, with 208 in total, i.e., 76.47% of the connections found on the entire network. Thus, 167 illegal connections were identified in Lama Fofana (80.28%), 15 in Denver (7.22%), and 26 in Sans Loi (12.5%). These connections vary in diameter from 60 to 140 mm. Supplementary Figure 7 is an illustration of a defective connection on the main sewer.

The second section had few uncontrolled and defective connections. Only 28 connections (11.13%) were identified in this section. These defective connections were mostly observed on the secondary collectors at the level of the houses. Their diameter varied from 60 to 140 mm. Eleven connections were identified at Nouveau Bureau, 17 at Camp Militaire, specifically in the GEM1, GM2, and GEM3 housing estates. The malfunctions related to the network (blockages and backflow) in this part were more evident in the Nouveau Bureau. They extend to the level of the Michel Halaire high school. On the other hand, they were not very evident in the GEM1,2,3 housing estate. Also, two different branches were observed, i.e., legal connections made by SODECI on the main collector (collector 21/22). The first branch was seen at the level of the Camp

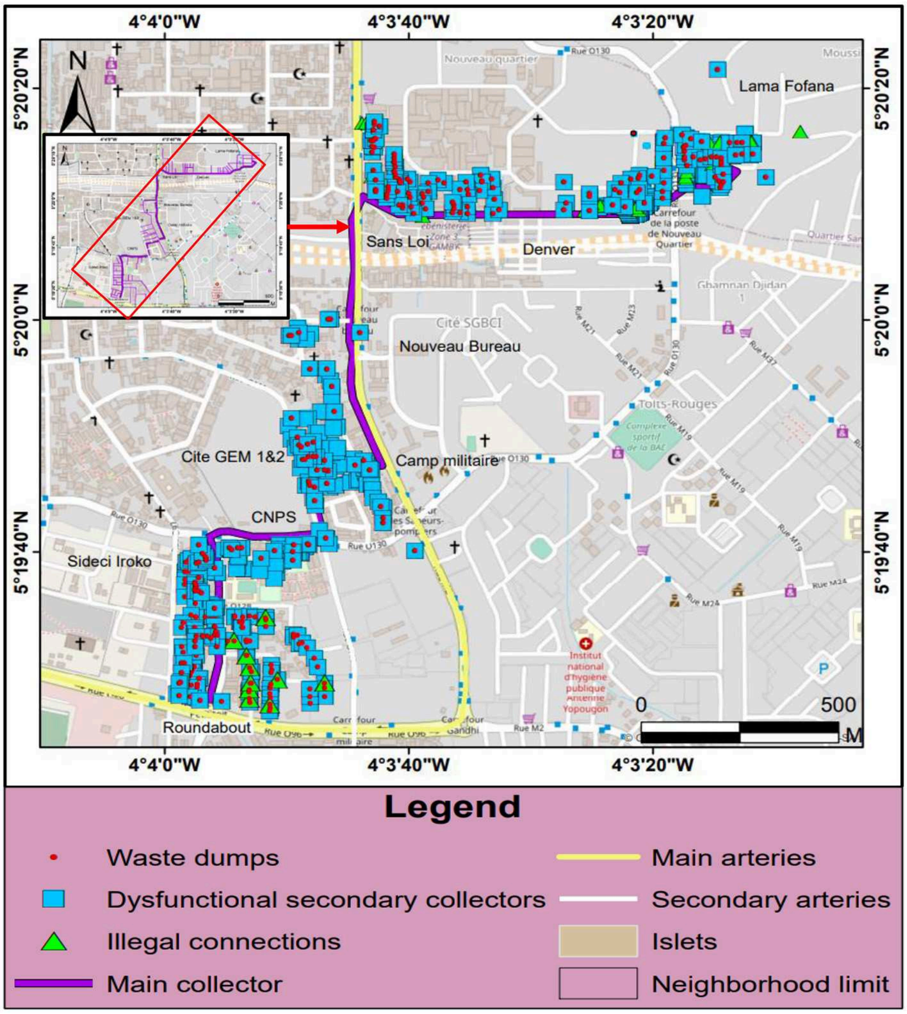

FIGURE 7
Spatial distribution of the different anthropogenic degradation factors along 21/22 collector.

Militaire market at the end of the GEM3 housing estate. The second branch was in front of the Nankoko pharmacy. The failures factors in this section are presented in Figure 8 part 2.

As for the anarchic and defective connections of waste water evacuation in the last part, 31 anarchic connections (i.e., 12.39%) were listed on both sides of the main collector. These connections were practically implemented by the residents in precarious conditions. This practice hurts the network, leading to serious problems of dysfunction in the area. The diameters of these connections vary from 40 mm to 120 mm. The malfunctioning of the network in this area was much more evident on the side of the Lycée Saint Francois and at the level of Saint Francois Roundabout. The spatial distribution of anthropogenic malfunction factors in the third area are presented in Figure 8 part 3.

3.3.3. Landslide phenomena

Rock fall phenomena have been observed along the network. These cave-ins were as a result of poor connection with very large diameter pipes on the network. They were caused by collapse of either houses or roads. These different phenomena were observed in almost all the different parts. They were more serious in Sideci Iroko, precisely at the Saint Francois Roundabout (see Supplementary Figures 8A, B).

3.4. Uniwax drainage system

Like the 21/22 collector, along the Uniwax channel, several factors were identified as being responsible for the dysfunction of the network. These factors mainly included illegal waste disposal, unauthorized and defectives connections to the system, structural dysfunction related to the channel (cracked, exposed, clogged, and broken), urban agriculture in the vicinity of the channel, bad practices solid waste and waste water management by residents, natural phenomena such as erosion and scouring in the unimproved parts, and the strong concentration of vegetation in the network.

Along the Uniwax drainage system, a total of 169 uncontrolled dumping of solid waste were identified, 110 unauthorized and defective waste water network connection, 41 illegal urban agriculture and vegetation and 189 problems related to structural dysfunction of the channel and high concentration of vegetation in

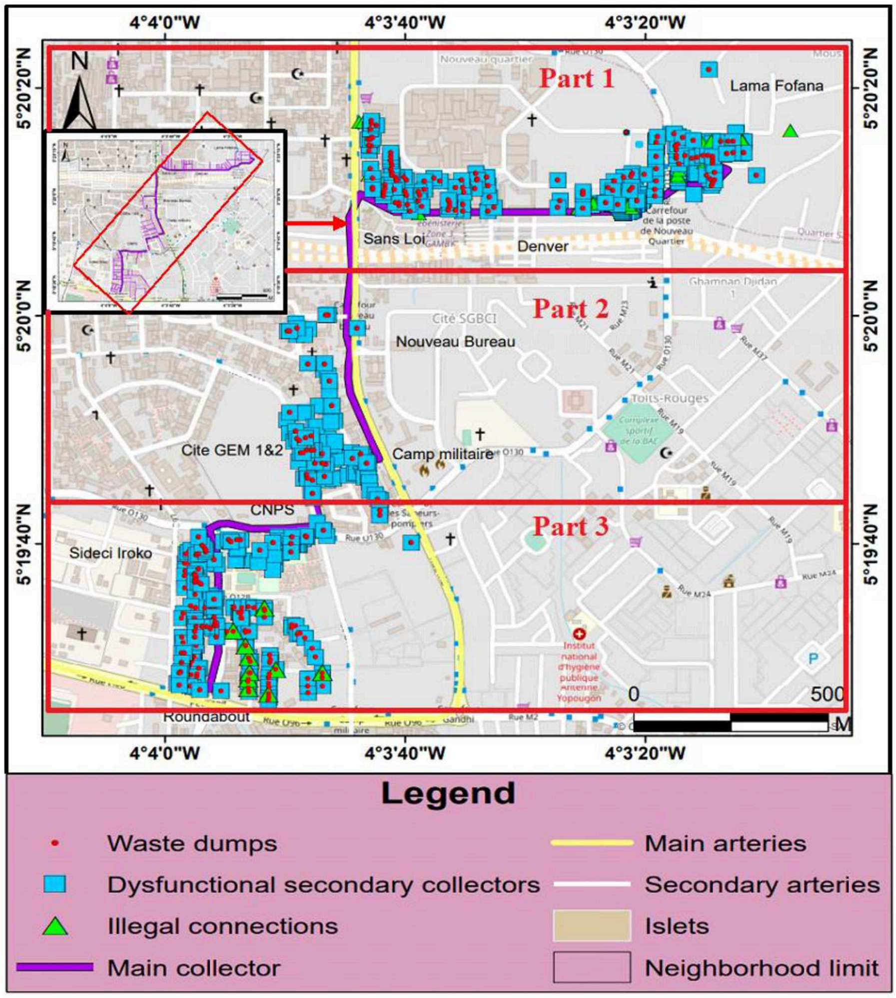

FIGURE 8
Spatial distribution of anthropogenic failure factors in each part of the 21/22 collector.

the unlined parts. The Figure 9 shows the total number of factors along the entire length of the network.

In the 10 sub-districts located along the channel, the degradation of the network was partly due to the different factors and activities.

The analysis of these results is presented in three (03) different zones which are UNIWAX 1, UNIWAX 2, and UNIWAX 3.

3.4.1. Structural malfunctions observed in the network

Thirty one malfunctioning problems were observed in the different districts located in UNIWAX 1. These problems represent 16.40% of the malfunctioning problems. The network was clogged with sand and solid waste in its major parts in Cité Abdoulaye Diallo up to the level of Lycée Technique. At the level of Banco 2, just after the Banco 2 Bridge, several areas of obstructions were identified in the canal, thus highlighting the total dysfunction of the channel. The channel was either exposed or broken (3.5%), cracked (2.6%), broken (5.9%), or blocked (4.4%). The network in this areas was in an advanced state of degradation and was not developed. This situation led to poor drainage of rain water, causing the rise of water in the area with enormous material damage and loss of life during the rainy season.

In UNIWAX 2, a total of 76 structural dysfunction problems were identified, i.e., 40.21% of the dysfunction problems along the canal. The most important were in Sicogi Aimé Césaire, Yaosehi, and Gbinta. Also, the geographical survey identified several obstruction zones on the canal (42.10% of the canal was totally blocked by illegal waste deposits). As for other structural problems, 27.63% of the system was bare, the most critical being in Sicogi Aimé Cesaire and Yaosehi (see Supplementary Figure 9); 14.49% of the network was broken and 15.78% was affected by erosion and landslides. Also, in the Gbinta district, the dysfunction was materialized by a progressive widening of the canal due to the phenomenon of erosion and landslides.

With regard to the question related to the structural problems of the drainage system in UNIWAX 3; 82 problems were identified representing 43.39% of the structural malfunctions along the network. These problems were considered to be those that prevent the system from functioning properly in the 3 neighborhoods located in the latter area. All these problems observed in the channel were due to the fact that either the canal was blocked (61.84%), broken and

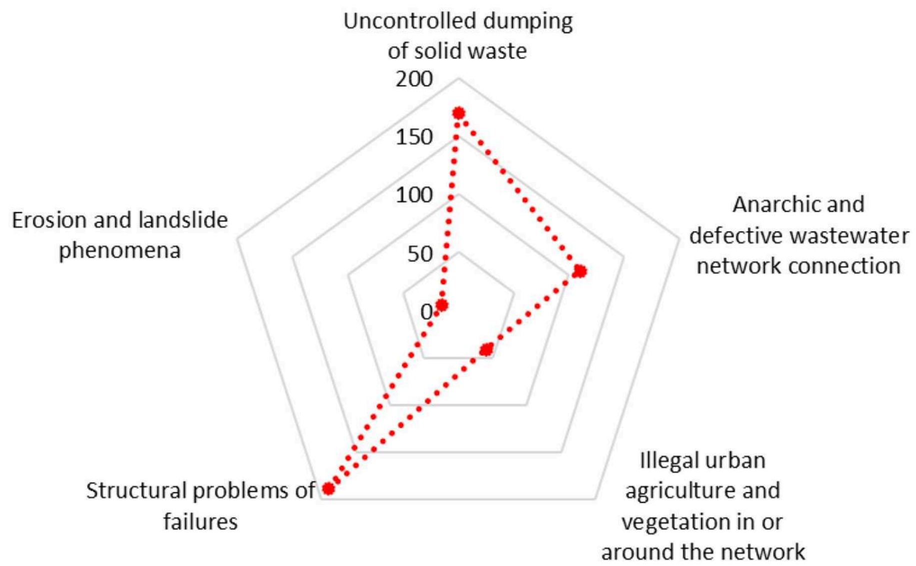

FIGURE 9
Frequency of failure factors along the Uniwax drainage system.

cracked (30.26%), eroded (7.89%), or clogged with sand or solid waste (100%). Most of these dysfunctional problems were identified in Kpimbly with 47 dysfunctional areas, 23 in Azito and 6 in Beago. The phenomenon of dysfunction was more in this third part compared to the first two zones. In this sector, the channel was in an advanced state of degradation and was not developed. The phenomenon of erosion was more in this last part with 3 different types of erosion namely lateral erosion, regressive erosion and gully erosion. The spatial distribution of the factors in the first part of the channel is presented in Figure 10, UNIWAX 1.

3.4.2. Unauthorized dumping of solid waste

Poor disposal of household waste in UNIWAX 1 has led to several piles of illegal solid waste deposits in the network and its immediate surroundings. Thirty one dumping sites were identified, including 12 in Cité Abdoulaye Diallo and 19 in Banco 2. The waste consisted of plastic bags, organic matter, mud, animal's excrement, pieces of brick from buildings, old mattresses, municipal solid waste, tires, chairs, and spoilt armchairs. The waste in the channel was made up of a linear chain in the network in this part. It was more concentrated at the level of the technical high school and after the Banco Bridge, which represents 61.3% of the deposits in this part. The waste represented 18.35% of the deposits along the canal with a volume of 1,230 m^3. During the rainy season, all this waste was found in the canal, thus blocking the passage of water. During the rainy season, all the garbage was found in the canal, blocking the passage of water. Thus, the volume of water increased considerably in the drainage network and leaves its bed, causing flooding in the area.

In UNIWAX 2, the immediate environment of the channel was characterized by a large number of illegal dumps. Most of these dumpsites were located in the network. The analysis of the situation revealed that of the 60 dumpsites identified in this area, about 84% were located directly in the network and the remaining 14% were located in the immediate vicinity. The distribution of litter in the canal of the different sub-districts was as follows: Fourteen dumps in Sicocogi Aimé Cesaire (23.33%), 8 dumps in Siccogi (13.33%), 21 dumps in Yaosehi (35%), and 17 dumps in Gbinta (28.33%). As in the first part, the waste was constituted in a linear chain over long distances and represented 35.5% of the waste observed along the system, i.e., a volume of 2,379.56 m^3 (see Supplementary Figure 10).

In terms of the environmental problems of waste management in UNIWAX 3, 78 dumping sites were observed in this area. All 78 dumping sites correspond to a volume of $\sim$ 3,093.43 m^3 or 46.15% of the dumping observed along the network. Of the 78 dumping sites found, 64% were located directly in the network and 16% within 5 m of the drainage system. Kpimbly and Azito shared the largest volume (92%) of the waste with 1,926 m^3, 906.3 m^3, and Beago 13.65 m^3, respectively.

3.4.3. Unauthorized and defective connections of factories and local residents to the network

As for the unauthorized connections of wastewater drains in UNIWAX 1, 29 unauthorized connections were identified, representing 26.37% of the unauthorized connections along the canal. Fourteen of these connections were identified in Cité Abdoulaye Diallo and 15 in Banco 2. These networks have very large diameters ranging from 40 to 120 mm. This type of connection created cracks and breaks in the canal and weakened it. The waste water from these uncontrolled connections from industries was a significant contributor to the increase in water flow in the canal and the types of effluent transported had a negative impact on the canal (see Supplementary Figure 11).

Also, most of the household toilets located at the edge of the rain water drainage system in this area were directly connected to it. Since the canal was practically blocked in this area, these unauthorized waste water connections led to the stagnation of water in the canal and this constitutes a crucial factor in the growth of disease vectors in these neighborhoods.

Illegal sewage networks (or sewage outfalls) are scattered throughout UNIWAX 2 with a proportion of 40% of connections along the sewage system. Their concentration was much higher in Sicogi Aimé Césaire and Yaosehi. These networks favor water stagnation and they were sources of mosquito proliferation. Thus, 17 of these brackets were identified in Sicogi Aimé Césaire, 8 in Sicogi, 13 in Yaosehi, and 7 in Gbinta. It should also be noted that in Gbinta, all the toilets located next to the channel were connected directly to it. The spatial distribution of the factors in the second part of the channel is presented in Figure 10, UNIWAX 2.

At UNIWAX 3, the network is also subject to several anachronistic and defective connections. This leads to a progressive dysfunction of the collector in this area. These defective connections represent 33.63% of the problems on the collector in this zone. With regard to the road infrastructure along the 21/22 collector, most of the roads were degraded. They are either cracked, interrupted, blocked, abandoned or even difficult to access and impassable. An estimated 72% of these roads were inaccessible or in a deplorable condition.

3.4.4. Peri-urban agriculture and high concentration of vegetation in and around the network

In addition to the other factors identified in UNIWAX 1, several banana farms were identified in the immediate vicinity of the network between Cité Abdoulaye Diallo and the Lycée Technique de Yopougon. The roots of these banana trees had a negative impact on the concrete used for the network. Also, a high concentration of Chinese bamboo were identified in the network at Banco 2. As the channel was not constructed at Banco 2, the roots of the bamboo trees exerted pressure on the soil structure and caused sand to be deposited on the canal walls, resulting in the narrowing of the canal diameter (see Supplementary Figures 12A, B). This is the major cause of the degradation of the network in this area, leading to poor drainage of rain water. This leads to the rise of water by overflowing the network during heavy rains.

In contrast to the first upstream section, the vegetation in the middle section had less negative impact on the structure of the network in the vast majority of the neighborhoods. In this sector, the vegetation was less dense and less concentrated than in sector 1 with fewer large trees. However, 15 banana farms and several horticultural practices were identified on both sides of the system in Sicogi Aimé Césaire and Yaosehi. In addition, a high concentration of vegetation and large trees were observed in Gbinta, causing most of the structural problems and geohazard phenomena in the area. The Figure 10 UNIWAX 3 shows the spatial distribution of the different factors in part 3 of the network.

The whole of UNIWAX 3 was covered by heavy vegetation with large trees. It should also be noted that there were several banana farms in the vicinity. This vegetation had a negative impact on the system with tree roots being the major cause of structural degradation of the system and the genesis of geohazard in the area.

3.5. Urban geohazard on the network

During the field visits and observations, the urban geohazard phenomena encountered along the canal were mainly erosion and landslides and were located along the network. Therefore, the characterization of urban geohazard in the study area was limited

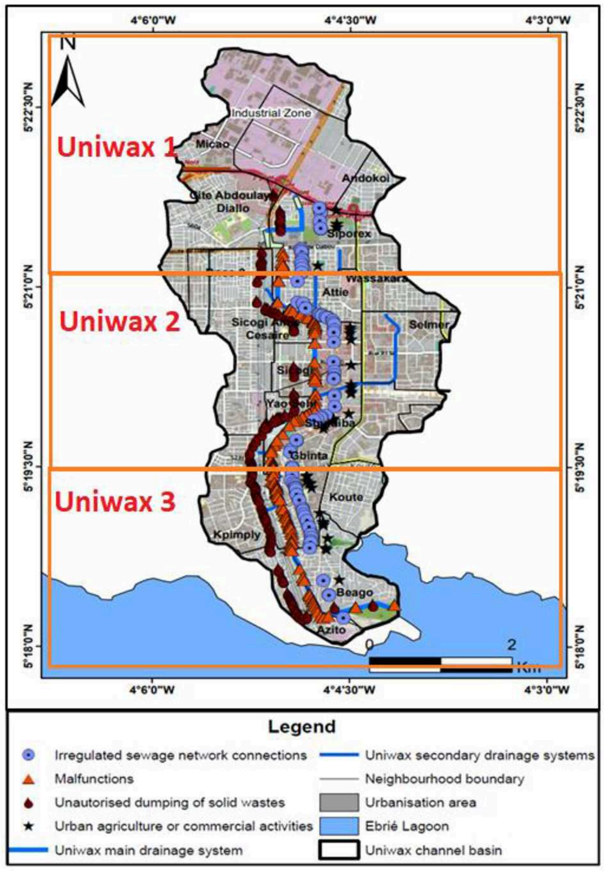

FIGURE 10
Spatial distribution of the different malfunctioning factors along the Uniwax drainage system.

to that of water erosion, followed by landslides, in view of the parameters considered.

3.5.1. Erosion and slumping phenomena observed along the Uniwax drainage system

Inadequate management of urban drainage was noted in precarious neighborhoods. The worrying phenomena of erosion, landslides and flooding were observed in the districts. These phenomena were located along the water drainage channels, which were, for the most part, undeveloped. From the point of view of water erosion of the soil, three different forms of erosion were observed in the different districts located along the drainage system: (i) regressive erosion, characterized by a detachment of the soil preferentially from downstream to upstream following the direction of the water flow in the channel (see Supplementary Figure 13). This form of erosion caused scarping and very steep slopes (>5%). In the developed part of the canal and the undeveloped part, it caused the progressive destruction of the structure; (ii) Lateral erosion, characterized by a pronounced detachment at the level of the slopes of the canal (see Supplementary Figure 14). This caused the canal to widen at these points. These phenomena were largely observed in Banco 2, Gbinta, and Yaosehi. The width of the channel measured at the different locations where lateral erosion occurred, varied between 36

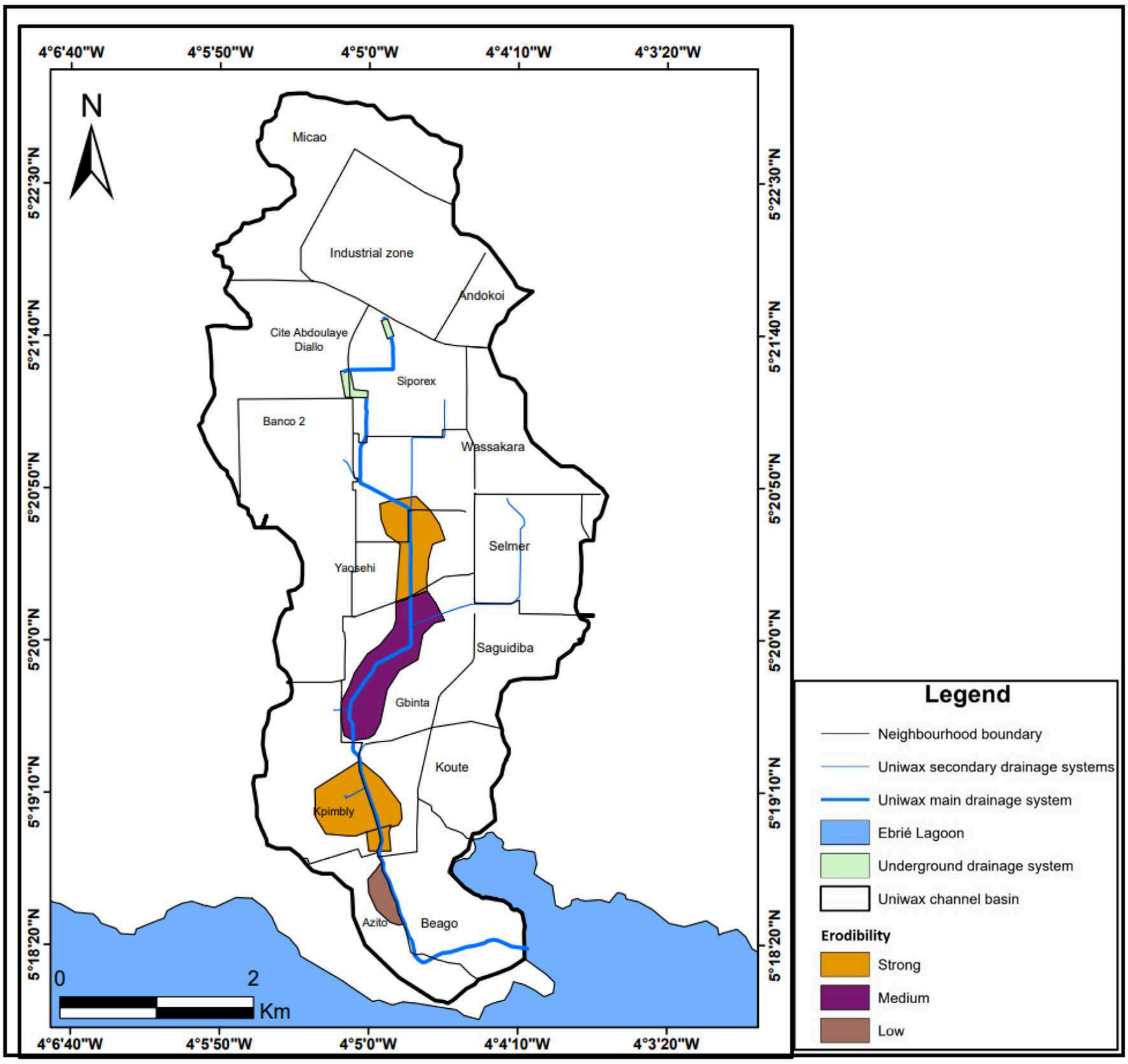

FIGURE 11
Frequency of erodibility phenomenon along the Uniwax drainage system.

and 44 m and (iii) gully or depth erosion, where the detachment of soils follows a depth gradient (see Supplementary Figure 15). Under these conditions, the underlying formations were soils with a poor resistance to water erosion. The depths measured in these areas of the canal during the field visits varied between 15 and 17 m. Figure 11 below show the frequency of erodibility phenomenon along the Uniwax drainage system.

3.6. Poor behavioral practices of residents on both sides of urban sewer and drainage systems

3.6.1. Socio-economic characteristics of households in structured neighborhoods in the study area

This section presents the results of the household survey conducted among residents, 163 of whom were in Yopougon Nouveau quartier and 245 along the Uniwax canal. In both areas, 408 people were interviewed, 68.6% ($n = 280$) of whom were men and 31.4% ($n = 128$) of whom were women aged between 18 and 40. The responsibility of head of household falls in 88% of cases to the male gender against 12% held by women. Each head of household was in charge of an average of eight people.

With regard to the level of education, more than half of the respondents (69.9%, $n = 114$) in the Nouveau Quartier had attended school (traditional school) and 7.2% ($n = 12$) said they had studied at a Koranic school. On the other hand, 22.9% ($n = 37$) of respondents had not received any formal education. For the respondents along the Uniwax Canal, the study showed that 68.25% ($n = 167$) had not received any formal education, while only 31.75% ($n = 78$) had received formal education, divided between the traditional school and the Koranic school.

In addition, the majority of households visited (88.4%), lived in common yards in the two different zones. Indeed, concerning the average monthly income of the heads of household, 24% of the working population had a monthly income between USD 97.80

(91.27€) and USD 163.00 (152.11€); 11% of the working population earned between USD 244.50 (228.17€) and USD 326.00 (3042.22€) per month; and 9% of the working population had a monthly income of about USD 489.00 (456.33€)

3.6.2. Description of the built and inhabited environment along the sewerage networks

Different types of housing were identified throughout the study area which are: (i) modern housing (<14% of the sample), which has most of the technical urban networks and basic urban health and educational services; (ii) Mixed housing (21% of the sample), is characterized by neighborhoods accessible by good roads and served by urban technical networks at rates varying from 20 to 60%. The presence of other basic urban services (education and health) is optional and (iii) so-called "traditional" housing, 65%, is characterized by neighborhoods that are difficult to access (roads in poor condition) and located at a far distance from, or even absence of, water and electricity networks and basic urban services.

The standard of the built environment was fairly diversified in the study area and was marked by four main groups classified according to the decreasing level of standing (Table 6). The "residential" houses built with so-called permanent materials (breeze blocks/bricks, tiles, sheet metal/tile, plywood/plaster ceiling, garden, fence, water, electricity, and telephone). This type of structure is generally the characteristic of modern housing; the "economic" houses, identical to the previous ones but with a lower degree of finishing. This type of structure is also characteristic of modern housing; the "evolutive" houses, with a lower degree of finishing, are characteristic of a group of houses generally overlooking a central courtyard (common courtyard) with sometimes village constructions. Finally, the "slum" houses built of un-plastered breeze blocks/earth bricks or temporary materials (planks, cob, more, or less plastered). Most of the houses located along the drains were dominated by basic and evolving dwellings thus generating a large quantity of solid waste which eventually ends up in the urban sewage system.

TABLE 6 The proportion of habitat types according to the study districts.

Neighborhoods	Types of housings	Area occupied (Km^2)	Percentages (%)
	Residential	0.2	8
Lama Fofana	Economic	0.82	17
	Evolutive	4.6	75
Denver	Economic	0.53	11
	Evolutive	4.1	89
Sans Loi	Economic	0.51	10
	Evolutive	5.3	90
	Residential	4.22	52
Nouveau Bureau	Economic	2.6	44
	Evolutive	0.33	6
	Residential	1.15	19
Camp Militaire	Economic	3.7	66
	Evolutive	0.89	15
Sideci Iroko	Economic	4.23	76
	Evolutive	1.2	24
	Residential	0.93	8
Zone Industrielle	Economic	1.26	31
	Evolutive	3.96	43
	Slum	3.63	18
	Residential	0.22	3
Banco 2	Economic	0,74	17
	Evolutive	4,53	80
Siccogi Aimé Cesaire	Evolutive	3.25	68
	Slum	3.21	32
Siccogi	Economic	1.35	55
	Evolutive	0.56	45
Yao Séhi	Evolutive	3.96	19
	Sommaire	2.21	81
Kpimply	Scalable	6.08	7
	Slum	9.48	93
Azito	Evolutive	5.67	6
	Slum	3.25	96
Beago	Evolutive	0.33	82
	Slum	1.2	18

3.6.3. Knowledge and perceptions of the population on the operation of the sewer and drainage systems

The knowledge and perceptions of urban populations were assessed in 408 households located on both sides of the collectors. The perceptions of the urban populations, in the two study areas, on the role and functioning of the collectors are illustrated in Figure 12.

Analysis of this Figure 12 shows that 100% of the interviewees recognized the existence of sewage and drainage system in the study area. Indeed, more than 66% of the urban population did not know the difference between waste water and rain drainage systems. Up to 62% perceive drains as the preferred place to dispose of waste and that water would carry this waste. Only 38% know that waste was largely responsible for the malfunctioning of drains and that it is not good to put waste there. This perception of the 253 populations concerning the management of the sewers makes it possible to analyze the degree of ignorance of the populations and to know the primary role of the urban sanitation networks. Two indicators were identified by the population as being the cause of system dysfunction, namely: poorly planned urbanization and solid waste.

3.6.4. Management and disposal of household waste and waste water

Among the households visited along the Uniwax drainage system, 85.21% ($n = 209$) did not have any garbage containers and dump

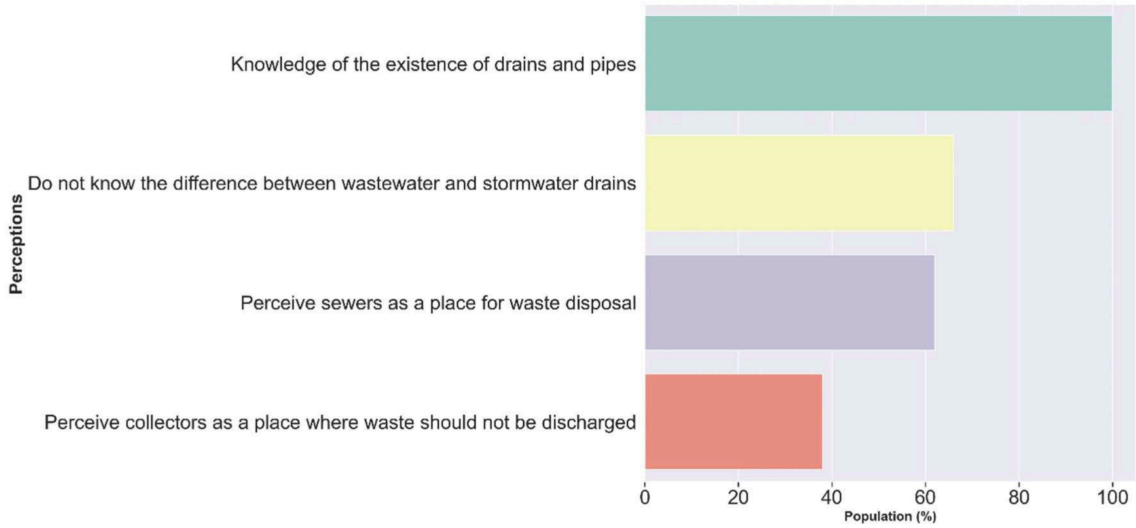

FIGURE 12
Perception of the population of Yopougon on the operation of the sewer and drainage systems.

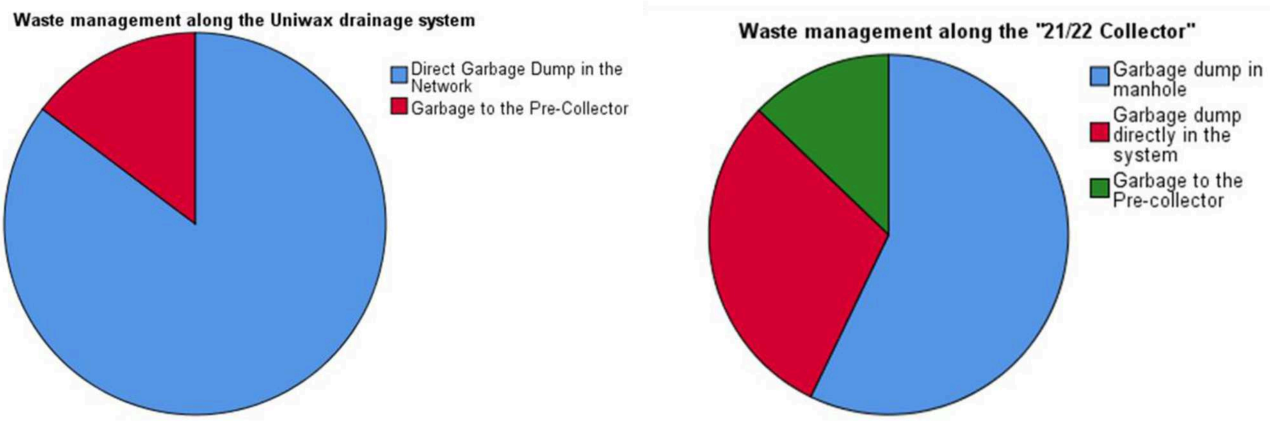

FIGURE 13
Waste management mode along the Uniwax drainage system and 21/22 collector.

their garbage directly into the network on a daily basis (Figure 13). Of the remaining households with garbage cans, 14.79% ($n = 36$) empty them two to three times a week, alternating between collection trucks and other modes of disposal (pre-collectors, garbage bins, and the network).

As for the evacuation of waste in the network, the practice was serious in the precarious settlements located in the middle and downstream sectors. These practices were essentially linked to the level of education of the population, on the one hand and the lack of containers or the inexistence of garbage containers on the other hand. Among residents living along the 21/22 collector in the Nouveau quartier, 62.24% of households own garbage bags. Thus, 49.6% deposit their garbage bags on the dysfunctional manholes that end up in the sewer. Of the remaining 37.6% who did not own garbage cans, 26.3% throw garbage directly into the sewer, as is the case in Lama Fofana, Denver and Sans Loi. However, 11.3% use pre-collectors for waste collection. These pre-collection services were used exclusively in the second and third parts. Also, several commercial activities were observed in the two areas generating about 32% of the waste found in the drains.

Regarding waste water, poor management was observed in both areas. Several uncontrolled connections were observed on the networks for the evacuation of liquid waste, generating large quantities of water in the systems. Most of the wastewater discharged by residents was loaded with chemical effluents and solid objects that endanger the operation of the pipes. These waters were discharged at variable frequencies depending on the household, industrial and commercial activities observed in the two areas. Also in the two different zones, almost all the households use the network for the evacuation of their waste water.

3.7. Socio-economic and environmental consequences in the study area

The field surveys identified several environmental and socio-economic problems related to the malfunctioning of the urban sewage systems in the study areas. The problems affecting the urban technical networks were poorly drained wastewater, the obstruction of wastewater and rainwater drainage systems, and the rupture of pipes leading to the backflow of wastewater onto the road. The consequences include the destruction of urban infrastructure, the reduction of the life span of urban networks, particularly the roadway which has become impassable, and the slowing down of economic activities; the pollution of the urban environment generates insalubrity and foul odors in all areas. The environmental problems caused by highly charged wastewater are of concern in the study areas. These include the pollution and degradation of the quality of the lagoon where all the wastewater was discharged, leading to the disappearance of aquatic species (fish), the contamination of the soil leading to the deterioration of its quality, erosion and gullying of the soil. The progressive deterioration of the living environment in Lama Fofana, Denver, Sans Loi, and practically all the neighborhoods located along the Uniwax canal, the destruction of the urban heritage, the increased insalubrity in the neighborhoods, the risks of diseases and other ailments, the slowing down of socio-economic activities and the increase in the risks of accidents should also be highlighted. Also, atmospheric pollution with the release of nauseating odors exposing the inhabitants to intestinal diseases. In addition, sanitary problems, due to the non-treatment of wastewater and its stagnation in gutters and open spaces, have been identified in the area, leading to the proliferation of disease vectors (mosquitoes, flies, cockroaches, and rodents) as well as foul odors. The presence of germs and pathogenic microbes in wastewater is a source of contamination of drinking water following infiltration (Gbinta, Kpimbly, and Azito boreholes), soil and food, thus exposing local residents to waterborne diseases.

4. Discussion

4.1. Anthropogenic factors

Although several socio-environmental factors contribute to the malfunctioning of the urban drainage systems, the direct field observation method helped to distinguish four environmental problems linked to the progressive degradation of the systems. These socio-environmental problems were related to poor solid waste management, structural problems of the drainage system, peri-urban agriculture and vegetation on both sides of the pipes, and defective unauthorized connections to the systems. They attest to the degree of exposure to the different areas of the Yopougon municipality.

This proximity of the dumping of waste to the drainage system leads to blockages and therefore constitutes a potential source of malfunction of the systems (Zohoori and Ghani, 2017). In fact, during heavy rainfall, the waste can be washed into the drainage system and obstructs the flow of water, thus causing backflow and flooding in the study area. This possibility was verified since, more than 78.6% of the different sections of the pipes were blocked by waste and sand.

The geographical survey also revealed several unauthorized and defective connections from households and industrial companies to the various networks. Indeed, wastewater from households and industries was loaded with solid effluents that negatively impact the system. These connections led to the leaks and breaks in the systems. Studies by Ouattara et al. (2021) and Kablan (2017) had shown that defective connections were partly responsible for the malfunctioning of urban sanitation networks in the city of Abidjan, specifically the Cocody-Riviera municipality. Also, these connections increased the volume of water in the canal and promoted flooding in certain areas in case of rainfall. Furthermore, the 21/22 collector and the Uniwax canal, located in the Yopougon municipality, just like the other networks in the city of Abidjan, suffer from a chronic lack of maintenance and are currently faced with sizing and development problems simply because they are no longer adapted to the new realities of urbanization.

Along the Uniwax canal, for example, several sections were not developed and extend over long distances; this was the case of the section linking Banco 2 to Yaosehi, Yaosehi to Gbinta as well as the largest proportion (92%) of the third section.

According to surveys conducted with Sodeci, local residents and the Yopougon municipality, most of the pipes were built in 1975 for the waste water sewers and in 2007 for the Uniwax canal, and met the needs of rainwater sanitation, at a time when the vegetation on the upstream land was favorable to the infiltration of much of the rainwater. Successive housing developments have replaced the vegetation, leading to an increase in the amount of run-off. Alexis et al. (2021) and Ouattara et al. (2021), in their study on the Analysis of Domestic Waste water and rain water Systems in African Cities (Abidjan, Yaoundé, Lagos, Accra, and Johannesburg), have shown that urban drainage systems are often clogged with urban waste, especially when houses are built close to the drainage networks as observed along the 21/22 collector and Uniwax drainage system.

These obstructions in the wastewater and rainwater drainage channels are at the root cause of the structural and operational dysfunctions of the drains in the city of Abidjan (Kambiré et al., 2016). This situation is not specific to the city of Abidjan, in particular the Yopougon municipality. Several studies carried out in different urban areas have highlighted this state of affairs. The city of Ziguinchor in the south of Senegal has obstructions in its drainage channels that negatively impact urban drainage (Bouly et al., 2019). Also, the cities of Isiolo, Lomé Maroua, and Conakry face similar drainage difficulties according to studies conducted by Karanja (2014), Ndongo et al. (2015), Gbafa et al. (2017), and Bangoura (2018). The same applies to the Enugu metropolis (Okoye et al., 2018). Furthermore, the waste could be carried into homes during floods and impact on the health and wellbeing of residents as pointed out by Tuo et al. (2019). As for breaks, ruptures and denudation of pipes, they are evidence of violent flooding and the types of effluent transported during the rainy season, faulty unauthorized connections and also large solid objects resulting from accelerated and poorly planned urbanization.

4.2. Structural factors

Video sewer inspection is a non-destructive and effective verification approach to visibly inspect the interior of underground sewer pipes and sewer lines (Boaz et al., 2014). Its application allows the identification and recording of structural and functional defects. Thus, it can help to distinguish and locate deterioration, leaks or blockages. The method also allows for better visualization of defects such as tree roots, broken slabs, faulty mortar connections, in-line blockages, negative slopes, pipe collapse, offset joints, pipe cracks, sludge, or grease accumulation. The method is not widely used in sub-Saharan Africa because of the great difficulty of accessing the pipes in some places and also because of the obstruction of the pipes by the poor management practice of the network by the local residents (Sodeci, 2018). It should also be noted that many countries in sub-Saharan Africa use on-site sanitation systems (septic tanks) to the detriment of collective sanitation, hence its low use on the continent (Defo et al., 2015). As Côte d'Ivoire has a collective sanitation network of 2,300 km, Sodeci, which is in charge of collective sanitation, has acquired this tool for better management of its systems. The municipality of Yopougon, precisely Yopougon Nouveau quartier is facing a real operational problem of the sewers, hence this study was initiated with the contribution of Sodeci to evaluate the types of failures on the 21/22 collector. In addition, several functional problems related to the age of the network were identified during the geographical survey and the video camera survey in the study area. These deficiencies are either a cause or a consequence of a structural deficiency. It is important to pay attention to them, as they can have negative consequences for the users. Five types of functional deficiencies were detected along the 21/22 collector, namely: insufficient hydraulic capacity, seepage/exfiltration, obstructions, holes, and leaks/breaks.

The insufficient hydraulic capacity observed in the main sewer and in the secondary sewers means that the pipe was not able to evacuate the collected wastewater properly. There were several reasons for this structural defect. Firstly, it was caused by almost non-existent maintenance and changes in land use (urban development) during the lifetime of the pipe, leading to an increase in the flow of wastewater to be conveyed through the network. Secondly, defects related to the water tightness of the network have led to an increase in infiltration flows in the pipe. Finally, various types of obstruction (accumulation of debris or collapse of the pipe) cause occasional backflow in the sewer pipe in practically the entire first part of the collector (Lama, Fofana, Denver, and Sans Loi). Moreover, Yopougon was not the only municipality in Abidjan and even in Africa that shows dysfunctions related to insufficient hydraulic capacity. Koffi (2012) noted the same trend in Cocody, another municipality in Abidjan. According to his study, the reduction of the hydraulic load of the pipes by solid objects constitutes a major source of dysfunction of the network which is shown through backflow in Angré château and Cocody Center. Further beyond our borders, Ndongo et al. (2015) and Iloms et al. (2020) noted that problems related to the reduction of a hydraulic load of urban drainage networks constitute an alarming problem in several African cities, such as Maroua, Jonesburg, Accra, and are 52% responsible for flooding by backflow in these cities.

The infiltration/exfiltration phenomenon observed in the study area was caused by hydraulic overloading in the wastewater system. Infiltration in these areas was a major source of structural damage caused by elements of the sewer system (migration of soil particles from the liner or pipe bed). These problems have evolved over time and the failure to postpone intervention has led to serious problems such as the collapse of some pipes at the Sacré Coeur pharmacy. The voids created in the ground have also caused damage to nearby infrastructure (roads, utilities, risk of collapse of some houses) as observed at the Saint François roundabout. It should also be noted that the presence of uncontrolled connections causes serious seepage problems in the area. As the pipes were gravity-fed, seepage occurs in damaged areas or in the wet section of the pipe or in areas where there was an overload in the pipe and the internal pressure was higher than the external pressure. Indeed, this phenomenon is also the result of leaking water in the vicinity, combined with the presence of leaking connections, defective materials and structural defects (dysfunctional manholes, or defective loose connections). A study in the United States (Selvakumar et al., 2004) recognized that seepage and exfiltration in sewers contribute to the progressive degradation of pipes as well as being responsible for the destruction and collapse of roads in several municipalities in the last decade.

In addition, almost the entire main sewer as well as the upstream secondary sewers are confronted with blockages. These obstructions were seen by the presence of objects or materials in the pipe that limit the flow of water through reducing the available space; structures such as reducers are not included in the obstructions. Examples of obstructions are hard deposits (long-standing hardened deposits), intrusive objects or water-borne objects (deposits or objects). The causes of these defects includes: poor waste management practices in the study area (dumping of solid objects of all kinds into the pipes, etc.) and also almost non-existent maintenance of the sewer (Bamba and N'Doli, 2018). Wayou (2010) showed in a study on the diagnosis of the functioning of the sewerage system of the commune of Yopougon Niangon, that 70% of the residents use the sewers as a dumping ground for household waste, which is the reason for the blockage of the sewers. Similar results were obtained by Dadjo (2018) who observed that on average 45% of the drains studied in the city of Cotonou in Benin were blocked, 15% of which were deliberately blocked by local residents. With regard to the lack of maintenance, some structures were inaccessible due to the fact that constructions (kiosks, shops, houses, etc.) were positioned there, which made it impossible to clean them.

These obstructions were also due to the installation of certain infrastructures whose profile crosses the sewer. In the study area, deposits, caused by gravity, were not removed regularly, so they settle and harden on site, depending on their nature and time. Deposits generally came from industrial and commercial waste water, direct discharges of garbage by people into the system, surface water and seepage water. Intrusive objects were poles, construction debris due to poorly planned urbanization, unauthorized penetrating connections, crossing pipes (aqueduct and gas). They create a restriction of the section and were the cause of debris accumulation and eventually backflow as observed by Fofana (2017) in Andokoi in the commune of Yopougon. To prevent deposits from accumulating and becoming obstructions, it is recommended that sewer systems be cleaned periodically. Some sections of the pipes may require more frequent cleaning. This includes the entire area from Lama Fofana, through Denver, to Sans Loi. Some types of obstruction can be removed by reaming, while others will need to be removed by spot excavation or complete reconstruction.

The video camera inspection also identified several types of leaks in the pipe including cracks, circular, longitudinal, multiple leaks and holes. Circular cracks and fractures were observed around the entire circumference of the pipe and were located in the Center of the pipe section, at the joint and at the connection to the manholes. These types of structural dysfunctions have been identified in Lama Fofana in the vicinity of the Sacré Coeur pharmacy. Also, a multitude of longitudinal cracks were detected in the pipe. These were marked by visible lines on the surface of the pipe along the longitudinal axis. As for the fractures, they were seen by open cracks. All these different deficiencies were the result of bending loads that exceeded the capacity of the pipe or the influence of the temperature of the transported effluents. Also, several cracks and multiple fractures as well as holes observed in the pipe were responsible for backflow, collapse of pavements and damage to other infrastructures as observed along the entire length of the collector. These defects were more pronounced in Lama Fofana, Denver, Sans Loi, and Sideci Iroko. This was confirmed by Ali and Choi (2019) whose study concluded that leaky sewers were responsible for damage to urban infrastructure in Germany and also contributed to groundwater pollution. In most cases, a spot repair by excavation will be required. However, a trenchless intervention can be carried out if it is certain that no void exists in the ground behind the wall.

4.3. Environmental and socio-economic impacts of system dysfunction

With regard to the socio-economic and environmental impacts, the dysfunction of the networks has led to the progressive degradation of roads in several neighborhoods in the two study areas, as observed in Lama Fofana, Camp militaire, Cité Abdoulaye Diallo, Banco 2, and almost 62% of the roads in Kpimply. This fact was also noted by Kablan et al. (2019) in his study in which he underlines the destruction of the roadway in some neighborhoods of Cocody as a result of wastewater run-off from dysfunctional sewers and open-air networks.

Also, the landslide phenomenon has caused the displacement of several families along the Uniwax canal. 7.35% of families have been affected by this phenomenon. These displacements of families were explained by a widening of the canal occupying the surfaces occupied by the houses (this is the case of several families located along the system in Banco 2, Gbinta, and Kpimbly). These impacts were comparable to those of the Cocody-Riviera municipality. Indeed, in a study carried out on the M'Badon Canal, Ouattara et al. (2021) showed that erosion and landslides forced 11.2% of families located in Akouédo village to vacate their homes and move permanently. During displacement, people spent a lot of money (on average 640 USD), which becomes a burden that modest families cannot bear. Therefore, putting in place a well-structured pipe management strategy could help to avoid this social dislocation of families.

4.4. Solid waste and wastewater management practices

The preferred method of examining solid and liquid waste management practices in communities was the household survey (Ouattara et al., 2021). This enabled the attitudes and risk practices of the households in the study area to be identified in relation to the management of household waste and wastewater. Here, the level of education of the inhabitants and the length of stay in the surveyed areas were relevant criteria that underline the reliability of the results obtained. Although some residents handed their waste to the pre-collectors (26%), the majority of residents living along the drains (74%) do not own waste bins and used the drains as a public dumping ground, especially in neighborhoods with low levels of education. This situation highlights the reasons for the clogging of the drains due to the misuse of the drains by the residents. Examination of the solid waste disposal method helped to clarify on the extent of the situation. Indeed, even if some people used the pre-collectors, many residents prefer to dispose of their waste in the drains, as observed in Lama Fofana, Denver, and Sans Loi, as well as in the second and third parts of the Uniwax canal. There are several reasons for this. If the lack of civic-mindedness and the low level of education of the population can be considered as the main reason, the galloping demography, the accelerated urbanization and the inefficiency of the public authorities cannot be ignored.

Indeed, the rapid demographic growth of the municipalities has rendered the previously conceived urban plans and other master plans non-operational. At the same time, it has accelerated the uncontrolled development of the various districts. This increase in needs of all kinds, out of all proportion to local availability, has led to a break in the capacity of existing infrastructures, particularly in terms of rainwater and domestic drainage as well as other networks. Studies and surveys conducted in the field have revealed a greater share of several irregular settlements on both sides of the drains in the Yopougon municipality. Faced with the difficulties experienced by the municipal authorities in satisfying the demands expressed, the populations settled without right or title, most often in areas unsuitable for habitation, thus creating a proliferation of precarious and unhealthy neighborhoods. This situation was at the root of the increase in all kinds of waste, which was one of the major causes of unhealthy neighborhoods, the main receptors of which were the rain water and waste water drainage channels and the urban road network (Foorginezhad et al., 2021). Bangoura (2018), in a study on the management of solid household waste in the city of Conakry, showed that 76.6% of household waste was generated by precarious neighborhoods whose destination was the street and urban sewage systems.

In the specific area of solid waste, management remains poor in the Yopougon municipality, despite the efforts of the municipal technical services. Collection was irregular and unsystematic, and the material means of collection were insufficient and most often unsuitable and inappropriate. In the recent past, the rate of household waste collection varied from 32 (2001) to 98% (1998) over the period from 1994 to 2007 (Aké, 2008). This was found (NGambi, 2016) in five African capitals (Dakar, Bujumbura, Yaoundé, Cotonou, and Nairobi). Their study showed that the rate of waste collection in all the cities taken into account does not exceed 50% and the average was 36.7%. This waste thus ends up in the drains, causing them to malfunction.

As for wastewater management, the waste water drainage network did not sufficiently cover all the districts, even though the area seemed to be developed. For the most part, standalone sanitation was the norm in some neighborhoods: toilets with a connection to a septic tank. In areas where the groundwater table was sub-surface, it was possible that groundwater was contaminated by latrines and leaking septic tanks. Household waste water (washing and cooking water) was mostly discharged through uncontrolled connections to the rain water network and to the public highway, as 60% of the 21/22 collector was blocked, contributing enormously to the deterioration of the environment and the pavement.

5. Conclusion and recommendations

The initial aim of this research work was to carry out a functional diagnosis of the urban sanitation networks of the Yopougon municipality in Abidjan. This diagnosis was to distinguish the sections actually responsible for overloading or overflowing from those showing signs of failure, for which the responsibility lies with the other sections of the network. The usefulness of such an approach was in the establishment of intervention priorities to maximize the return on investment allocated to operational and structural rehabilitation and to develop tools for better management of the city's urban sewerage networks. As demonstrated in this work, this objective has been largely exceeded. The diagnosis of the networks was carried out in a meticulous manner. A general application methodology was proposed, which allowed the identification of the different dysfunctional factors of the operational performance of each section of pipe of the two sewerage networks. This performance methodology was built from factors intrinsic and extrinsic to the network pipes. The intrinsic factors involved the structural condition of the pipe. These were the various defects identified during the video camera survey stage (cracks, fractures, obstructions etc.). The extrinsic factors involved the environment of the pipe in which these defects originated. These were mainly human factors responsible for the dysfunction of the network (poorly planned peri-urban agricultural activities on both sides of the pipes, illegal solid waste deposits, defective unauthorized connections, etc.). The analysis of the results obtained in this study revealed the need to take corrective measures at the household level as well as at the network level, also taking into account unplanned urban agriculture, waste water management and solid waste collection.

As a result of this study, the following recommendations were advanced: Information, training and awareness campaigns for households on hygiene and health risks due to wastewater should be carried out, channels such as television, radio, schools and colleges could be used; the involvement of households in the entire process of implementing environmental sanitation projects; taking into account the opinion of local residents on the form of organization of the management of the systems envisaged in the neighborhoods in order to ensure the efficiency and sustainability of the sanitation systems. Because of the difficulties linked to access to certain neighborhoods, it would be wise for the municipal authorities to equip and encourage pre-collectors to collect waste in the neighborhoods and to put them in an area accessible to collection vehicles. Also, a raise awareness among the population and instill in them a culture of risk and develop a local consultation framework to harmonize the activities of the various actors, in particular civil society, non-governmental organizations (NGOs), and the private sector involved in promoting hygiene and sanitation, by involving young people, representatives of housing estates and village leaders; set up modern structures for pre-collection and collection of household waste (grouping centers for household waste, modern municipal landfill) and increase the capacity of the rolling stock for collection and pre-collection along the canal and carry out regular cleaning and maintenance work on the pipes to facilitate the drainage of waste water and rain water; this could reduce flooding caused by overflow in the network.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

ZO and KD: conceptualization and methodology. ZO, ES, and KA: software and resources. AK-B, KD, KA, KK, and MK: validation and supervision. ZO and ES: formal analysis. ZO, KD, AK-B, KA, ES, and KK: investigation. ZO, KA, KD, and KK: data curation. ZO, AK-B, KD, KA, and MK: writing original draft preparation and writing review and editing. ZO: visualization and project administration. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

KK was employed by Societe de Distribution d'Eau de Cote d'Ivoire (SODECI).

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2023.1032459/full#supplementary-material

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