Consistent Classification System for Sewer Pipe Deterioration and Asset Management

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Abstract: Sewer pipe deterioration is driven by a finite number of root causes and processes. Thus, it should be both feasible and advantageous to have a uniform classification system that can be universally applied in sewer deterioration modeling and asset management. However, a literature review of existing classification systems revealed several problems and inconsistencies, and no widely adopted system. This work proposes a uniform classification system that can be used for different purposes in the fields of gravity pipe deterioration and asset management. This paper focuses on separated sewer systems, but the proposed system can be easily adapted for combined sewer and stormwater systems. The proposed system is based on three top-level categories of failures, defects, and factors with subcategories based on functional considerations. Each category is unambiguously defined and a classification flow diagram is proposed. This work demonstrates how existing parameters can be consistently classified, discusses the interactions between different defects and failures, and illustrates the application of the proposed system to the processes causing overflow failures due to sedimentation. **DOI: 10.1061/(ASCE)WR.1943-5452.0001545.**

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Introduction

The critical role of sewer pipelines in the sewer collection system has forced utilities to consider proactive asset management strategies (Grigg 2012; Salman and Salem 2012). Utilities are willing to invest in efficient, proactive asset management strategies to minimize the cost of owning and operating infrastructure assets while delivering the desired service levels to customers (Roghani et al. 2019). The main goals of a proactive asset management strategy are avoiding catastrophic failures, optimizing maintenance and rehabilitation strategies, and accurately planning for future requirements (Hawari et al. 2020).

The proactive asset management process for sewer networks consists of the following components: (1) data collection and processing, (2) deterioration models and condition assessment, (3) proactive asset management, and (4) implementation.

Data collection and processing play an important role as the initial step in acquiring more reliable condition assessment irrespective of frameworks used (Yin et al. 2020a). This includes investigating those factors affecting sewer pipe performance; inspecting the infrastructure's physical and functional condition manually or with different technologies such as closed-circuit television (CCTV), ground-penetrating radar (GPR), or sewer scanner and evaluation technology (SSET); and using professional and trained operators or automated defect detection models to analyze data (Moradi et al. 2019; Yin et al. 2020b).

Deterioration models and condition assessment facilitate the decision-making process by predicting the current and future condition of sewer segments. In other words, deterioration models provide condition assessment by evaluating the deterioration of sewer pipes, considering certain influencing factors to make informed decisions about complementary investigations, maintenance, repair, or potential replacement (Hawari et al. 2020; Baik et al. 2006).

Deciding whether and when rehabilitation or replacement is needed constitutes the proactive asset management step. The asset management strategy is then implemented, and the process is repeated.

Performance classification systems are used to make sense of the large range and complexity of parameters involved in sewer asset management. A review of the literature published showed that several classification systems have been proposed to investigate the variables that affect sewer pipeline performance (e.g., Ana and Bauwens 2010). Each classification system was developed for different purposes within the asset management process. While there are similarities among them, significant differences and inconsistencies limit their wider application. Besides the fact that different numbers and types of categories are used, few systems provide clear definitions for the classes. In addition, there are often internal contradictions within a system and contradictions between different systems. As a result, there is no widely accepted and consistent classification system for sewer asset management parameters.

Given that all the classification systems are applied to some aspect of the pipe deterioration and asset management cycle, it should be both feasible and advantageous to define a uniform classification system that can be universally applied in the deterioration modeling and asset management fields. Benefits of a uniform classification system (adapted from Finisdore et al. 2020) include the following:

- a unifying language;
- a consistent basis for selecting or categorizing parameters;
- a consistent basis for developing metrics and functional relationships;

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- the ability to compare the results of different studies; and
- improved knowledge transfer and management.

The development of such a new classification system was the main aim of this work.

The proposed system is based on existing classification systems, but is different from anything currently in existence. It is based on three top-level categories of failures, defects, and factors. Each of these categories is clearly defined according to their subcategories and components that can be unambiguously applied.

At the heart of the proposed system is the realization that (1) the condition of sewer pipes is affected by many factors that are not problems in themselves, and (2) most problems (e.g., a crack in a pipe) in sewer pipes do not constitute a failure in themselves. Thus, the term "factor" is defined as a parameter that may influence the condition of a sewer pipe but is not a problem in itself. "Defect" is defined as a problem in a sewer system that is undesirable and may require monitoring but does not require immediate action. Finally, "failure" is defined as a problem for which society would expect immediate action.

In the first part of this paper, existing classification systems in the sewer asset management domain are grouped by purpose and then discussed. The existing systems are compared, and problems—such as a lack of clearly defined concepts, internal inconsistencies, and contradictions between systems—are discussed. A new classification system is then proposed with clear definitions of all terms and consistent categories and subcategories. The proposed system is discussed, pointing out potential weaknesses and improvements, and its application is demonstrated. Although this paper focuses on separated sewer systems, the same principles apply to combined sewers and stormwater systems, and can be adapted to these systems with ease.

Current Classification Approaches

The literature reviewed for this paper is based on publications that apply classification systems of parameters affecting sewer pipe performance. These publications were selected from peer-reviewed journals, conferences, codes, and other sources since 2001. The distribution of publications reviewed is as follows: five from peer-reviewed journals; four from conference papers; three from codes; and two from research theses. The publications were grouped by the purpose of the classification system according to the asset management cycle steps. A summary table and a brief description of the classification systems are provided under each heading.

Data Collection and Processing

Understanding and collecting parameters affecting the deterioration process of sewer pipelines is the first step in implementing any asset management strategy (Angkasuwansiri and Sinha 2013). A summary of the data collection and processing papers and their classification systems is provided in Table 1.

Angkasuwansiri and Sinha (2013) noted that a complete list of parameters that affect sewer pipes did not exist, and they compiled an alphabetical list from available literature, providing a brief description and the potential impact for different pipe materials. They also provided a table summarizing potential sources of data for the parameters. Although the paper noted that failures depend on pipe characteristics, the surrounding environment (internal and external) and operational practices, no attempt was made to further classify the parameters.

A number of guidelines for pipe inspection have been published, including EN-135082 in Europe (CEN 2011), Pipeline Assessment Certification Program (PACP) in the United States (NASSCO 2001), Conduit Reporting Code (WSA05) in Australia (WSA 2020), and the Gravity Pipe Inspection Manual Standard of New Zealand (NZGP 2019). Each of these guidelines provides a procedure for documenting present condition and defects in pipelines. These codes are related to each other—for example, the New Zealand's code is based on EN 13508-2 and WSA05. Table 1 presents the New Zealand code and NASSCO's classification systems. These standards specify an agreed set of descriptors to classify defects and features in pipelines and impose a universally compatible process for the transfer of data (NZGP 2019).

PACP classifies defects and features into the following five groups: continuous defects, structural defects, operational and maintenance defects, construction features, and miscellaneous features (NASSCO 2001). PACP's defect and feature classifications have been applied in other studies—for example, in a review on automizing sewer inspection using computer vision models (Moradi et al. 2019).

In the Gravity Pipe Inspection Manual Standard of New Zealand (WNZ 2019), a coding system for describing features and defects observed in gravity pipes is presented. Features are defined as attributes or components of pipelines or any information gathered by inspection that cannot be classified as defects. Defects are defined as faults that weaken the strength, durability, water tightness, or hydraulic performance of pipelines. Defects are classified into two groups, namely structural (related to strength characteristics), and service (related to performance). According to this coding system, defects are quantified, and weighted scores are assigned to them to determine the condition grade of individual pipes.

Stanić et al. (2014) applied a hazard and operability (HAZOP) approach to identify the main processes responsible for the structural or operational failures of sewer elements, as well as the possibility of obtaining information on them. The HAZOP results were applied in a fault-tree analysis for risk estimation, as shown in Fig. 1. The top level of the hierarchy is described as "top failure events" and categorized into two main groups: system and element performance. System failures were defined as occurring when the load exceeds the pipe capacity, or the pipe capacity is inadequate for the imposed load. In element failures, the load exceeds the pipe strength, or the pipe strength is insufficient for the imposed load, causing sewer collapse. It is argued that element failures do not necessarily lead to system failures, which seems unlikely to be the case in practice.

Deterioration Modeling and Condition Assessment

Significant effort has been made to develop deterioration models and condition assessment approaches to better understand the performance of sewer pipes. Condition assessment supports decisions on repair, rehabilitation, or renovations of assets for utilities (Mohammadi et al. 2019). Papers on deterioration modeling and condition assessment and their classification systems are summarized in Table 2.

Davies et al. (2001) identified and described the factors that influenced the structural stability of a rigid sewer pipe and categorized them into three main groups: construction features, local external factors, and other factors. The influence of each parameter was discussed comprehensively in the study. It was concluded that a sewer pipe must be considered as a composite structure consisting of the pipe itself, the ground in which it is buried, and the local environment.

In a review of statistical models used for predicting structural deterioration of urban drainage pipes by Ana and Bauwens (2010), factors that lead to sewer structural deterioration were

Table 1. Classification systems used in the data collection and processing

Source	Main categories	Subcategories	Parameters
Angkasuwansiri and Sinha (2013)	Alphabetical list of parameters	None	Age, backup flooding, bedding condition, blockage, cathodic protection, closeness to trees, coating, condition, connection density, cover depth, design life, diameter, dissimilar materials, disturbances, exfiltration, extreme temperatures, failing utilities, FOG (fat-oil-grease), flow velocity, frost penetration, function, groundwater table, hydrogen sulfide gas (H_2S), inflow and infiltration (I&I), installation, joint type, lateral, length, lining, live load, location, manhole, manufacture, material type, moisture content, odors, operational pressure, overflow, precipitation, seismic activity, slope, slope stability, soil corrosivity, soil pH, soil redox potential, soil resistivity, soil sulfides, soil type, stray currents, surcharging, tidal influences, thrust restraint, trench backfill, trench width, type of cleaning, vintage, wall thickness, wastewater quality, wet/dry cycles
PACP (NASSCO 2001)	Features	Construction	Tap, intruding sealing material, line, access point
		Miscellaneous	General observation, joint length, lining change, material change, shape/size change, water level, not visible
	Defects	Continuous	Truly (extends more than 1 m), repeated (appears in a length of pipe in at least 3 out of 4 of the joints)
		Structural	Cracks, fractures, broken, hole, deformed, collapse, joint, surface damage, lining features, weld failure, point repair, brickwork
		Operation and maintenance	Deposits, roots, infiltration, obstacle obstructions, vermin, grout test and seal
Moradi et al. (2019) (based on PACP)	Defects	Structural	Cracks (longitudinal, circumferential, multiple, spiral), joint (offset, angular, fracture, separated), deformed, hole, collapsed, broken
		Construction	—
		Operation and maintenance	Roots, deposits, infiltrations, obstacles
Gravity Pipe Inspection Manual Standard of New Zealand (WNZ 2019)	Features	—	Liner construction, lateral connections, inspection points
	Defects	Structural	Surface damage (such as corrosion and damage on pipe surface), cracked pipes (such as cracks, broken pipe, pipe holes, deformed pipes, and collapses in rigid pipes), deformation in flexible pipes, masonry pipes, roots, joint faulty, lateral faulty
		Service	Debris greasy, encrustation deposits, root intrusion, obstruction, blocked pipes, dipped pipes, exfiltration, infiltration, and water level
Stanić et al. (2012) (Fig. 1)	Top failure events	System failure (load > capacity)	Flooding, frequent combined sewer overflows (CSOs), soil contamination, exposure to health hazards
		Element failure (load > strength)	Collapse of structural elements, breakdown of mechanical elements

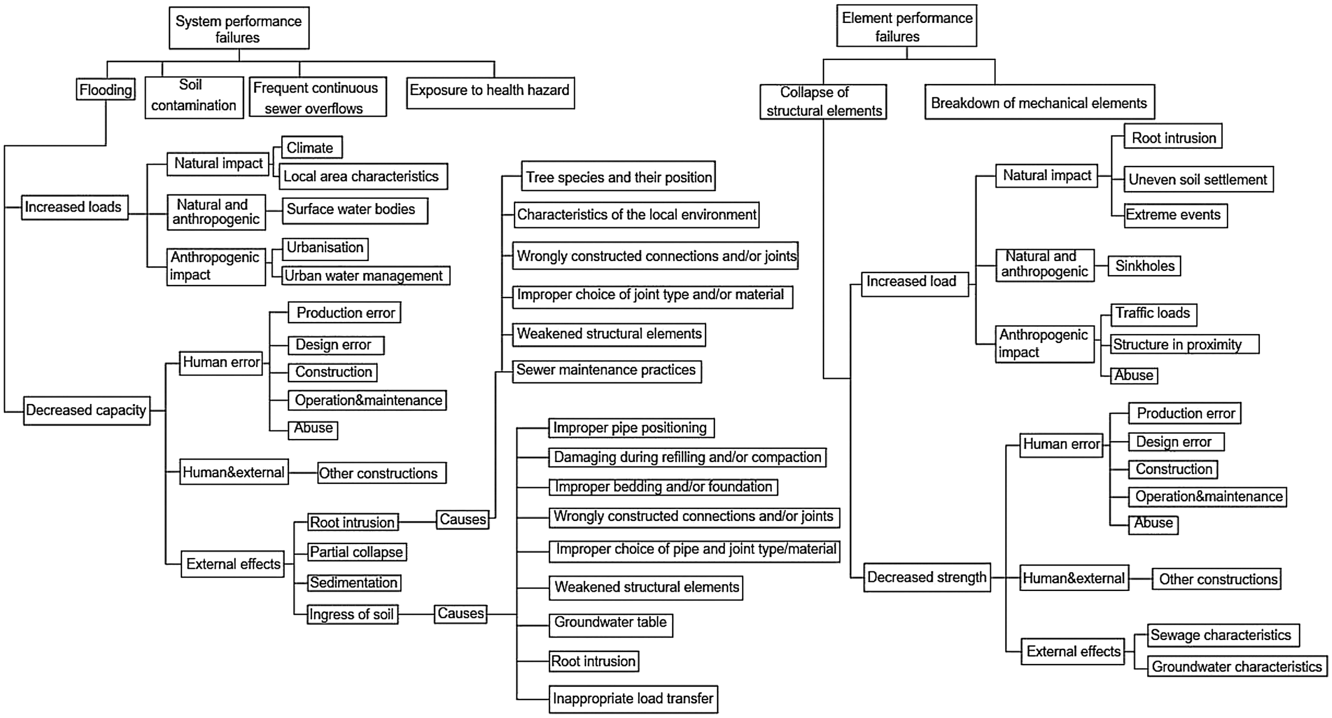

Fig. 1. Fault tree for failure mechanisms in sewer systems obtained through a HAZOP analysis. (Adapted from Stanić et al. 2012.)

Table 2. Classification systems used in deterioration modeling and condition assessment

Source	Main categories	Subcategories	Parameters
Davies et al. (2001)	Factors	Construction	Load transfer, standard of workmanship, sewer size, sewer depth, sewer bedding, sewer material, sewer joint type and material, sewer pipe section length, sewer connections
		Local external	Surface use, surface loading and surface type, water main burst/leakage, ground disturbance, groundwater level, soil/backfill type, root interference
		Other factors	Sewage characteristics, inappropriate maintenance methods, asset age
Ana and Bauwens (2010)	Factors	Physical	Pipe age, pipe shape, pipe size, sewer depth, sewer length, sewer material, sewer slope, sewer type, joint type, and material
		Environmental	Groundwater level, infiltration/exfiltration, presence of trees, soil, backfill type, traffic, and surface loadings
		Operational	Sediment level, sewage characteristics, maintenance and repair strategies
		Construction	Installation method, standard of workmanship
Chughtai and Zayed (2007b)	Structural factors	Physical	Pipe age, pipe diameter, pipe length, pipe material, pipe depth, pipe gradient
		Operational	Maintenance and repair strategies
		Environmental	Type of soil, type of wastes, bedding condition, frost factor, the proximity of other utilities, traffic volume, and groundwater
Chughtai and Zayed (2007a)	Operational factors	Hydraulic	Inadequate flow capacity, infiltration and inflow, inadequate sewer gradients
		Nonhydraulic	Random blockage, debris-fats-greases, roots, pumping station/screening equipment failure, operational and maintenance history
Hawari et al. (2017)	Factors	Physical	Pipeline age, pipeline diameter, pipeline length, pipeline material, pipeline coating conditions, installation quality
		Operational	Flowrate, blockages (e.g., roots, sediments), infiltration and inflow, corrosive impurities, maintenance and break strategies, operating pressure in pressurized pipelines
		Environmental	Soil type, bedding conditions, location (e.g., traffic load), groundwater level, ground disturbance (e.g., construction work)
Laakso et al. (2018)	Factors	Pipe attributes	Age, installation year, diameter, material, location, depth, length
		Attributes related to pipe environmental	Soil type, road class, intersections with other pipes, distance to a tree
		Attributes related to the network structure	Estimated annual sewage flow, water consumption of all water users upstream of the pipe

grouped into four categories: physical factors related to the pipe attributes; environmental factors related to the characteristics of the surrounding environment; operational factors related to how pipes operate; and construction factors related to the manner of construction.

Chughtai and Zayed (2007b) conducted a study on predicting sewer pipeline conditions for prioritizing detailed inspections. Factors that may influence the structural condition of pipes were grouped into three main categories: physical, operational, and environmental. In another paper by the same authors, factors that can affect operational conditions were grouped into two categories: nonhydraulic and hydraulic. Hydraulic problems occur if the sewer capacity is inadequate to handle high flows, while nonhydraulic problems are not due to a lack of flow capacity (Chughtai and Zayed 2007a).

In a study by Hawari et al. (2017), a simulation-based condition assessment model for sewer pipes is presented to accurately evaluate and assess their condition. Factors were placed into three main categories: physical, operational, and environmental. Seventeen factors affecting gravity pipeline performance and one other factor affecting pressure sewers were included in the model. Factors are weighted through a distributed questionnaire and included in a model. A detailed description and definition for each factor were provided. However, the "factor" and "category" terms were not defined, and it is not clear how factors are selected and incorporated into categories.

Laakso et al. (2018) combined inspection results with weighted influencing factors to predict sewer pipe condition and locate pipes with serious defects that need urgent renovation or replacement. This study divided influencing factors into three categories: pipe attributes; attributes related to the pipe environment; and attributes related to network structure. While the study stated that the installation year represents the quality of construction work, it is categorized as a pipe attribute.

Proactive Asset Management

The classification systems of the two studies identified as being aimed at proactive asset management are summarized in Table 3.

Opila (2011) used the structural condition scores of buried sewer pipes for risk-based decision making. Factors leading to failures were categorized into three groups: pipe design and installation, quality of installation, and ongoing environmental or operational. Also, a failed pipe was defined as one requiring action ranging from rehabilitation to replacement to return the pipe condition to the desired level of service. Thus, the occurrence of a failure may vary depending on the required level of service provided by the pipe. A failure can range from a small leak to a complete pipe collapse. It was argued that most pipe failures are caused by several contributing factors rather than a single factor. Failures are classified into five categories: structural, operation and maintenance, hydraulic capacity, economic, and water quality.

The wastewater renewal framework for gravity pipelines in New Zealand (McFarlane 2018) defines and categorizes service failures. These failures occur when the wastewater system is incapable of providing the intended service. The failures are grouped into four categories: operational, strength, containment, and capacity. Operational failures occur when a sewer pipe is unable to convey the quantity of flow that it was designed to convey. Strength failures occur when a sewer is unable to withstand the forces

Table 3. Classification systems used in implementing proactive asset management in sewer pipelines

Source	Main categories	Subcategories	Parameters
Opila (2011)	Factors	Pipe design and installation	Pipe structural properties, manufacturing- storage-handling of pipes, pipe material- thickness- diameter- length, joining plastic to metal/concrete pipes
		Quality of installation	Jointing techniques, bedding material, and placement
		Ongoing environmental/operational	Internal physical loading (including operational pressure, operating cycles, external physical loading (including soil overburden, traffic patterns, traffic loads), chemical, biochemical, electrochemical environment (including internal (water–pipe interactions), external (soil–pipe or groundwater–pipe interactions), Changes in ground condition (including weather condition, shrinking or swelling of the soil, frost loads, local disturbance (including nearby digging, soil erosion, changes in the water table, root intrusion)
	Failures	Structural	Subcauses: pipe collapses, breaks, cracks, and corrosion
		Operations and maintenance	Subcauses: debris deposits, roots, infiltration, and obstacles
		Hydraulic capacity	Subcauses: wall friction change, subsidence, changing catchments, infiltration, rainfall, guideline changes
		Economic	
		Water quality	
Wastewater Renewal Framework for Gravity Pipelines in New Zealand (McFarlane 2018)	Service failures	Operational	Subcauses: silt, fat, and roots
		Strength	Subcauses: degradation of sections of pipelines, deterioration of pipe wall, shock events
		Containment	Subcauses: joint leakage, leakage through cracked and damaged pipes, infiltration
		Capacity	Subcauses: wet weather flow, growth in upstream areas

applied to it either during normal operation or shock events such as earthquakes. Containment failures occur when a sewer is unable to stop ground water leaking in or wastewater leaking out. Finally, capacity failures occur when a sewer is unable to convey the required quantity of flow.

Discussion

The literature review shows that, while there are similarities among approaches, there is no consistent approach to the classification of sewer system deterioration modeling or asset management. It is, therefore, difficult to interpret and compare different studies to build a consistent and scientific understanding of how sewer pipes deteriorate and fail.

Despite the fact that the classification systems discussed were developed for different purposes, they consider the same underlying problem of sewer pipe deterioration and, thus, it should be possible to develop a consistent classification system that can be used for different purposes.

This section discusses the main differences and problems in the reviewed classification systems, including inconsistent terminology, missing or inconsistent definitions, and inconsistent classifications.

Inconsistent Terminology

The classification systems studied used a wide range of terms to describe their categories, such as parameters, features, defects, factors, and failures. Fig. 2 illustrates the range of terms used by publications in different steps of the asset management process. While papers on Deterioration Models and Condition Assessment consistently used the term "factors," both "factors" and "failures" are used in Proactive Asset Management and four different terms in Data Collecting and Processing.

As can be expected, there are similarities in what is grouped under the same term by different studies. However, in some cases, different terms are used for the same concept, while others use the same term for different concepts. For instance, Angkasuwansiri and Sinha (2013) used the term "parameter" as an umbrella term that includes infiltration and overflows, while Stanić et al. (2012) classified overflow as a "failure." Hawari et al. (2017) used "factor" as an umbrella term that includes infiltration and blockage, while Laakso et al. (2018) limited "factor" to attributes related to pipe, environment, and network structure.

Missing or Inconsistent Definitions

The problem with inconsistent terminology is exacerbated by the fact that terms are not explicitly defined in most studies. Only three

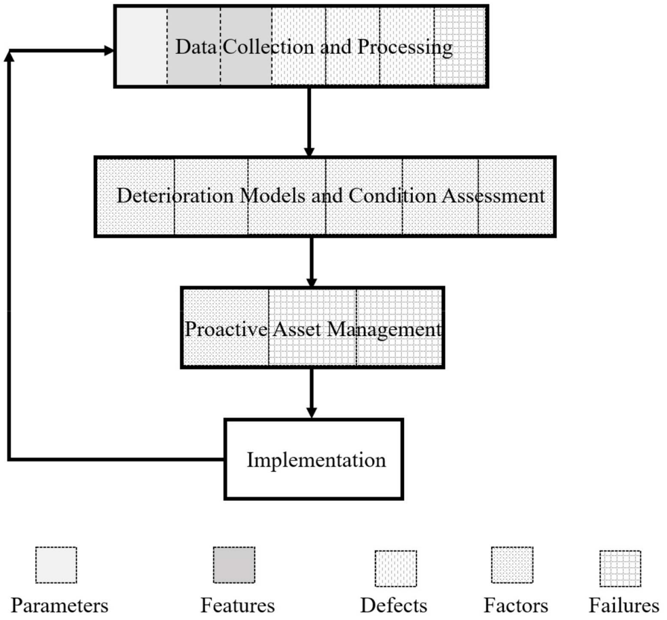

Fig. 2. Frequency of terms used in different steps of the asset management process.

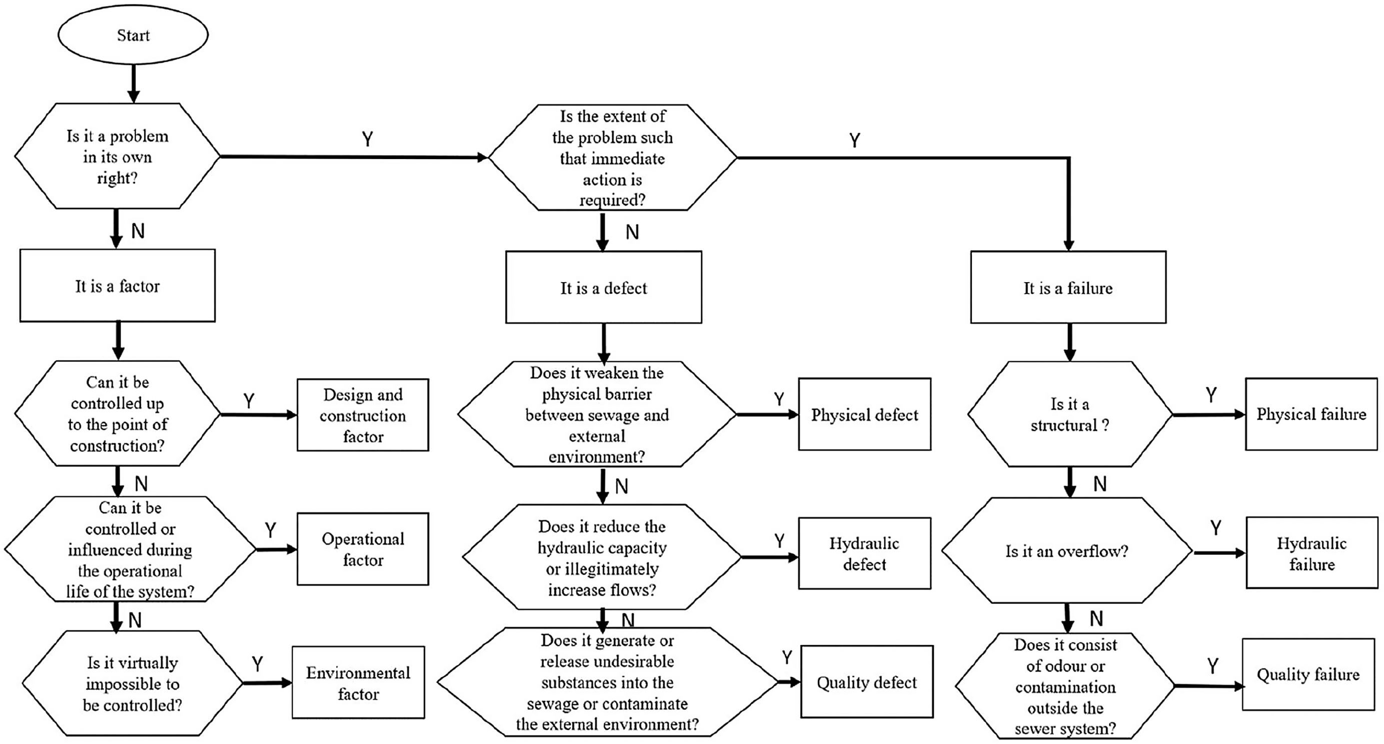

Fig. 3. Flow diagram for the proposed classification system.

of the 13 papers reviewed defined all classification terms used, and one defined some of the terms used. Stanić et al. (2012) defined all terms related to failure and its classification. The guidelines studied define all terms related to defects and features and their classifications. Chughtai and Zayed (2008) defined terms used in their classification systems, including "physical," "operational," and "environmental," but did not define "factor."

Where terms were defined, the definitions were sometimes inconsistent. For instance, the New Zealand Gravity Pipe Inspection Manual (WNZ 2019) defines defects as "faults in the pipeline that deteriorate the strength, durability, water tightness, or hydraulic performance of the pipeline," while Marne (2013) defines defects as "deviations that can be seen in the physical state of the sewer pipeline." Not only do these two definitions of defects differ in content, but "deviations" in the second definition is subjective and leaves significant room for interpretation.

There are significant inconsistencies in the definition of failures. Stanić et al. (2012) categorizes failures in terms of pipes' capacity and strength specifications, while Opila (2011) defines failures in terms of the desired level of service. A particular difficulty with defining failures is how to distinguish between failures that have little or no impact on the operational capacity of the pipe (such as a crack), and failures that lead to blockage of the pipe and sewage spills (such as a pipe collapse).

Inconsistent Classification

Several inconsistencies in the way that terms are classified were observed. For instance, Ana and Bauwens (2010) and Hawari et al. (2017) classified age as a physical pipe feature, while Davies et al. (2001) classified age under other factors.

Additionally, while Opila (2011) classified a sewer pipe's installation quality as an independent category, Hawari et al. (2017) classified it as a physical attribute, and Davies et al. (2001) and Ana and Bauwens (2010) classified it as a construction attribute.

Proposed Classification System

This section proposes a consistent classification system for deterioration modeling and asset management of gravity sewer pipes. The classification system is partly based on previous systems, but aims to avoid the problems and inconsistencies of existing systems. It identifies categories and subcategories based on conceptual or functional groupings. A flow diagram for classifying any parameter into a primary factor, defect, or failure category is given in Fig. 3. Note that, where a parameter can be placed in more than one category, the flow diagram is meant only to identify the primary category, while secondary effects are discussed later this section.

Main Categories

Sewer failures generally do not occur suddenly in an otherwise perfect system, but happen at the end of a long and complex deterioration process. They are influenced by several parameters, some that are problems in themselves (e.g., sedimentation or pipe wall cracks) and others that are not (e.g., rainfall or urban densification). Based on these observations, we propose three main categories: failures, defects, and factors.

In some cases, the difference between a defect and failure may only be a matter of degree—for example, sewage leaking through a pipe crack may result in limited and localized soil contamination (a defect) or contaminate a nearby drinking water supply (a failure). Thus, to clearly demarcate the boundary between defects and failures, failures are defined in terms of societal expectations—that is, a problem that society would expect immediate action on.

The following definitions are proposed for the main categories:

- ***Failure:*** *A state or event that has a negative impact on people, property, or the environment and which society would expect immediate remedial action on*. Examples include sewer pipe collapse, sewage overflows, groundwater contamination, and disagreeable odors.

- ***Defect:*** *An undesirable problem or condition in the sewer system that does not constitute a failure in its own right*. Examples include pipe cracks, sediment buildup, and hydrogen sulfate production. Defects often worsen over time and can interact with other defects or factors to cause failures. Defects are common in most sewer systems and, while they are undesirable and may be monitored or used as the basis for prioritizing maintenance interventions, they are generally tolerated.
- ***Factor:*** *A property, condition, or event that may contribute to a defect or failure but is not a problem in its own right*. Examples of factors include pipe material, sewage composition, and rainfall.

Subcategories

Subcategories were defined for each of the three main categories based on the most appropriate conceptual or functional grouping.

The concept of system integrity, defined for water distribution systems by the National Research Council (NRC 2006), provided a valuable basis for further classifying failures and defects. This report defined three integrity domains in which system failures may occur—physical, hydraulic, and quality—which were adapted to sewer systems through the following definitions:

- ***Physical integrity*** *refers to the maintenance of a physical barrier between the sewer system interior and the external environment*.
- ***Hydraulic integrity*** *refers to the maintenance of a desirable sewer flow capacity, minimum and maximum velocities, and sewage age*.
- ***Quality integrity*** *refers to maintaining acceptable sewage quality inside the sewer system, avoiding the release of undesirable substances or generation of undesirable byproducts, and avoiding contamination of the external environment*.

The value of adopting this subclassification is that, while the different integrity domains are interrelated, each domain can be lacking despite the other two being intact. Thus, all three must be intact to ensure full system integrity. For instance, a system may have perfect physical integrity (no pipe breaks or cracks) and quality integrity (no undesirable substances in the sewage), but lack hydraulic integrity due to insufficient pipe flow capacity, resulting in overflows during a peak wet weather event. It is worth noting that a system may lack hydraulic integrity (and thus overall integrity) even before the overflow failure occurs due to lack of adequate flow capacity to handle a foreseeable peak flow event. Once the overflow failure occurs, multiple additional failures will result, such as land and surface water contamination. However, the primary cause of such failure is lack of hydraulic integrity, which was present even before the failure occurred.

Failure Subcategories

Failures can be classified into the following categories based on the type of integrity loss they are primarily caused by:

Physical failures *occur when sewer components structurally fail through a break or collapse to the extent that immediate remedial action is required*.

Hydraulic failures *occur when the flow in system components exceeds their hydraulic capacity to the extent that this leads to sewage overflows*.

Quality failures *occur when releases into the sewage, internal sewage processes, exfiltration, or overflows lead to contamination or odors inside or outside the system to the extent that immediate remedial action is required*.

Table 4 provides a classification for the primary cause of failures that occur in sewage systems. As noted in the table, different types of failures are strongly linked. In particular, physical failures (pipe collapse or pipe break) will generally result in a blockage or flow path to the surface, leading to a hydraulic failure (overflow). In turn, hydraulic failures will invariably result in quality failures in the form of land and surface water contamination, and sometimes also coastal contamination and odor.

Table 4. Classification of sewage system failures

Category	System failure
Physical	Pipe collapse[a] Pipe break[a]
Hydraulic	Overflow[b]
Quality	Odor Groundwater contamination Land contamination Surface water contamination Coastal contamination

[a] Very likely to cause hydraulic failure through sewage overflow.

[b] Very likely to cause quality failures through land and surface water contamination, possibly also coastal contamination and odor.

Defect Subcategories

Similar to failures, defects are classified based on the type of integrity they primarily impact.

- ***Physical defects*** *weaken or breach the physical barrier between the sewage and the surrounding environment*. This includes internal and external damage to pipes, linings, and joints.
- ***Hydraulic defects*** *reduce the capacity of sewer components to carry legitimate sewage flows.* Legitimate sewage flows include all inflows that the sewage system is designed to carry, such as industrial and household wastewater. Hydraulic defects include problems that reduce the hydraulic capacity of system components (deposits and obstructions) and problems that illegitimately increase sewage flows, such as connections to the stormwater system, private drainage connections, and groundwater ingress.
- *Quality integrity refers to maintaining acceptable sewage quality inside the sewer system (i.e., avoiding the release of undesirable substances or generation of undesirable by-products), and avoiding contamination of the external environment.* Undesirable substances are fluids or items that consumers should not release into the sewage system, such as engine oil, cooking oil, wipes, and sanitary products. It excludes releases that would be considered normal, such as fats and oil from dishwashing. The problem with undesirable substances is related to the quality or makeup of the sewage rather than the volume of fluid (which would constitute a hydraulic defect).

In some cases, defects also affect another category, such as physical defects that also act as hydraulic defects, including pipe deformation, misalignments, and seals or liners that obstruct the flow path. Other examples include hydraulic defects that also act as quality defects, such as sediments or roots providing additional surface area for slime layers that convert sulfates in the sewage into ionic sulfides. Table 5 provides a classification for the main defects that occur in sewage systems.

It should be noted that the defects that affect more than one category are either primarily structural with a secondary hydraulic impact, or hydraulic with a secondary quality impact. In each case, the primary classification also appears first in the flow diagram (Fig. 3), with secondary categories obtained from Table 5 or engineering judgment.

Factor Subcategories

Factors are (by definition) not problems in their own right but may contribute to defects or failures. Thus, factors are not amenable to

Table 5. Classification of sewage system defects based on the type of integrity they primarily impact and grouped by where they occur

Defect category	Defect group	Defect
Physical	Pipe	Cracks
		Holes
		Fractures
		Internal corrosion
		External corrosion
		Deformation[a]
		Scouring
		Undetected construction damage
		Third-party damage
	Joints	Cracks/holes/fractures
		Damaged seal
		Pulled out
		Extruding seal[a]
		Misalignments[a]
	Linings	Tears/breaks
		Scouring
		Corrosion
		Delamination[a]
		Bulging[a]
	Bedding	Voids
Hydraulic	Deposits	Sediments[b]
		FOG[b]
	Obstructions	Debris[b]
		Roots[b]
	Undesirable inflows	Groundwater infiltration
		Stormwater cross-connections
		Rainwater ingress (including on private properties)
		Pool backwash releases
Quality	Release of undesirable substances	Oil
		Fat
		Grease
		Wipes
		Paper
		Rubbish
		Sanitary products
	H_2S production and release	Dissolved sulfide
		Turbulence
		Splashing
		Exfiltration

[a] Also act as hydraulic defects.
[b] Also act as quality defects.

Table 6. Classification of factors affecting sewage systems based on whether and when they can be influenced

Factor category	Factor group	Factor
Design and construction	Planning and design	Land use
		User connection density
		Approach (combined/separate)
		Pipe layout
		Traffic loads
		Construction loads
		Interaction with other services
	Pipe characteristics	Shape
		Diameter
		Section length
		Material
		Lining (internal)
		Coating (external)
		Joint type
		Design life
	Installation properties:	Installation date (age)
		Installation method
		Installation quality
		Trench width
		Slope
		Distance between manholes
		Cover depth
		Pipe bedding
		Trench backfill
		Restraints
Operational	Water consumption	
	Sewage composition	Corrosive impurities
		Sediments
		Acceptable FOG load
	Maintenance strategies	Inspection regime
		Frequency of sewer cleaning
		Sewer cleaning methods
		Quality of repairs
	Temporary loading	
	Trees near system	
Environmental	Soil	Expansive properties
		Deficit index
		Corrosivity
		Sulfides
		pH
		Redox potential
		Moisture content
		Groundwater level
		Wet/dry cycles
		Tidal influences
		Movements
		Frost penetration
		Sinkholes
	Climate	Rainfall
		Temperature
	Catastrophic events	Earthquakes
		Wildfires

categorization under the integrity classification used for failures and defects. After considering different strategies, it was decided to categorize factors according to whether and when they can be influenced in the following way:

Design and construction factors *can be controlled up to the point of construction and then cannot be changed without major work*. Costs associated with design and construction factors would normally be classified as capital costs. Examples include pipe material, diameter, and slope.

Operational factors *can be controlled or influenced during a system's operational life, whether by the sewer service provider or the municipal authority*. Costs associated with operational factors would normally be classified as operational costs. Examples include household water consumption, products allowed into the sewer system, inspection frequency, and maintenance actions.

Environmental factors *cannot be controlled or influenced*. This includes in-situ soil properties, rainfall, and natural disasters.

Table 6 provides a classification of the main factors in sewage systems.

Discussion

It is possible to classify the deterioration of sewer pipe systems in different ways depending on the purpose and parameters

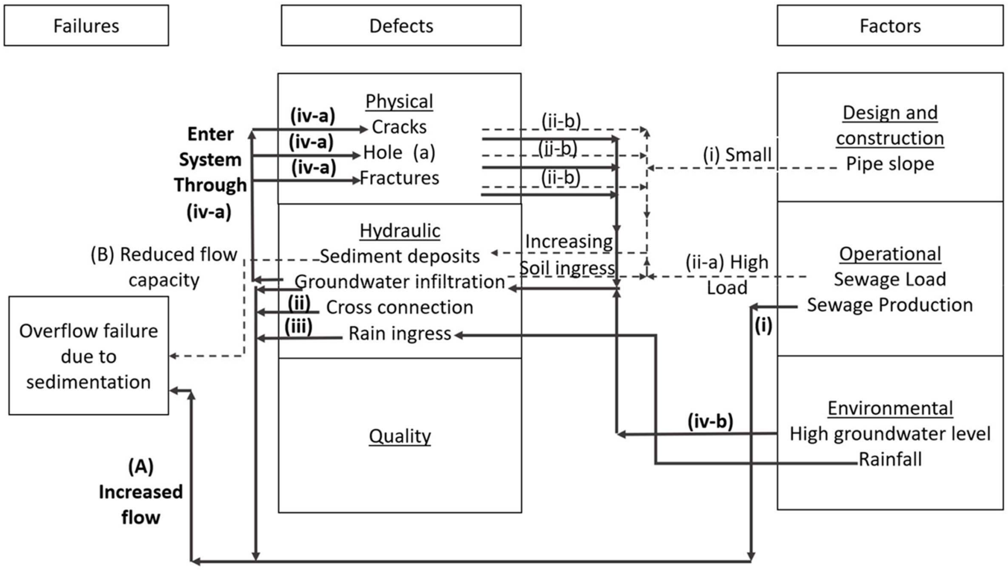

Fig. 4. Schematic illustration of the causes of sewage overflows due to sedimentation.

considered, as is evident from the literature. The aim of this paper is to propose a single consistent and rational classification system that can be used for different purposes in modeling sewer pipe deterioration or asset management processes. It is based on the premise that the different studies are subject to the same underlying parameters and processes, and that the benefits of adopting a single classification system far outweighs the cost.

No classification system is perfect, and thus it is necessary to adopt a pragmatic approach, adopting a system with the best overall fit and lowest number of anomalies considering the range of possible applications.

In developing the proposed classification system, particular challenges were finding a suitable classification structure, demarcating categories and subcategories, formulating definitions, and fitting known parameters into the proposed system. It took several iterations to develop the proposed system, and further adjustments may be necessary in the future—for instance, if new parameters are identified that the system cannot classify.

It should be recognized that there are interactions within and between categories and that a mix of factors and defects will influence most failures. To illustrate the complexity of these interactions and influences, the proposed classification system is applied to illustrate the processes responsible for overflow failures due to sedimentation. This is illustrated in Fig. 4 and can be described as follows, working back from the failure event.

Overflow failures due to sedimentation in a given pipe occurs when:

1. Sewage flow exceeds the capacity of the pipe.
   a. Increased sewage flow is determined by
      (1) sewage production, which is at a maximum during certain times of the year and day;
      (2) cross connections to the stormwater system, which increase flow during rainfall events;
      (3) rainwater ingress, which increases flow during rainfall events; and
      (4) groundwater infiltration, which is caused by
         (a) cracks, holes, and fractures in the system, combined with
         (b) high groundwater level.
   b. Reduced hydraulic capacity due to sedimentation is caused by
      (1) small pipe slopes that reduce flow velocity; and
      (2) high sediment loads in sewage, which is caused by
         (a) high sewage sediment loads; and
         (b) high groundwater level infiltrating through cracks, holes, and fractures, carrying soil particles into the pipe.

Conclusion

This study highlights the large differences and inconsistencies in classification systems used in different studies in the sewer deterioration and asset management fields. It proposes a classification system based on three top-level categories of factors, defects, and failures. Each of these categories and subcategories is clearly defined, and a flow diagram is provided to guide the user in classifying any given parameter. Sewer systems are highly complex, with a large array of components, loads, deterioration processes, and impacts on society and the environment. This makes the classification of parameters that affect or are affected by sewer systems a challenging task, as evident from the number of different classification systems described in the literature.

Despite the significant number of objectives that analyses of sewer system deterioration or asset performance may have, these analyses are all influenced by the same factors, deterioration processes, and failure types. Thus, it should be possible to develop a consistent classification system that can be applied in a broad range of deterioration or asset management studies. The purpose of this work was to propose a uniform classification system that may fulfill this purpose or form the basis for an improved unified classification system.

It should be stated that no classification system will be without its weaknesses, and it is unlikely that a perfect system can ever be found. Decisions on whether to change a system should be taken on the basis of whether the benefits outweigh the costs, rather than whether it is devoid of any problems or inconsistencies.

Far more important than a perfect classification system is the need for researchers and practitioners in sewer systems to use the same classification system. This will allow the body of professionals in sewer asset management to communicate more effectively by "speaking the same language," making it possible to compare different studies and build up a consistent knowledge base to move the understanding and management of sewer systems going forward.

Data Availability Statement

No data, models, or code were generated or used during the study.

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