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When population science meets urban sewer networks: Decoding remaining life using life table analytics

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ABSTRACT

Global urban sewer infrastructure faces an unprecedented aging crisis, with cascading failures threatening public health, environmental protection, and urban resilience. The American Society of Civil Engineers estimates a $271 billion investment gap for US sewer systems alone, highlighting the urgent need for sewer aging analysis to optimize resource allocation. Current analysis methodologies face a critical implementation barrier: their complex data type requirements limit practical adoption across diverse municipal contexts. This study is inspired by the recognition that sewer pipelines, like human populations, experience age-related deterioration, and the demographic life table can be applied to analyze the dominant factors in this process. The methodology transforms traditional multi-parameter models into a two-input approach requiring only current age and dominant analytical factor, while maintaining statistical rigor through Wilcoxon signed-rank tests with Bonferroni correction. As one of Asia's leading metropolitan centers, Hong Kong presents an ideal case study for sewer aging analysis. Therefore, comprehensive empirical validation was conducted across 148,389 pipeline segments spanning four major regions, 18 districts, six soil types, and diverse environmental conditions, culminating in a quartile-based risk classification system integrated with GIS visualization for immediate spatial risk assessment. This streamlined approach enables immediate implementation using minimal data requirements and facilitates the transition from reactive repair strategies to predictive management approaches. This ease of implementation supports sustainable urban development and resilient sewer systems globally, providing a viable solution to the global infrastructure crisis.

Nomenclature

Abbreviation	
CCTV	Closed-circuit Television
AI	Artificial Intelligence
ERL	Expected Remaining Life
AE	Age Expectancy
IoT	Internet of Things
GIS	Geographic Information System
PVC	Polyvinyl Chloride
AIC	Akaike Information Criterion
DSD	Drainage Services Department
AADT	Average Annual Daily Traffic

1. Introduction

Urban sewage systems are vital to public health and environmental protection(Yang et al., 2025; Chen et al., 2024; Yuan et al., 2022; Zeydalinejad et al., 2024). In many developed countries, these networks were built in the 19th and early 20th centuries (Hall and Lobina, 2008) and have now exceeded their intended service life. Consequently, metropolitan areas face mounting operational challenges (Butler et al., 2017; Marlow et al., 2013; Yang et al., 2025). For example, in 2017, the

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American Society of Civil Engineers rated the U.S. sewage network as a "*D*+," estimating that $271 billion would be needed to restore it to a basic level of functionality (Kaddoura and Zayed, 2021). These challenges manifest as reduced operational efficiency, frequent service disruptions, environmental contamination, and elevated public health risks (Kamali et al., 2022; Sojobi and Zayed, 2022; Xia et al., 2024; Yang et al., 2026). Furthermore, these problems will worsen as urban populations surge to unprecedented levels, with projections indicating approximately 6.4 billion urban residents by 2050 (Jiang et al., 2008).

To tackle these challenges, cities have traditionally utilized closed-circuit television (CCTV) inspections to assess pipeline conditions. However, CCTV inspections are constrained by significant operational limitations, including resource-intensive processes, scheduled inspection intervals that may miss emerging deterioration, and restricted network coverage (Hawari et al., 2018; Liu and Kleiner, 2013; Rayhana et al., 2020). These limitations become increasingly pronounced as urban infrastructure continues to age, underscoring the need for a transition from inspection-based detection to predictive analytics approaches (Sousa et al., 2014).

In response to this need, various predictive modeling approaches have been developed. These include physical models (Liu et al., 2023; Miszta-Kruk, 2016; Shadabfar et al., 2023; Teplỳ et al., 2018; Yoon et al., 2021) grounded in materials science and corrosion theory, statistical models (Altarabsheh et al., 2019; Ghavami et al., 2020; Li et al., 2019;

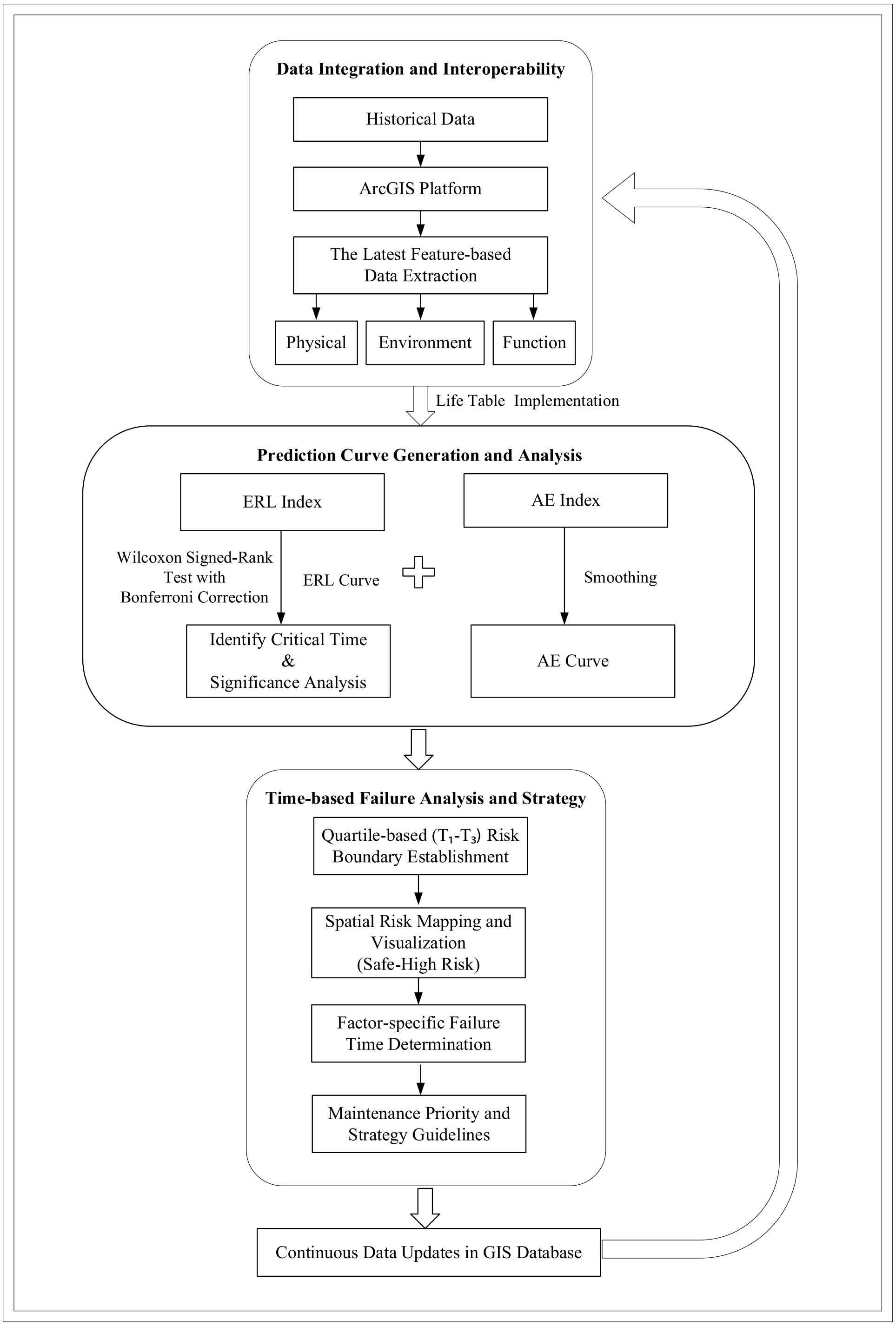


Fig. 1. Life Table-based Assessment Framework.

Yang et al., 2025) based on historical maintenance records, and artificial intelligence (AI) models (Fontecha et al., 2021; Sousa et al., 2014, 2014; Yin et al., 2020) employing machine learning algorithms. While these techniques exhibit technical sophistication and provide comprehensive failure predictions, they share a critical drawback: complex data types requirements, which pose significant implementation challenges for many municipal authorities.

Building on this rationale, this study introduces a life table statistical framework for assessing pipeline remaining life. Drawing from demographic principles, this approach offers distinct advantages over existing methods: specifically, it requires only basic current age data and dominant analytical factor information, making it particularly accessible for utilities with limited monitoring resources. Furthermore, the framework utilizes straightforward mathematical computations, avoiding the need for complex iterative algorithms commonly employed by other methods. Another key benefit is its ability to produce intuitive visual outputs, such as remaining life curves, which facilitate immediate interpretation and support informed maintenance decisions. By providing municipal authorities with this practical analytical tool, the framework promotes a shift from reactive repair strategies to proactive preventive maintenance planning, fostering more efficient and sustainable infrastructure management.

2. Research methodology and analytical framework

This section presents the comprehensive research methodology employed in this study, including the life table analysis technique and the integrated framework for sewer pipeline remaining life assessment. Fig. 1 illustrates the complete analytical workflow, demonstrating how the study integrates life table analysis with polynomial smoothing and GIS-based visualization to generate a dynamic assessment of sewer remaining life, ultimately informing proactive maintenance and renewal strategies.

The methodology encompasses three core components: life table analysis for calculating Expected Remaining Life (ERL) and Age Expectancy (AE) indicators (Section 2.1), the Wilcoxon signed-rank test for statistical significance validation (Section 2.2), and the development of the integrated assessment framework incorporating polynomial smoothing and spatial-based risk visualization (Section 2.3). The details regarding data acquisition, preprocessing, and database construction are subsequently introduced in Section 3.

2.1. Life table analysis

Life table analysis is employed here to investigate the remaining life of sewer pipes. While it is traditionally used in demographic studies, it has demonstrated robust applications in engineering and reliability research. The method discretizes continuous time into uniform intervals (commonly annual) yet retains the sequence of events across pipelines' remaining life. This setup enables the estimation of ERL and the calculation of AE.

In the life table framework, age intervals are denoted as $[t, \cdot t+1)$, with l_t representing the number of surviving pipelines at age t, and d_t denoting the number of pipeline failures during interval $[t, \cdot t+1)$. The mortality rate $q(t)$ for the interval $[t, \cdot t+1)$ is defined as:

$$q(t) = \frac{d(t)}{l(t)} \tag{1}$$

For each age interval $(t, t+1)$, the average number of surviving pipelines (L_t) is computed as:

$$L_t = \frac{l(t) + l(t+1)}{2} \tag{2}$$

The total remaining service time (T_t) beyond age t is calculated as the sum of the average survivors for all intervals from t to the maximum observed age t:

$$T_t = \sum_{k=t}^{w} L_k \tag{3}$$

This formulation enables the estimation of two principal metrics. The *ERL*, representing the expected additional service years beyond age *t*, is calculated as:

$$ERL = \frac{T_t}{l_t} \tag{4}$$

and the *AE*, indicating the total age expected at age *t*, is then derived as:

$$AE = ERL + t \tag{5}$$

2.2. Wilcoxon signed-rank test

The Wilcoxon signed-rank test is employed here to compare differences between two or more paired samples groups within a single factor at each age. This non-parametric method is selected because it does not assume a specific data distribution, thereby offering greater robustness in situations where the normality assumption is violated. Moreover, it effectively handles ordinal data and exhibits reduced sensitivity to outliers compared to parametric alternatives.

For age $t = 0,1, 2\ldots,80$, let X_t^A, X_t^B, and X_t^C represent the ERL for pipes with different categories *A*, *B*, and *C* respectively within the same factor. The signed differences D_t between any two categories (e.g., category *A* versus *B*) are calculated as:

$$D_t = X_t^A - X_t^B \tag{6}$$

These differences are then ranked according to their absolute values, maintaining their original signs. Let R_t represent the rank of $|D_t|$, and the test statistic W is computed as:

$$W = \sum_{D_t > 0} R_t \tag{7}$$

The standardized test statistic Z is computed as:

$$Z = \frac{W - n(n+1)/4}{\sqrt{n(n+1)(2n+1)/24}} \tag{8}$$

where n is the number of non-zero differences at that age. For factors with three or more categories, multiple pairwise comparisons are conducted (e.g., A-B, A-C, and B-C for three categories). To account for these multiple comparisons, the Bonferroni correction is applied to control the familywise error rate. The adjusted significance level α' for each test is calculated as:

$$\alpha' = \frac{\alpha}{m} \tag{9}$$

where α is the desired overall significance level (typically 0.05) and assuming m is the number of comparisons. For three categories (A, B, C), $m = 3$, resulting in $\alpha' \approx 0.0167$. For factors with more than three categories, m is calculated as $m = k(k-1)/2$, where k is the number of categories. For factors with only two categories, no Bonferroni correction is necessary ($m = 1$, $\alpha' = \alpha = 0.05$), as only a single pairwise comparison is conducted. The Bonferroni correction is selected for its simplicity and conservative nature in controlling Type I error rates.

2.3. Development of the life table-based sewer pipeline remaining life assessment framework

This study develops a life table-based assessment framework to analyze sewer pipeline aging patterns. The framework leverages GIS to integrate historical datasets and evaluate remaining pipeline life through three stages: core life table index generation, index-based polynomial smoothing, and spatial-based risk visualization.

2.3.1. *Core life table index generation*

The core life table index generation stage applies demographic life table methodology (Section 2.1) to calculate discrete ERL and AE values at consecutive age intervals for each factor category across physical, functional, and environmental dimensions. This process establishes the fundamental discrete data points required for the subsequent index-based polynomial smoothing stage. These discrete points serve as a foundation for identifying inter-group differences through the Wilcoxon signed-rank test with Bonferroni correction.

2.3.2. *Index-based polynomial smoothing*

Building on the discrete ERL and AE values derived from life table analysis, polynomial smoothing techniques are utilized to generate continuous predictive curves. Polynomial functions, typically of degrees $n = 3$ to 5, are fitted to the discrete data points using least-squares optimization. Model selection is guided by the Akaike Information Criterion (AIC) to identify the optimal polynomial degree. The resulting smoothed curves enable continuous evaluation of remaining life for any pipeline age and support comparative analyses across different factor categories. These continuous curves allow the identification of critical transition points where performance patterns exhibit significant shifts and facilitate the quantification of the independent contributions of physical, functional, and environmental factors to pipeline remaining life across various service stages.

2.3.3. *Spatial-based risk visualization*

In the spatial-based risk visualization stage, pipelines are categorized into four risk levels based on quartile-derived boundaries of the remaining life distribution: safe (above T_1, green), low risk (T_1 to T_2, yellow), moderate risk (T_2 to T_3, orange), and high risk (below T_3, red). A GIS-based spatial visualization system provides intuitive visual outputs that integrate statistical predictions with geographical contexts, allowing managers to pinpoint high-risk segments and optimize maintenance resource allocation effectively. This classification framework also supports flexible determination of failure boundary time, accommodating conservative, balanced, or aggressive management strategies tailored to organizational risk tolerance and resource constraints.

2.3.4. *Self-Updating mechanism for continuous model evolution*

Finally, the framework incorporates a self-updating mechanism for continuous model evolution and adaptation. As new pipeline installation and failure data are added to the database, the system automatically recalculates life table parameters, updates ERL and AE values, and regenerates the polynomial coefficients for the smoothed curves. Risk thresholds and spatial classifications are dynamically adjusted based on the updated dataset, transforming the framework from a static analytical tool into a dynamic decision-support system. This adaptability enables the framework to effectively capture shifting failure patterns as infrastructure networks age and environmental conditions change.

3. Data acquisition, preprocessing, and database construction

The single-factor analysis method assesses the independent impact of individual factors on pipeline failure. This approach requires two primary data inputs: (1) the current age and (2) the dominant analytical factor being analyzed. Based on these inputs, life tables are utilized to estimate the remaining service life and life expectancy of pipelines. Its main advantage lies in generating valuable insights with minimal data requirements, making it practical even in resource-constrained settings, though additional data can enhance analysis accuracy.

3.1. *Data sources and requirements*

This study utilizes two primary data sources: drainage infrastructure records from the DSD in Hong Kong and environmental data from various government agencies. The DSD records include GIS-formatted data detailing pipe characteristics (location, installation date, length, materials, maintenance history, diameter, and network connectivity) and CCTV inspection.

To examine the relationship between environmental conditions and pipeline deterioration, the study incorporates external parameters from multiple agencies: traffic data (AADT) from the Transportation Department, weather records (temperature and precipitation) from the Hong Kong Observatory, land use information from the Planning and Lands Departments, and soil profiles from the Geotechnical Engineering Office. All data sources follow standardized collection protocols and quality control measures to ensure reliability and consistency.

3.2. *Data cleaning and interoperability*

The data processing phase addressed two key challenges: data format standardization and maintenance record management. The initial datasets came in varying formats - CCTV inspection records in PDF with examination dates and condition assessments, pipeline information in GIS format containing district details and physical attributes, and environmental data from government agencies in various digital formats.

To standardize the data, Optical Character Recognition (OCR) technology was employed to extract information from PDF-formatted CCTV reports, followed by the implementation of a custom Python program with manual verification. This process converted all datasets into a uniform tabular structure, normalized date formats and measurement units, standardized condition grading systems and defect classifications according to the HKCCEC framework, and established consistent pipeline naming conventions, creating an integrated database for analysis.

The maintenance documentation required special handling to distinguish between maintained and unmaintained pipelines. Using keyword identification for maintenance activities, we segregated and restructured the records. For pipelines with maintenance history, we split the data into two chronological segments: installation to maintenance, and maintenance to the latest inspection, enabling accurate tracking of pipeline conditions over time.

3.3. *Data integration and management*

The ArcGIS-based centralized management system integrates multiple datasets into a unified database, enabling both historical storage and real-time updates of pipeline information. Through unique identifiers and geographical coordinates, the system links maintenance records to specific pipeline segments, while its spatial analysis capabilities ensure automated alignment and systematic data organization. Environmental variables like traffic load, weather data, and land use are directly mapped to the pipeline network. The database maintains accuracy through systematic updates, instantly incorporating new operational data to support comprehensive analysis and timely risk response.

3.4. *Database construction*

The integrated database is organized into three primary categories: physical factors, functional characteristics, and environmental parameters. This structure supports comprehensive failure timing analysis and facilitates subsequent analysis efforts.

Physical factors include length, material, diameter, and age, which serve as foundational parameters for assessing condition. Functional characteristics define pipeline segments as storm drains or sanitary sewers. Environmental parameters track external influences through temperature, rainfall, land use, humidity, district, traffic, and soil types. Continuous variables were systematically classified using tertile-based divisions to provide quantitative boundaries for analysis. This development process, as illustrated in Fig.2, demonstrates how the ArcGIS-based framework provides a robust foundation for remaining service life analysis and hazard assessment.

4. Framework implementation and results

This study's findings are organized into three sections. Section one (4.1–4.3) presents ERL indicators from life table analyses. Section two (4.4) introduces a GIS-based system for assessing pipeline failure risks and determining boundary times. Section three (4.5) outlines critical warning periods and maintenance strategies for effective pipeline management.

4.1. Physical factor-based analysis

4.1.1. Length

Pipeline length significantly affects construction complexity, quality control feasibility, and the number of joints per segment, all of which influence long-term structural performance. Longer pipelines face greater challenges in maintaining consistent installation standards and coordinating construction activities, while shorter segments may have fewer potential failure points but different stress distribution characteristics. During the initial service stage (Age 0–50), short pipelines exhibit the highest ERL (Table 1), likely due to their simpler structure and fewer joints enhancing structural integrity. Medium-length pipelines rank second, possibly because their moderate length facilitates construction quality control. Long pipelines perform worst, possibly due to increased complexity in quality control and installation coordination. In the second stage (Age 51–64), medium-length pipelines achieve the highest ERL, likely due to balanced geometric features that minimize stress concentration. Short pipelines drop to second place, possibly because early high-stress regions have incurred fatigue damage. Long pipelines continue ranking lowest but show slower degradation, possibly indicating that initial installation stresses are being relieved. During the third stage (Age 65–78), medium-length pipelines maintain their leading position, potentially because their moderate length may have facilitated beneficial organic coating development through steady flow. Long pipelines gradually close the ERL gap, possibly because long-term settling has achieved stability, and their system resilience helps distribute localized deterioration impacts. Short pipelines drop to the lowest ranking, perhaps because their structural simplicity amplifies aging effects. Using the Wilcoxon Signed-Rank Test with a Bonferroni correction (Table S1 in Supplementary Materials), statistically significant differences in ERL performance patterns are observed between long pipelines and both medium and short pipelines ($p < 0.0167$). Although the comparison between medium and short pipelines revealed notable differences ($p = 0.0194$), it does not meet the stringent Bonferroni-corrected significance threshold. Service stage recommendations include: Stage 1 - maintain short and medium pipeline performance while monitoring long pipeline installation stress; Stage 2 - focus on short pipeline fatigue damage and conduct regular medium pipeline inspections while monitoring long pipeline critical sections; Stage 3 - implement enhanced maintenance for short pipelines, maintain medium pipeline strategies, and ensure long pipeline system stability.

4.1.2. Material

Pipeline material fundamentally determines chemical resistance, mechanical properties, and degradation mechanisms when exposed to

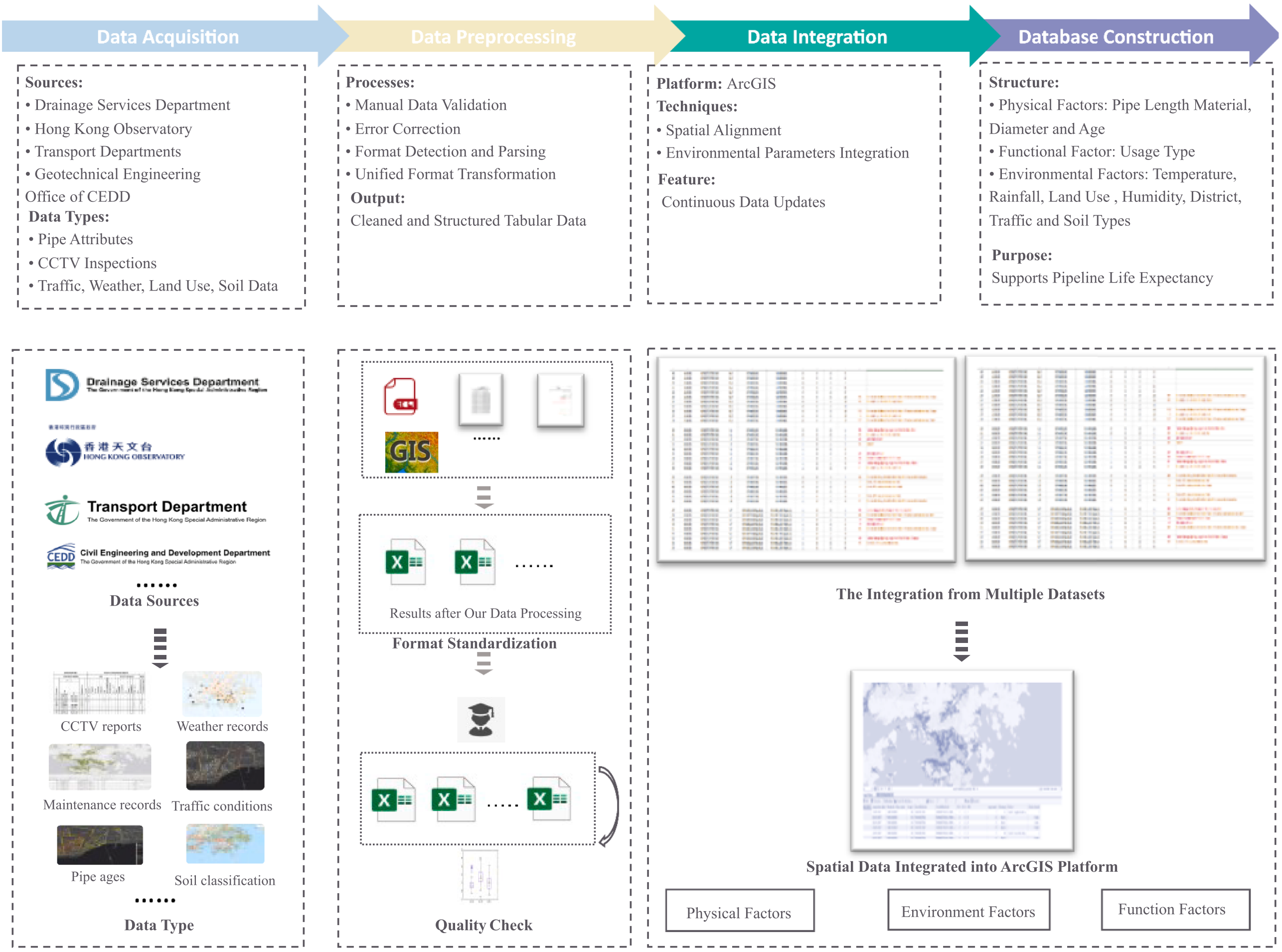
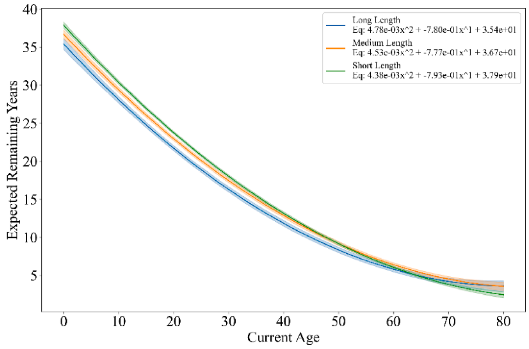
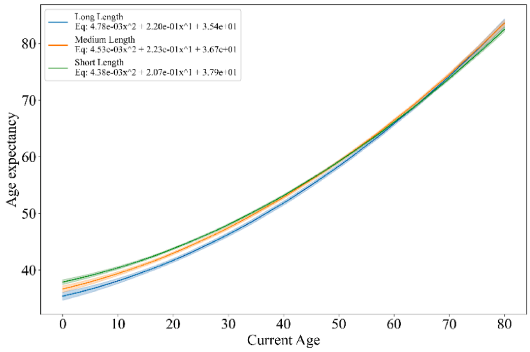
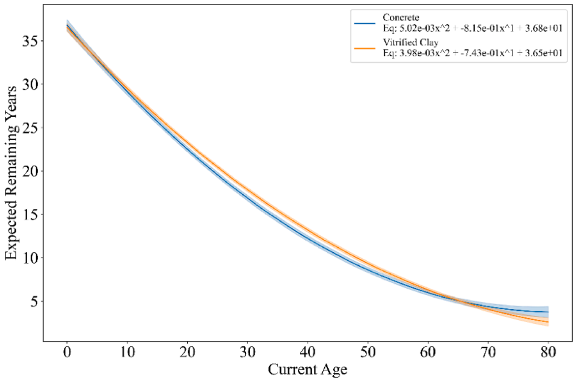
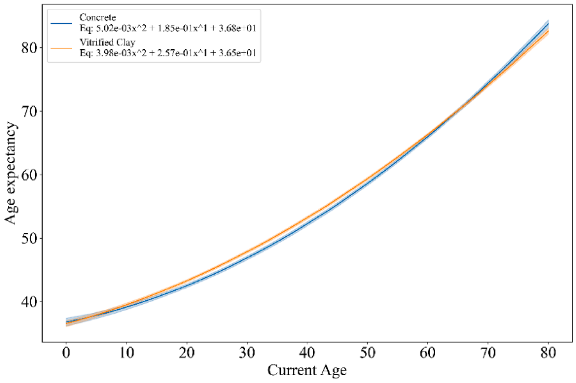
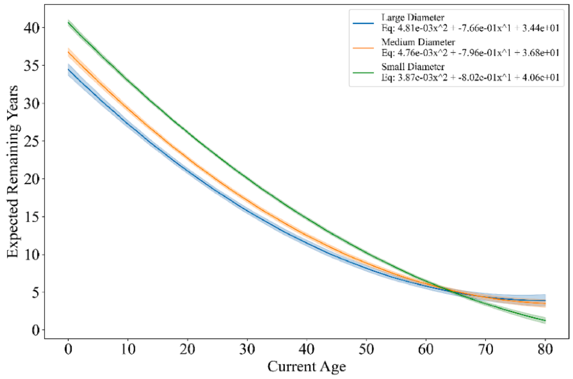
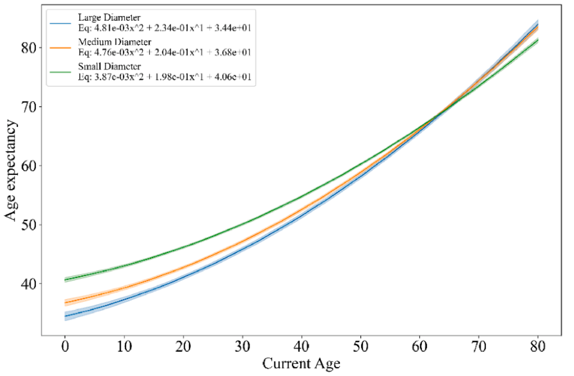


Fig. 2. ArcGIS-based Pipeline Data Collection and Processing Workflow.

Table 1

Expected Remaining Life and Age Expectancy Curves of Physical Factors.

Types	ERL	AE
Length		
Material		
Diameter		

wastewater environments. Different materials exhibit varying responses to acidic compounds, soil movements, and long-term environmental stresses, making material type a critical factor in predicting pipeline longevity. From installation until around age 4, concrete and vitrified clay pipes show nearly identical ERLs (Table 1), as both materials maintain original structural properties before deterioration mechanisms initiate significant degradation. Between ages 5–64, vitrified clay pipes demonstrate more favorable ERL than concrete pipes, possibly due to the superior chemical resistance of clay to acidic wastewater compounds, while concrete's porous nature may increase vulnerability to chemical deterioration. By age 65, the ERL advantage reverses with concrete pipes exceeding vitrified clay pipes, possibly because surviving concrete develops protective surface layers through calcium carbonate precipitation under alkaline conditions, creating a barrier that reduces further carbonation(Schock, 1999), while clay's inherent brittleness may become critical as decades of ground movements create cumulative stress points. Wilcoxon Signed-Rank Test confirms significant difference in ERL between concrete and vitrified pipelines ($p < 0.0250$). Engineering guidance includes: standard maintenance for both materials during ages 0–4; enhanced chemical protection treatments for concrete pipes during ages 5–64; replacement planning for vitrified clay pipes and structural reinforcement for concrete pipes beyond age 65.

4.1.3. Diameter

Pipe diameter fundamentally influences structural stress distribution, joint failure probability, and hydraulic performance in sewer systems. Larger diameter pipes experience greater external loads and have more joint connections per unit length, while smaller pipes may face different blockage and flow capacity challenges over their service life. Throughout most of the service period (from installation until around age 62), small diameter pipes consistently demonstrate the highest ERL values (Table 1), followed by medium diameter pipes, with large diameter pipes showing the lowest ERL. This performance pattern may be explained by structural mechanics principles: smaller pipes typically experience less stress from external loads and may be less susceptible to joint failures due to reduced circumference; medium diameter pipes show intermediate performance balancing advantages of smaller pipes while experiencing challenges of larger infrastructure; large diameter pipes demonstrate lower performance primarily due to greater susceptibility to installation defects, increased stress concentrations at joints, and more significant impacts from soil settlement and external loading. However, after approximately age 62, a notable trend shift occurs where small diameter pipes show accelerated ERL decline, dropping below both medium and large diameter pipes, while medium and large diameter pipes maintain a more gradual decrease with nearly overlapping performance curves. This shift likely stems from smaller pipes becoming more vulnerable to blockages, material degradation at critical points, and reduced flow capacity impacts over time, while medium and large diameter pipes demonstrate similar long-term durability due to greater wall thickness and structural capacity, providing reserve strength beneficial in extended service conditions. The Wilcoxon Signed-Rank Test reveals statistically significant differences among the ERLs of small, medium, and large diameter pipelines ($p < 0.0167$). Differentiated maintenance strategies are recommended: For age 0–62, large diameter pipes require frequent inspections due to lower ERL, medium diameter pipes need moderate monitoring, and small diameter pipes can have less intensive inspection schedules. After age 62, small diameter pipes need increased attention and possible replacement due to rapidly declining ERL, while medium and large diameter pipes should maintain regular evaluation schedules.

4.2. *Function factor-based analysis*

Pipeline function determines the type and concentration of conveyed fluids, directly influencing corrosion mechanisms and degradation patterns. Foul pipes handle chemically complex wastewater with organic matter and acidic compounds, while stormwater pipes primarily transport diluted rainwater with different pH levels and contaminant loads, leading to distinct deterioration trajectories over time. Statistical analysis reveals two distinct phases in ERL performance between foul and stormwater pipes (Table 2). During the initial phase (Age 0–9), stormwater pipes show slightly higher ERL, likely due to lower corrosivity of rainwater causing slower early-stage deterioration. In the middle phase (Age 9–64), foul pipes demonstrate superior ERL performance, possibly stemming from specialized design features and materials optimized for foul corrosivity, anti-corrosion treatments, and potentially more rigorous maintenance protocols. After age 65, stormwater pipes begin showing higher ERL, possibly reflecting cumulative effects of long-term chemical and biological loads accelerating foul pipe degradation, while stormwater pipes maintain better structural stability due to lighter load conditions. Foul and stormwater pipes show significant ERL differences according to the Wilcoxon Signed-Rank Test ($p < 0.0250$). These findings suggest specific maintenance strategies: for foul pipes, enhanced early-stage protection (Age 0–9) and late-stage monitoring (beyond age 65) for accelerated degradation; for stormwater pipes, enhanced inspection and maintenance during the middle phase (Age 9–64) to address relatively faster deterioration during this period.

4.3. *Environment factor-based analysis*

4.3.1. *Land use*

Land use type determines the chemical composition and characteristics of wastewater entering sewer systems, significantly influencing pipeline degradation rates. Different land uses generate distinct wastewater profiles: residential areas produce relatively stable domestic sewage, commercial areas contribute detergents and food-related chemicals, industrial zones discharge potentially corrosive compounds, while green spaces primarily contribute minimal organic loads but present unique challenges from root intrusion and soil conditions. Pipeline performance varies across land-use categories. Residential area pipelines demonstrate the highest ERL throughout their whole life (Table 3), possibly attributed to stable foul composition, reduced corrosiveness, and minimal flow variations. Commercial area pipes consistently rank second, likely because, despite exposure to detergents and restaurant wastewater, the overall corrosiveness remains relatively low. Industrial area pipes initially outperform those in green areas; however, after approximately age 21, industrial pipes experience the most rapid deterioration, and their ERL falls below green area pipes, potentially due to cumulative damage from chemical exposure in industrial wastewater. Despite facing challenges like plant root intrusion and soil movement, pipes in green areas show relatively better long-term durability in later years, possibly due to limited exposure to corrosive wastewater and less frequent usage patterns. Wilcoxon Signed-Rank Test indicates significant ERL disparities among commercial, residential, industrial, and green areas ($p < 0.125$). Targeted maintenance strategies are recommended: industrial areas should enhance wastewater pretreatment and utilize corrosion-resistant materials; green areas should implement root intrusion prevention while monitoring seasonal flow variations and geological impacts; commercial areas should enforce grease discharge controls alongside regular cleaning protocols; and residential areas should maintain good performance through regular inspections and prompt repairs.

4.3.2. *Humidity*

Environmental humidity significantly influences concrete durability through moisture-induced chemical processes, affecting both material degradation mechanisms and soil-structure interactions around buried pipelines. Humidity variations can alter the stability of protective oxide

Table 2
Expected Remaining Life and Age Expectancy Curves of Function Factors.

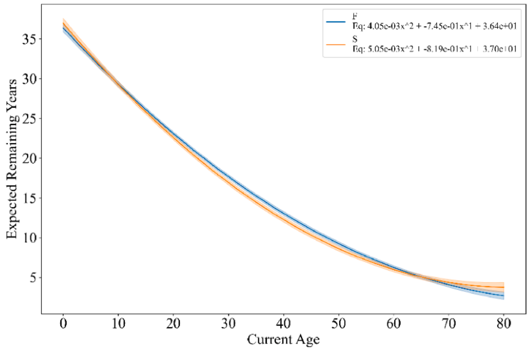
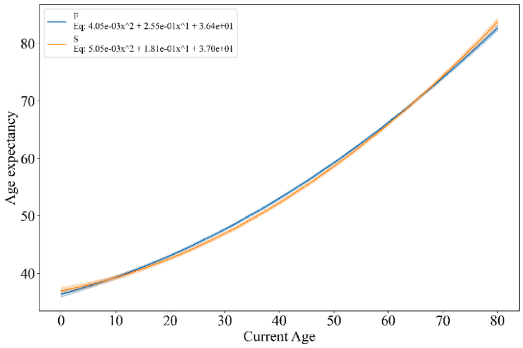
Types	ERL	AE
Function		

Table 3
Expected Remaining Life and Age Expectancy Curves of Environment Factors.

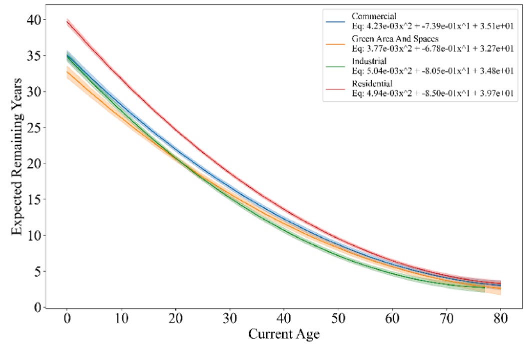
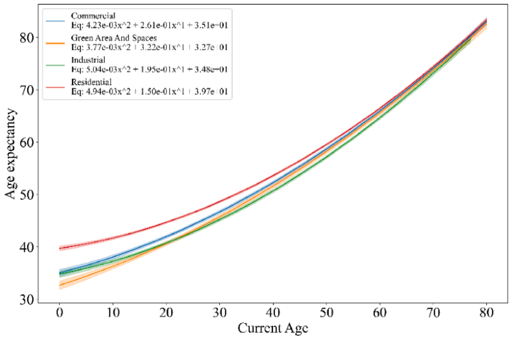
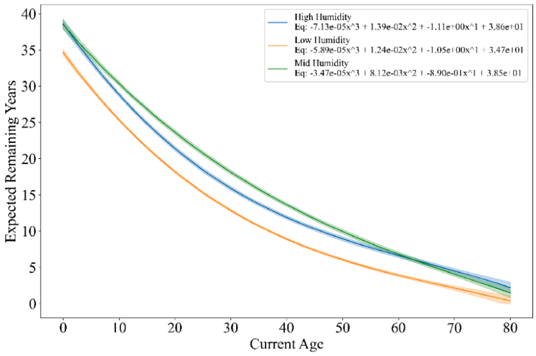
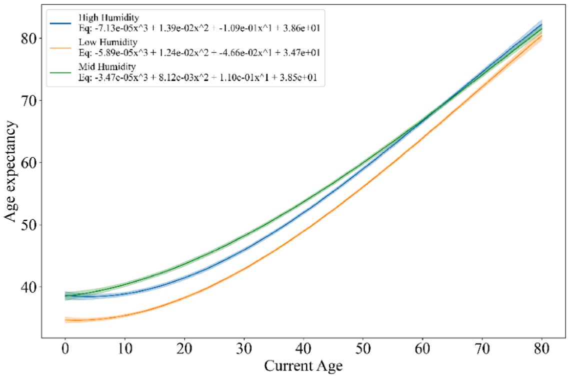
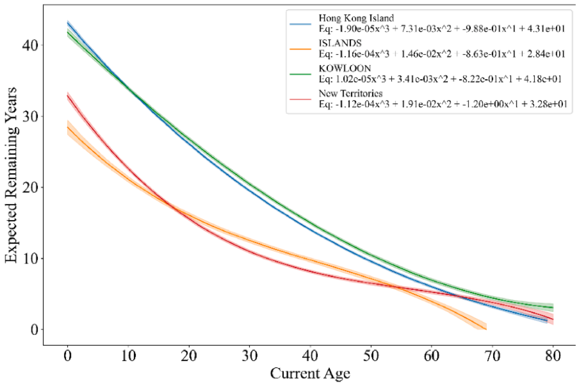
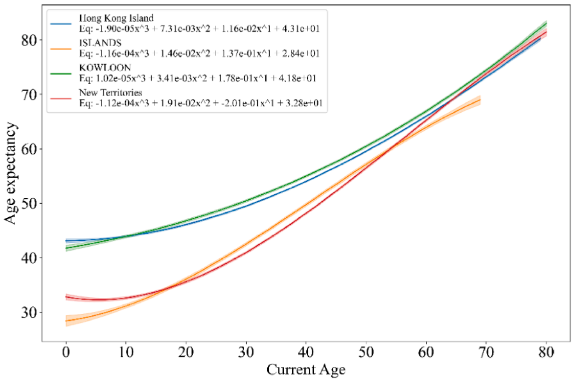
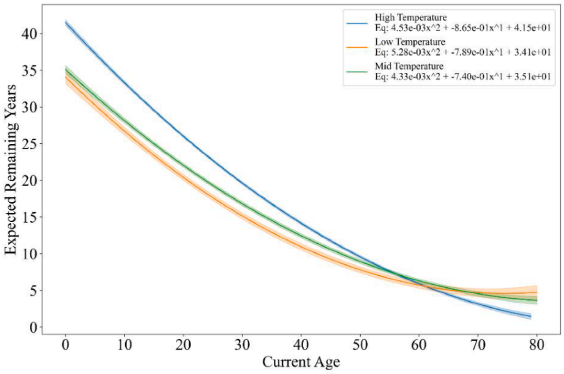
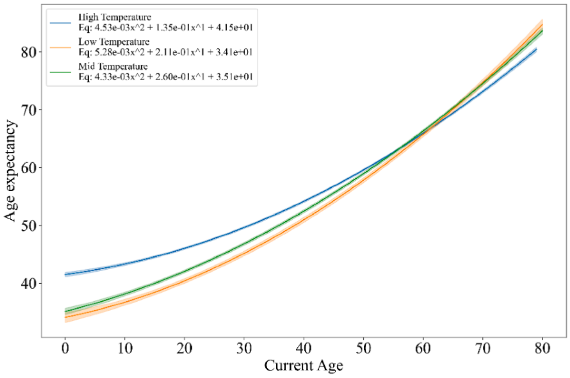
Types	ERL	AE
Land Use		
Humidity		
District		
Temperature		

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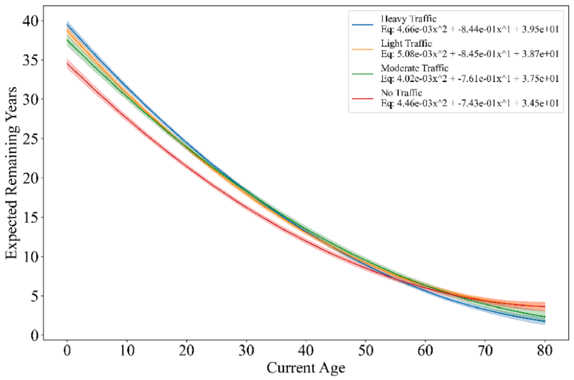
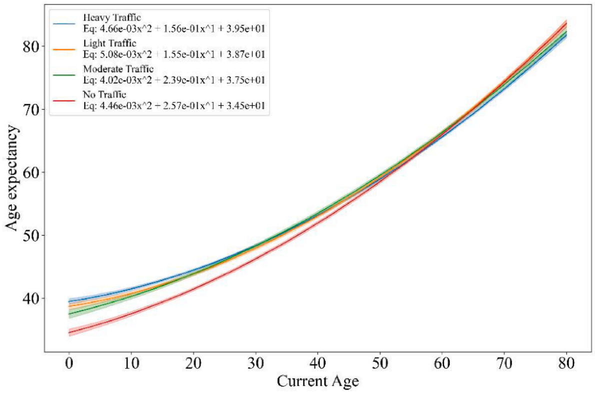
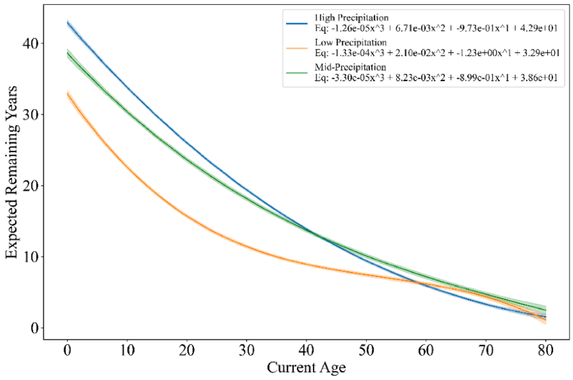
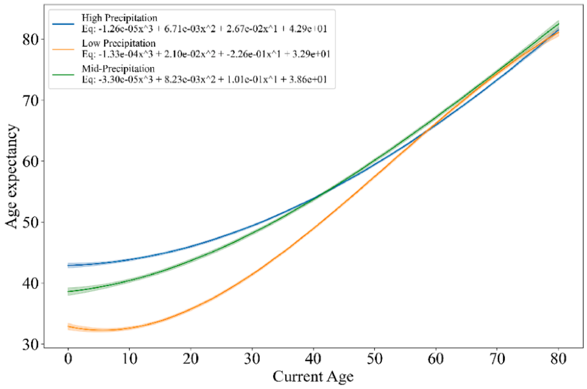
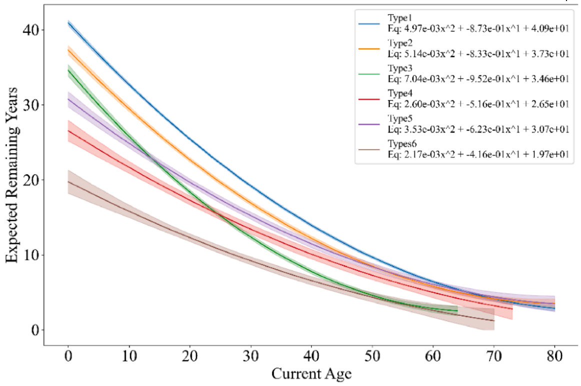
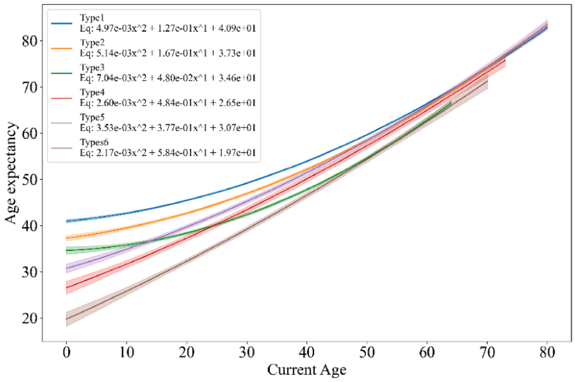
Table 3 (*continued*)

Traffic		
Rainfall		
Soil		

layers, influence microstructural evolution in concrete matrices, and modify soil moisture content, which collectively impact pipeline structural integrity over time. Low external environmental humidity regions (annual average ambient relative humidity from Hong Kong Observatory) consistently demonstrate the poorest ERL performance (Table 3), possibly due to moisture-related deterioration mechanisms in aging concrete infrastructure. Humidity fluctuations can affect concrete through alteration of protective surface layers and microstructural evolution in the concrete matrix, along with changes in soil-pipeline stress distribution, which collectively lead to microcracks and localized stress concentration. From age 1 to approximately age 62, medium-humidity environments maintain ERL advantage over both high and low humidity conditions, possibly indicating that materials achieve optimal physicochemical stability within a specific humidity range. After age 63, high-humidity conditions begin to surpass medium-humidity performance, likely due to surface characteristic evolution over long-term service and cumulative environmental effects. Wilcoxon Signed-Rank Test shows significant differences in ERL metrics among low, medium, and high humidity environments ($p < 0.0167$). Recommendations include: for low-humidity environments, implement full lifecycle enhanced monitoring with shortened replacement intervals; for medium-humidity environments, increase inspection frequency and develop systematic infrastructure renewal plans as operation approaches or exceeds 63 years, incorporating partial or complete replacement strategies determined through economic efficiency assessment; for high-humidity environments, develop specialized maintenance programs prioritizing early and mid-term performance changes while establishing dedicated reserve funds for upgrades and retrofitting.

4.3.3. District

Geographic districts represent variations in development history, construction standards, geological conditions, and maintenance resource allocation that collectively influence pipeline performance. Different districts in Hong Kong were developed at different times with varying investment levels, face distinct environmental challenges such as marine exposure or geological conditions, and may have different population densities affecting usage patterns and maintenance priorities. Before reaching age 63, Hong Kong Island and Kowloon pipelines consistently outperformed those in the Islands and New Territories (Table 3), likely reflecting differing infrastructure investment priorities, construction standards, and maintenance resource allocation between urban centers and peripheral regions. From installation to age 10, Hong Kong Island's pipelines exhibited slightly higher ERL than Kowloon's, with both maintaining high values due to early development and favorable construction conditions. Between age of 11 and 63, Kowloon's ERL surpassed Hong Kong Island's, possibly attributed to more favorable geological conditions, better network layout, and effective maintenance strategies. Initially, the Islands and New Territories displayed lower ERL values, with New Territories showing a slight advantage, likely reflecting lower infrastructure investment during early development. Around age 17, performance curves intersected, with Islands temporarily outperforming New Territories, possibly due to lower population density and reduced usage intensity. By age 55, the Islands' ERL declined sharply, suggesting unique environmental conditions and maintenance challenges accelerated degradation. After age 63, New Territories and Hong Kong Island ERL converged, with New Territories maintaining a slight advantage, possibly reflecting lower cumulative stress from later development. Islands performed worst, reaching zero ERL at approximately age 70, while Kowloon continued exhibiting high durability. Wilcoxon Signed-Rank Test with Bonferroni correction (Table S2) shows statistically significant differences ($p < 0.0125$) between Hong Kong Island and the other three regions, and between Kowloon and New Territories. However, the Islands and New Territories comparison shows no significant difference ($p = 0.0776$). Region-specific recommendations include: Kowloon should establish model management systems and conduct routine inspections beyond age 50; Hong Kong Island should increase intermediate maintenance frequency and conduct comprehensive evaluations after age 63; New Territories should strengthen quality monitoring from age 17–54; Islands require comprehensive renewal plans beyond age 55, prioritizing corrosion-resistant materials, dedicated monitoring systems, and emergency resource allocation plans.

4.3.4. *Temperature*

Environmental temperature significantly influences sewer system performance through multiple mechanisms, including alteration of wastewater viscosity, microbial activity rates, chemical reaction kinetics, and material thermal expansion/contraction cycles. Research has shown that temperature effects on sewer sediment behavior involve complex and interacting processes, with different environmental conditions producing varying impacts on erosion resistance, particle interactions, and microbial activity that are not yet fully understood. Temperature variations affect concrete and pipe joint materials differently, influence corrosion processes, and impact the physical properties of transported fluids, making temperature a critical factor in long-term pipeline durability assessment. From installation to age 56, pipelines exhibit a clear ERL pattern across temperature zones: highest in high-temperature regions, moderate in medium-temperature regions, and lowest in low-temperature regions (Table 3). This variation may arise from the influence of environmental temperature (ambient atmospheric temperature data collected from the Hong Kong Observatory) on operating conditions. Temperature affects the rheological properties of sludge and sediment, thereby altering flow resistance and deposition behavior (Hii et al., 2017). Between age of 57–60, medium-temperature pipelines achieve the highest ERL while high-temperature pipelines drop to second place, possibly suggesting that prolonged high-temperature exposure begins inflicting cumulative thermal stress and material degradation, whereas medium temperatures provide more stable operating conditions. From age 61–67, medium-temperature pipelines continue exhibiting highest ERL with low-temperature rising to second place while high-temperature pipelines decline to the lowest level, indicating that thermal degradation effects may become increasingly significant with age. After age 68, low-temperature pipelines overtake medium-temperature ones with the highest ERL, while high-temperature pipelines continue declining to nearly zero, suggesting that sustained moderate to high temperatures may eventually compromise long-term structural integrity, whereas lower temperature environments may provide more stable conditions for extended pipeline durability. Comparative analysis via the Wilcoxon Signed-Rank Test demonstrates significant ERL differentials between all temperature environments (< 0.0167). Maintenance recommendations include: for high-temperature pipelines, increase inspection frequency at 50 years, focusing on thermal stress degradation, with replacement recommended at 61 years; for medium-temperature pipelines, enhance monitoring at 68 years to track performance deterioration; for low-temperature pipelines, defer replacement under resource constraints while maintaining routine monitoring beyond 68 years as they remain most reliable.

4.3.5. *Traffic*

Traffic loading directly impacts pipeline structural integrity through continuous vibrations, dynamic pressure variations, and cumulative stress from vehicular weights transmitted through pavement and soil layers to buried infrastructure. Different traffic intensities create varying levels of mechanical stress that can accelerate joint deterioration, cause structural fatigue, and influence long-term pipeline performance, making traffic exposure a critical factor in durability assessment. Pipeline systems in all traffic zones (heavy, medium, and light load zones) exhibit nearly identical effective ERL trajectories for pipelines under age 58, consistently outperforming those in non-traffic zones (Table 3), possibly due to enhanced construction standards designed for anticipated traffic loads. Non-traffic zone pipelines maintain lower ERL during this period, likely because construction requirements are less stringent given reduced external pressure expectations. However, after age 58, non-traffic zone pipelines gradually display greater ERL, as their initial lower quality is compensated by minimal environmental stress, while traffic zone pipelines may degrade faster despite higher construction standards due to continuous vehicular vibrations and pressures. Wilcoxon Signed-Rank Test analysis with Bonferroni correction (Table S3) shows statistically significant differences in ERL performance patterns between non-traffic zones and all traffic zones ($p < 0.0125$). However, differences among traffic zones themselves were not statistically significant, with $p = 0.5976$ between heavy and light traffic zones, $p = 0.6751$ between heavy and moderate traffic zones, and $p = 0.072$ between light and moderate traffic zones, strengthening the observation that traffic zones exhibit similar ERL patterns while significantly differing from non-traffic zones. Based on this analysis, maintenance priorities should initially focus on non-traffic zones for pipelines under 60 years old, and later shift to traffic zones as structural deterioration accelerates.

4.3.6. *Rainfall*

Rainfall significantly influences wastewater characteristics and hydraulic conditions within sewer systems, affecting both chemical and physical degradation processes. High rainfall dilutes sewage concentrations but increases hydraulic scouring forces, while low rainfall creates concentrated corrosive conditions but reduces flow-induced erosion, leading to distinct deterioration patterns that vary with pipeline age and material adaptation over time. For pipes aged 0 to 42 years, high-rainfall regions show optimal ERL performance (Table 3), likely due to rainfall's diluting effect on sewage. Performance is somewhat lower in moderate-rainfall areas, while low-rainfall regions experience concentrated sewage contributing to corrosive substance buildup, potentially accelerating early degradation. For pipes aged 43 to 59 years, moderate-rainfall regions outperform high-rainfall areas, possibly because sustained exposure in high-rainfall zones makes even robust designs vulnerable to corrosion, erosion, and material fatigue over time.

For pipes over 60 years old, moderate-rainfall systems maintain optimal ERL performance, while low-rainfall regions tend to outperform high-rainfall zones. This pattern possibly reflects material stress adaptation: moderate rainfall regions likely achieve a balance between environmental stress and repair, developing stable protective structures, while low rainfall areas appear to adapt to concentrated sewage through extended low-use periods. In contrast, high rainfall regions are likely to face persistent scouring that possibly exceeds adaptive capacity, preventing protective layer formation. The Wilcoxon Signed-Rank Test with Bonferroni correction demonstrated significant differences between low precipitation and other precipitation categories ($p < 0.0167$). Although differences between medium and high precipitation are substantial ($p = 0.0326$), they did not achieve statistical significance under the conservative Bonferroni threshold (Table S4). Asset management strategies should be customized according to precipitation levels: high precipitation systems require enhanced maintenance starting at age 42; moderate precipitation systems benefit from balanced maintenance to preserve durability; low precipitation systems, despite poor initial performance, demonstrate unexpected resilience after age 60.

4.3.7. *Soil*

Soil conditions fundamentally determine the geochemical environment surrounding buried pipelines, influencing corrosion rates, structural support characteristics, and long-term stability. Different soil types exhibit varying electrical conductivity, pH levels, moisture retention, chemical reactivity, and mechanical properties that directly affect pipeline material degradation, joint integrity, and overall structural performance over time. ERL curves (Table 3) show that pipelines in Granite Rock (Type 1) and Backfill (Type 2) conditions generally performed better throughout service life, likely due to uniform and stable support that evenly distributes strains and minimizes differential settlement, plus limited groundwater activity that reduces corrosion risks and maintains consistent soil properties. Type 6 (Graphitic Siltstone, Sandstone, and Marble) consistently showed the poorest performance, possibly attributed to high electrical conductivity and chemical reactivity. Type 3 (Granodiorite) exhibited the most pronounced variation, initially exceeding all types except 1 and 2 during age 0–13, possibly due to dense crystalline structure, but then experiencing continuous deterioration from year 14 with steep decline around year 25, ultimately approaching Type 6 levels by year 60, likely due to active mineral weathering and accelerated corrosion. Type 4 (Tuff and Lava) and Type 5 (Superficial Deposit) showed middle-ground patterns with initially worse performance than Types 1–3 but stable deterioration rates over time. Type 5 consistently outperformed Type 4 despite being relatively loose, possibly because of more uniform pressure distribution and fewer fracture surfaces. Through the Wilcoxon Signed-Rank Test with Bonferroni correction (Table S5), statistically significant differences in ERL performance patterns are found ($p < 0.0083$) for all pairwise comparisons except Type 3 vs Type 4 ($p = 0.0203$), which doesn't meet the stringent Bonferroni-corrected threshold that controls Type I errors but may increase Type II error risk. Maintenance recommendations include: standard inspections for Types 1 and 2; intensified monitoring and corrosion protection for Type 3 during the critical 14–25-year period; early reinforcement followed by routine maintenance for Types 4 and 5; and comprehensive protection with cathodic protection from installation for Type 6.

4.4. *GIS-Based pipeline risk assessment and visualization management system*

This study employs the quartile method to define failure boundary time, arranging all pipeline remaining lifespans in descending order with T_1, T_2, and T_3 representing the first, second, and third quartiles, respectively. Pipelines are categorized into four risk levels: safe/no risk (green) for lifespans greater than T_1, low risk (yellow) for lifespans between T_1 and T_2, medium risk (orange) for lifespans between T_2 and T_3, and high risk (red) for lifespans below T_3.

In practice, managers determine a pipeline's current service age and use single-factor remaining life curves to estimate remaining service life, then compare this with predefined quartile thresholds for risk categorization. Organizations adjust quartile thresholds based on risk tolerance: conservative approaches may use T_1 as the failure limit, prioritizing safety, balanced strategies may use T_2, allowing low-risk operation, while aggressive strategies may apply T_3, permitting medium-risk operation. Pipelines below T_3 require immediate monitoring, assessment, or replacement. This flexible framework integrates statistical analyses, local conditions, and expert evaluations, enabling threshold adjustments according to operational or budgetary changes.

The above represents a single-factor GIS visualization designed for situations with limited data type resources. For organizations with more comprehensive datasets, more flexible multi-factor approaches can be implemented (see Supplementary Materials).

Table 4 illustrates a GIS-based pipeline risk assessment and visualization system for Hong Kong under three environmental conditions: temperature, humidity, and precipitation. Using temperature as an example, Table 4(a) displays Hong Kong's temperature zoning map with light red indicating high-temperature regions, beige for moderate-temperature areas, and dark blue for low-temperature zones. Three representative regions were selected for detailed examination, representing primary temperature conditions. Table 4(b) presents detailed risk distribution maps for these regions, with pipelines color-coded by residual lifetime risk levels: green for safe, yellow for low risk, orange for moderate risk, and red for high risk.

This spatial visualization enables managers to combine statistical forecasts from life table analyses with real-world geospatial factors including temperature, humidity, and traffic conditions. It allows quick identification of high-risk segments prone to imminent failures and low-risk segments requiring only routine monitoring. The tool supports resource optimization by focusing maintenance on critical areas while deferring less urgent tasks. Risk thresholds can be dynamically adjusted for evolving conditions such as climate changes, repairs, or policy updates. By integrating statistical analysis with spatial visualization, infrastructure managers can adopt data-driven approaches for both short-term interventions and long-term renewal strategies.

4.5. *Critical warning periods and intervention strategies for pipeline maintenance*

Table 5 presents a consolidated life table analysis that serves as a statistical framework for industrial maintenance practices. This table provides practitioners with stage-specific protocols and guidance on intervention timing

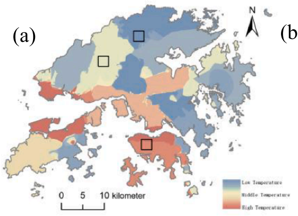
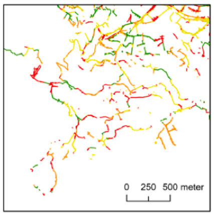
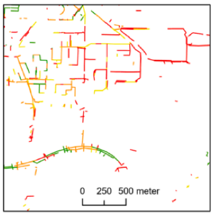
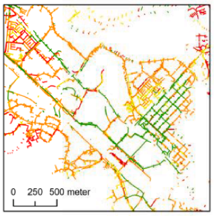
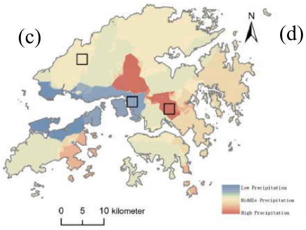
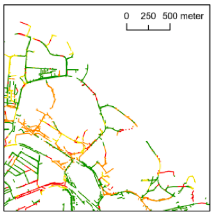
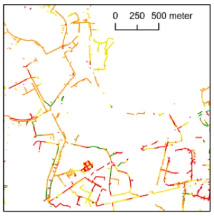
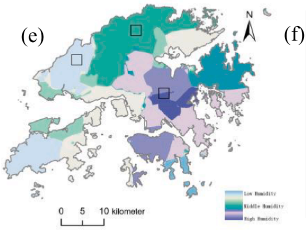
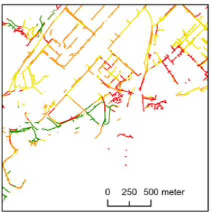
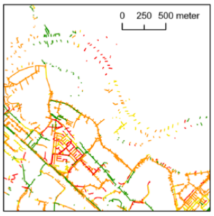
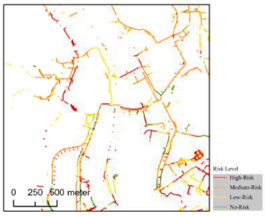
5. Discussion

This study illustrates the use of demographic life table methodology to evaluate failure time in urban drainage systems. The approach offers a practical solution for infrastructure management in data type-constrained environments, requiring minimal monitoring resources while providing reliable estimates of the remaining service life. Nonetheless, critical considerations related to its uncertainty, applicability, limitations, and potential areas for future development merit thorough discussion.

5.1. *Sensitivity and uncertainty analysis*

The present study conducts sensitivity analysis and uncertainty quantification to evaluate pipeline remaining life patterns. Through Wilcoxon signed-rank testing, the sensitivity analysis systematically evaluates differences between factor groups, revealing statistically significant variations across categories after Bonferroni corrections. These systematic differences demonstrate that classification criteria

Table 4
Pipeline Risk Visualization Under Individual Environmental Factors.

Temperature	 Temperature zones of Hong Kong	 High temperature zone	 Medium temperature zone	 Low temperature zone
Humidity	 Humidity zones of Hong Kong	 High humidity zone	 Medium humidity zone	 Low humidity zone
Rainfall	 Rainfall zones of Hong Kong	 High rainfall zone	 Medium rainfall zone	 Low rainfall zone

successfully distinguish meaningful variations in pipeline degradation behavior, particularly across environmental conditions and material characteristics.

For uncertainty quantification, confidence bounds are established through polynomial smoothing of life table outputs, incorporating variability from discrete ERL calculations. These statistical bounds validate the stability of smoothed estimates while providing practitioners with quantitative measures of prediction certainty for decision-making. The confidence intervals effectively capture inherent variability in life table estimates while confirming prediction robustness across sample variations.

Although this single-factor analytical approach cannot directly compare the relative significance of different factors, the identified patterns offer practical insights for maintenance prioritization under uncertainty. The statistically significant differences observed suggest that performance variations stem from genuine factor effects rather than random fluctuations. Future work could expand this methodology through multi-factor life table analyses or advanced machine learning approaches to explore factor interactions and relative importance.

5.2. *Framework adaptability and transferability*

The framework demonstrates strong adaptability across diverse urban settings through its core statistical methodology combining life table analysis with polynomial smoothing, which is grounded in established demographic principles while avoiding region-specific assumptions. This robust foundation enables straightforward adaptation by integrating local infrastructure data into the analytical framework.

The single-factor analytical approach offers significant utility for municipal authorities with data collection constraints. By independently analyzing variables such as pipe length, material composition, and environmental conditions, practitioners can derive actionable insights without comprehensive databases or complex monitoring systems, particularly benefiting drainage authorities in developing regions or smaller municipalities where extensive data infrastructure is impractical.

The risk classification system enhances transferability through a relative threshold approach using quartile-based risk boundaries (T_1, T_2, T_3) instead of absolute failure criteria. This adaptive mechanism automatically adjusts to local conditions and infrastructure characteristics, accommodating variations in infrastructure age, environmental factors, and maintenance standards while minimizing recalibration needs.

The integrated GIS functionality increases framework versatility by enabling spatial analysis across diverse geographic contexts. Whether applied to Hong Kong's dense urban landscapes or other spatial configurations, the framework consistently provides relevant visualization and spatial decision-support capabilities for various urban environments.

5.3. *Methodological limitations and accuracy considerations*

Despite its practical advantages, the single-factor approach has inherent limitations. This methodology fails to capture complex interactions among multiple variables, such as material properties, environmental stressors, and operational loading, which collectively influence pipeline deterioration mechanisms. While simplification reduces analytical complexity and data requirements, it may compromise accuracy in representing real-world failure processes where multiple factors interact.

The framework's reliance on historical failure patterns constrains its predictive capability for unprecedented events. Life table analysis assumes future failure trends will mirror historical patterns, which may be insufficient when infrastructure faces novel stressors, including climate

Table 5
Factor-Based Pipeline Management Strategies.

Categories	Subcategories	Life Characteristics	Maintenance Strategies
Physical Factors	Length	1) Stage 1 (0–50): Long pipelines perform worst due to complex installation control issues 2) Stage 2 (51–64): Short pipelines show dramatic decline caused by emerging fatigue damage 3) Stage 3 (65–78): Short pipelines deteriorate to lowest ERL as aging effects amplify	1) Stage 1 (0–50): Monitor short and medium pipelines performance, establish baseline monitoring for long pipelines 2) Stage 2 (51–64): Regular inspection of short and medium pipelines, monitor stress in long pipelines 3) Stage 3 (65–78): Enhanced maintenance of short pipelines, maintain medium pipelines, ensure long pipelines stability
	Material	1) Stage 1 (0–4): Both concrete and clay pipes perform similarly due to pristine initial conditions 2) Stage 2 (5–64): Clay pipes outperform concrete pipes due to better chemical resistance 3) Stage 3 (≥65): Concrete pipes surpass clay pipes while clay becomes vulnerable to stress points	1) Stage 1 (0–4): Standard maintenance for both concrete and clay pipes 2) Stage 2 (5–64): Enhanced chemical protection treatment for concrete pipes 3) Stage 3 (≥65): Plan replacement for clay pipes and implement structural reinforcement for concrete pipes
	Diameter	1) Stage 1 (0–62): Small diameter pipes show highest ERL, medium second, large diameter lowest due to stress and joint issues 2) Stage 2 (≥62): Small diameter pipes deteriorate to lowest ERL, while medium and large pipes maintain gradual decrease	1) Stage 1 (0–62): Frequent inspection for large pipes, moderate monitoring for medium pipes, less intensive inspection for small pipes 2) Stage 2 (≥62): Increase inspection for small pipes with replacement evaluation, maintain regular monitoring for medium and large pipes
Functional Factors		1) Stage 1 (0–9): Stormwater pipes outperform foul pipes due to lower corrosivity 2) Stage 2 (10–64): Foul pipes demonstrate better ERL than stormwater pipes, benefiting from specialized design 3) Stage 3 (≥65): Stormwater pipes surpass foul pipes as foul pipes show accelerated degradation	1) Stage 1 (0–9): Focus on early-stage protection for foul pipes 2) Stage 2 (10–64): Enhanced inspection and maintenance for stormwater pipes 3) Stage 3 (≥65): Increase monitoring of foul pipes for accelerated degradation
Environmental Factors	Land Use	1) Stage 1 (0–20): Residential highest ERL, followed by commercial, industrial, then green areas. Green areas rank lowest due to root intrusion and soil movement challenges. 2) Stage 2 (≥21): Residential and commercial maintain performance, industrial drops below green areas. Industrial declines from chemical exposure damage, while green areas benefit from less corrosive conditions.	1) Residential: Regular inspections and prompt repairs 2) Commercial: Grease discharge control and regular cleaning 3) Industrial: Enhanced wastewater pretreatment and corrosion-resistant materials after age 21 4) Green Areas: Root intrusion prevention and seasonal flow monitoring
	Humidity	1) Low Humidity: Consistently demonstrates poorest ER, due to: Stress distribution changes, Unstable oxide layer and Microstructural evolution. 2) Stage 1 (1–62): Medium humidity maintains best ERL due to optimal physicochemical stability, while high humidity shows medium performance. 3) Stage 2 (≥63): High humidity surpasses medium humidity due to surface characteristics evolution and cumulative environmental effects.	1) Low Humidity: Full lifecycle enhanced monitoring + shortened replacement intervals 2) Stage 1 (1–62): Regular inspection program for medium humidity and Early performance monitoring for High humidity 3) Stage 2 (≥63): Systematic renewal with partial/complete replacement options for medium humidity and Reserve fund for upgrades and retrofitting for high humidity
	District	1) Stage 1 (0–10): Hong Kong Island leads slightly over Kowloon due to early development and favorable construction conditions; Islands and New Territories show lower ERL from insufficient initial investment 2) Stage 2 (11–54): Kowloon surpasses Hong Kong Island	1) Kowloon: Establish model management system, conduct non-intrusive inspections for pipes over 50 years 2) Hong Kong Island: Increase maintenance after age 11, focus on commercial segments, comprehensive

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Table 5 (*continued*)

Categories	Subcategories	Life Characteristics	Maintenance Strategies
		through better geology and network layout; at age 17 Islands temporarily exceeds New Territories due to lower population density 3) Stage 3 (≥55): Islands decline sharply from environmental challenges; Kowloon maintains high durability while Hong Kong Island and New Territories converge, with New Territories slightly higher due to later development	evaluation after 64 3) New Territories: Strengthen monitoring for pipes between age 17–54 4) Islands: Implement corrosion-resistant materials, establish dedicated monitoring system, prepare emergency plan for age 70
	Temperature	1) Stage 1 (0–56): High temperature zones show best ERL due to lower viscosity and better flow; medium temperature maintains stable performance; low temperature areas suffer from viscosity issues 2) Stage 2 (57–60): Medium temperature zones lead as high temperature starts showing material damage; low temperature remains lowest 3) Stage 3 (61–67): Medium temperature maintains highest ERL; low temperature rises to second place while high temperature declines significantly due to cumulative heat damage 4) Stage 4 (≥68): Low temperature achieves highest ERL from slower degradation; medium temperature drops to second; high temperature approaches zero from thermal stress	1) High Temperature: Increase inspections at 50 years, focus on thermal stress damage, recommend replacement at 61 years 2) Medium Temperature: Maintain regular monitoring, enhance inspection after 68 years for fatigue damage 3) Low Temperature: Continue routine monitoring beyond 68 years, replacement can be delayed due to long-term durability
	Traffic Load	1) Stage 1 (<58 years): Traffic zones show highest ERL (uniform across heavy/medium/light), followed by non-traffic zones. Non-traffic zones rank lowest due to less stringent construction requirements. 2) Stage 2 (≥58 years): Non-traffic zones gradually surpass traffic zones in ERL. Traffic zones decline from continuous vehicle vibration/pressure, while non-traffic zones benefit from minimal environmental stress despite initial lower quality.	1) Stage 1 (<58 years): Focus on non-traffic zones due to lower initial construction standards 2) Stage 2 (≥58 years): Shift focus to traffic zones as structural deterioration accelerates from vehicle loads
	Rainfall	1) Stage 1 (0–42): High rainfall areas lead in ERL due to sewage dilution effects; moderate rainfall shows medium performance; low rainfall regions suffer from concentrated sewage corrosion 2) Stage 2 (43–59): Moderate rainfall zones surpass high rainfall areas as sustained exposure begins affecting initially robust systems; low rainfall maintains lowest position 3) Stage 3 (≥60): Moderate rainfall maintains best ERL through balanced stress-repair adaptation; low rainfall rises above high rainfall due to protective layer formation during low-use periods; high rainfall systems decline from constant scouring	1) High Rainfall: Enhance maintenance from age 42, focus on erosion and corrosion prevention, monitor material fatigue 2) Moderate Rainfall: Implement balanced maintenance approach to preserve durability, maintain regular inspection schedule 3) Low Rainfall: Monitor corrosion in early stages, adjust maintenance after 60 years to support adaptation mechanisms
	Soil	1) Stage 1 (0–13): Type 1 (Granite) & 2 (Backfill) lead due to uniform support and minimal groundwater activity; Type 3 (Granodiorite) shows strong initial performance; Type 4–6 display lower ERL 2) Stage 2 (14–25): Type 1 & 2 maintain superior performance; Type 3 begins declining;	1) Type 1 (Granite) & Type 2 (Backfill): Implement standard inspection routines due to inherent stability 2) Type 3 (Granodiorite): Focus on intensive monitoring and corrosion protection during 14–60 years period

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Table 5 (*continued*)

Categories	Subcategories	Life Characteristics	Maintenance Strategies
		Type 4 (Tuff/Lava) & 5 (Superficial) show stable deterioration; Type 6 (Graphitic) remains poorest 3) Stage 3 (25–60): Type 1 & 2 continue steady performance; Type 3 deteriorates rapidly approaching Type 6 levels; Type 4 & 5 maintain moderate stability, gradually closing gap with Types 1 & 2	3) Type 4 (Tuff/Lava) & Type 5 (Superficial): Early reinforcement followed by routine maintenance checks 4) Type 6 (Graphitic Siltstone/Sandstone/Marble): Install comprehensive protection measures from beginning, emphasize cathodic protection

change impacts, evolving wastewater chemical compositions, or new loading conditions from urban development. The method is particularly challenged by sudden failures triggered by exceptional events outside historical experience.

A further limitation lies in the temporal lag of the self-updating mechanism, which restricts responsiveness to emerging risks. Although the methodology integrates new failure data and recalibrates predictions over time, this process is not immediate. During rapid change periods, decision-makers may rely on outdated risk assessments, potentially compromising response effectiveness.

To address these limitations, practical implementation should integrate the life table framework within a comprehensive infrastructure management system rather than using it as a standalone predictive tool. The framework is well-suited for preliminary risk stratification to guide maintenance prioritization, particularly in resource-constrained environments or time-sensitive scenarios. However, risk classifications should act as triggers for detailed assessments using complementary methods rather than serving as definitive failure predictions. This integrative approach is especially valuable during transitional periods when organizations develop advanced analytical capabilities, providing immediate operational insights while enabling gradual incorporation of additional data sources and methods as institutional capacity evolves.

5.4. Future integration with complementary analytical approaches

This research addresses implementation barriers faced by municipal authorities in infrastructure assessment by developing an accessible analytical framework based on demographic life table principles. The methodology provides a practical alternative to complex multi-parameter models, requiring only basic current age data and categorical factor classifications while maintaining analytical rigor. Furthermore, the GIS-integrated visualization system transforms statistical predictions into actionable spatial insights. This spatial visualization capability allows municipal authorities to immediately identify priority intervention areas and optimize maintenance scheduling, supporting the transition from reactive to predictive infrastructure management.

Future advancements should aim to develop hybrid analytical frameworks that maintain the accessibility of the life table method while enhancing predictive accuracy. One promising direction involves integrating life table analysis with machine learning algorithms. This hybrid approach could leverage demographic methods for baseline risk stratification while employing ML to model complex interactions among environmental and operational variables. Such a hierarchical framework would retain low data requirements and computational simplicity for preliminary risk assessments, while providing greater precision for high-priority segments that require detailed analysis. Beyond algorithmic improvements, incorporating real-time monitoring data from Internet of Things sensor networks could further enhance the framework by allowing dynamic model calibration to reflect changing system conditions as infrastructure ages. Mechanistic materials degradation models could validate empirical findings, while climate risk assessments would expand the framework's capacity to evaluate resilience under projected environmental changes. These enhancements would bridge the gap between simplified demographic analyses and comprehensive infrastructure behavior modeling, offering municipalities a scalable pathway to improve their analytical capabilities as technical resources and data infrastructure mature.

6. Conclusion

This study applied demographic life table methods to evaluate the remaining service life of Hong Kong's sewer systems, providing a practical framework for maintenance prioritization when data is limited and establishing groundwork for proactive infrastructure management.

The study built a comprehensive pipeline database using ArcGIS, incorporating physical attributes (length, material, diameter), functional classifications (stormwater or sewage), and environmental conditions (location, land use, soil type, climate, traffic exposure) from 148,389 pipeline segments across Hong Kong's four regions. This database underwent thorough cleaning and standardization, serving as a scalable foundation for future infrastructure research globally.

Life table analysis produced two core indicators: ERL and AE, calculated across pipeline categories to reflect deterioration differences. The Wilcoxon signed-rank test with Bonferroni correction confirmed statistically significant differences among factor groups. Polynomial smoothing converted discrete outputs into continuous predictive curves for practical maintenance guidance.

The analysis revealed systematic degradation patterns with valuable insights. Physical factors show significant impacts: short pipelines maintain advantages until age 50–60 before rapid decline, while long pipelines improve in later stages. Concrete pipes outperform vitrified clay after age 65 despite clay's mid-life advantages. Small-diameter pipes require enhanced monitoring after age 62. Foul pipelines maintain superior performance during ages 10–64, while stormwater pipelines show better early and late-stage durability.

Environmental factors prove more influential. Industrial area pipelines reach critical thresholds at age 21, requiring immediate intervention. Regional variations show Hong Kong Island and Kowloon pipelines with 10–15-year ERL advantages over New Territories and Islands. Temperature, humidity, traffic, rainfall, and soil conditions demonstrate meaningful influences on performance reversals at different aging stages.

The study established a quartile-based risk classification system using thresholds T_1, T_2, and T_3: safe (green) above T_1, low-risk (yellow) T_1 to T_2, moderate-risk (orange) T_2 to T_3, and high-risk (red) below T_3. This flexible framework accommodates conservative, balanced, or aggressive management strategies. GIS-based spatial visualization provides intuitive risk distribution maps for identifying critical segments and optimizing resource allocation.

This research advances infrastructure management through a simplified yet rigorous remaining life assessment approach. The life table methodology offers municipal authorities a practical alternative to complex models while maintaining analytical robustness, particularly valuable for resource-constrained environments supporting transition from reactive to preventive maintenance.

Limitations include the single-factor approach's inability to capture complex multi-variable interactions and reliance on historical patterns, limiting predictive capability under unprecedented conditions. Future research directions include developing hybrid frameworks combining life table simplicity with advanced capabilities, incorporating IoT sensor networks for dynamic updates, and exploring integration with AI-based models to enhance predictive accuracy while preserving practical applicability.

CRediT authorship contribution statement

Jingchao Yang: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tarek Zayed:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition. **Dramani Arimiyaw:** Writing – original draft, Conceptualization. **Mohamed Nashat:** Writing – original draft, Data curation. **Ridwan Taiwo:** Writing – original draft, Investigation, Formal analysis. **Ghasan Alfalah:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition. **Xianyang Liu:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abdelazim Ibrahim:** Writing – original draft, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.wroa.2025.100467.

Data availability

All data supporting the conclusions of this study are available on request from the corresponding author.

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