**International Journal of Building Pathology and Adaptation**

**Modified sewer asset management to accommodate London’s future sustainable development**

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**Abstract**

This paper is about best practice in managing legacy drainage assets to support sustainable urban regeneration. The aims are to describe best practice sewer asset management and also to adjust the current reactive maintenance approach for sewers, to one that accommodates long term operational and town planning needs. The development of an improved sewer deterioration model provided an important tool for this.

This is a paradigm shift and goes beyond the current culture of OFWAT (Water Services Regulation Authority) supervision, 5-year AMP’s (Asset Management Period) and occasional environmental penalties. A new legislative model may be needed; especially because a report by UKWIR (Water Industry Research) in 2015 identified that nationally the rate of sewer network deterioration is outpacing available investment and significant health problems may arise in addition to those from developmental pressures.

This research adopts a mixture of qualitative and quantitative approaches to analyse a total network length of 24,252 km which represents 703,156 records of historic sewer structural condition inspection data. This was used to build an improved deterioration model. These models were used as inputs into a proactive asset management approach that improves upon recommendations in the SRM (Sewerage Rehabilitation Manual) developed by WRc (Water Research Centre).

The authors have researched and managed old sewer networks and present a review of the new issues raised by intensive development, particularly for the London region, but applicable elsewhere, and how these must lead to a modified risk, and novel incentive-based approach to asset management, if the system is not to fail.

Large, legacy databases of several decades of sewer network performance records have been combined and analysed as stratified, heterogeneous sets with Gaussian distributions; thereby improving on previous assumptions of homogeneous data. The resulting rigorous DMs are the foundation of new approaches to sustainable risk management of large urban networks.

**Keywords** Sewers and drains, Service life, Maintenance & inspection, asset management

Paper type Research paper

## Introduction

Asset Management (AM) is a vital tool for virtually all the institutions concerned with service delivery in the world because it combines the financial, management, technical and engineering practices. These help in ensuring that the service delivery level is up to the expectations of the customers, whilst at the same time ensuring minimal cost and assured longevity of such facilities.

The sewerage network (SN) in England and Wales contains some of the oldest and most comprehensive in the world with a net reported length of 302 000km (Clegg, et al., 1989). SN consists basically of the following: a series of pipes of different properties (gravity networks and rising mains), manholes and pumping stations (WRC, 1994). The research reported focused on gravity sewers, and a sewer is defined in this context as a manhole to manhole length.

In 2017, to ensure a safe, economical and sustainable urban infrastructure, a development plan for Greater London Authority (GLA) was published. The 2017 Draft London Development Plan has mapped ‘where particular flood risk and water-related constraints such as limited sewer capacity require an integrated approach to the provision of infrastructure and management of risk’ and stated that ‘Integrated Water Management Strategies should be considered for major development locations such as Opportunity Areas’ (Khan, 2017). In 2014 unpublished studies by an ICE (Institution of Civil Engineers) London panel on housing, with which one of the authors was associated, additionally identified there was a significant variation across London in terms of water supply pressures, power distribution capacity, travel capacity and the social infrastructure support needed for new developments.

Building resilience into the infrastructure was at the heart of the GLA plan, which stated;

* Basement construction must be managed effectively, most especially where there are multi-storeys with a basement that exceeds the building footprint. This can affect the structural stability of sewers and consequently cause flooding.
* Utilities in charge of managing sewers should have a flood risk management strategy to address flooding from sewers and the development.
* Critical sewers that could result into significant flooding should be identified and such sewers and upgrading these should be considered by the proposal for development.
* Measures for a sustainable sewerage system should be considered over the coming decades in areas of sewer capacity limitations. This will ease the burden on available networks and avoid reactive major sewer construction.

**SN Pathology**

If we extend the topic of building pathology to that of an infrastructure system that includes buildings and their external civil engineering services networks such as SN, then to some extent the system has already partially failed because it will not easily accommodate the proposed new and higher densification of population.

The GLA draft plan, based on extensive informed consultation, underscores the need for investment in the entire infrastructure to accommodate the ever-growing population. Population increases will always result in the need for more social and physical urban infrastructure such as hospitals, housing, schools and transportation networks to be built. Improving the asset management of the sewer network contributes to this goal.



Figure 1. Population increase in the UK and London using Spotfire analytic (Adapted from Office for National Statistics)

From 2011 to 2016, the population of London grew by 7.5% in contrast to the whole of UK which grew by only 3.7% over this 5 years period (TFL, 2016). As shown in Figure 1, the population in the UK is increasing and there is a need for government to put investment in urban infrastructure at the heart of their budgets. The majority of social infrastructure requires some form of building and consequently puts pressure on the SN. To build sustainability into the SN to accommodate future demand as specified in the 2017 draft London development plan, there is the need to be able to predict with confidence the future performance of older sewers. Prediction of the future condition of SN would require suitably frequent inspection of the SN and an analysis of the collected data to create an accurate Deterioration Model (DM).

This paper describes improved practice for the asset management of sewer networks to support sustainable urban regeneration, and to this end to adjust the current reactive maintenance approach to one that also accommodates long term operational town planning needs. An improved sewer service life prediction model was needed and this has been produced using stratified network properties. The stratification adopted is described later in the methodology section. It permits more reliable maintenance and inspection decisions than hitherto. Knowing service life characteristics, the inspection frequency for proactive management can be specified and the unplanned expense of reactive repairs avoided. This is beneficial in terms of cash flow and leads to coordinated repairs for larger segments of the network and a more informed estimate of network capacity for future regeneration plans.

**Literature review**

In the area of infrastructure, an early use of systematic AM was by the American Highway Administration (Berger, 1978). Earlier, around 1900 in the financial industry, whilst growing in importance, AM remained a subsidiary concern (Nigel, 2017). Contemporaneously, engineers were studying water pipe corrosion and implicitly systematic AM (Colebrook & White, 1938). So, AM had implicit and multi point origins as a systematic approach, but it was something of an afterthought. In many developed urban areas worldwide it still is a second string discipline.

In an extensive literature review, three areas of AM specifically for SN were identified by Tade (2018). His reference expands on the following summary which identifies weaknesses in practice and literature that this paper addresses:

1. Development of policy to proactively manage sewers,

There is still a major gap between utilities ‘business as usual’ sewerage management practices and the available management approaches (Nicolas, et al., 2017). There are uncertainties around sewer maintenance strategies introduced by weak DMs (Korving, et al., 2003). The consultative exercises and draft planning reports such as by the GLA Khan (2017) and the professional institutions informally will assist with these policy updates.

1. Deterioration models for sewer ageing (DM’s)

Recently, only 10% of Utilities in America were found to use DM’s for AM (Black and Veatch, 2013). Researchers have proposed several (rarely adopted) DM’s. Most of the proposed models are probabilistic and treat the network as homogenous. These include; logistic regression model (Ahmadi et al, 2014a Kley & Caradot, 2013, Hanusch et al, 2015) and Markov model (Baik et al. (2006), Rokstad and Ugarelli, 2015 Le Gat, 2008). There is not enough attention paid to physical mechanisms of failure.

Limitations such as quantity and quality of data have been identified by Kley & Caradot, (2013) and Rokstad & Ugarelli (2015). The poor data and probabilistic nature of the existing models is the major factor preventing utilities from using them for strategic investment plans. As of now, this uncertainty is yet to be addressed with the level of granularity neeeded by utilities.

As a result of these uncertainties, inspection frequencies were recommended by WRc (2001), Winnipeg (2001) and NRC (National Research Council of Canada). This was summarized by Zhao et al, (2001). This inspection frequency has been found to be unsatisfactory for current proactive plans. Hence the need to stratify data for new DM’s to dissolve this risk

1. Risk management

The AM of SN can help reduce the risks of catastrophic failures of the system as well as surprises in the budget (Vinnari & Hukka, 2009). For instance, the failure of the sewerage asset, failure to ensure proper maintenance of the infrastructure’s good condition could result in very hazardous effects on the health of humans and the environment. This could even influence the stability of the society (Doull et al., 2006). Proper infrastructural inspection and maintenance of the SN must thus be done in a timely manner to curb the consequences of the disastrous failures and ensure maximum lifetime of the vital sewerage assets. This is especially because the failure of a single critical sewer or a section of a sewer can lead to a tremendous economic loss (Motorola, 2009). The Sewer Risk Management website <http://srm.wrcplc.co.uk/home.aspx> now supplements the SRM and indicates the trend of developments in this area.

### Asset Management Framework

There are a number of conservation strategies which may be applied in the AM of SN to ensure the expected service delivery level. Each sewer repair will need to satisfy a cost benefit target. Therefore, to know the condition of the asset, the maintenance options of such an asset should be calculated and the cost calculations should be done to ensure maximum service level while incurring the lowest expense. In this research paper, focus will be on inspection planning to support effective decisions on future investments. Another key factor to take note of is the need to consider the varied types of sewers to deal with the additional system complexity of the network system.

Another complication is coordinating the existing reactive investment within a 5 years externally audited asset management period (AMP), with the as yet defined ambition for growth over 25 years. This issue was raised in a recent ICE (Institution of Civil Engineers) lecture on the challenging requirement of AMP 7 (ICE, 2018). This is currently underdeveloped. Who will pay today for SN that may come on line decades later? How will the optimization target of Figure 2 be managed?



Figure 2. Best value achieved by optimizing the total cost, risk and performance impact (Adapted from (ISO55000, 2014)

### Asset Management Approach

With regards to the framework put forward by the Institute of Asset Management, the management process of the asset begins from the optimization of life cycle of the very small components of the system and goes on until the point of considering the projects expected value. This is obtained from the entire system of portfolio, information, knowledge, people, network, and all the other components as presented in Figure 3. Increase in the complexity of the system is represented by each layer with the key challenges of substantiating the costs, sustainability, performance and the risks shown in every layer in the figure.

**Life cycle (Risks and serviceability)**

**Optimization of cost and risk**

**CAPEX value Performance and sustainability**

**AM System**

Figure 3. Levels of the AM system Adapted from (IAM, 2012)

### Asset Maintenance Strategies for Sewer Network (MSSN): Critical analysis

The SN is a vital part of all urban infrastructures. It, however, has a varied range of challenges both from the systems operational and the public health viewpoints respectively. Most especially, the buried nature of this asset makes identifying faults and problems difficult. The management of the SN is constantly evolving and becoming more sophisticated with time. This is because the systems are wearing out and being rendered more vulnerable to failures, thus increasing the cost of operation and maintenance.

There are a varied number of strategies that have been put in place for the maintenance of the asset. Such approaches can either be reactive or possibly proactive depending on the asset type (ISO55001, 2014). A preventive or proactive condition is aimed at the reduction of the chances of the occurrence of the system failures that lead to disruption. A corrective or reactive measure, on the other hand, is performed to rehabilitate an already failed system to make it assume its initial and original working condition. Such maintenance strategies are, however, in line with the importance and the condition of such an asset in the system. In this approach, the maintenance strategies are put under four categories variant in the reliability and the cost of maintenance.

***Maintenance based on the condition of the sewer***: This comes in two stages namely, occasional or continuous monitoring and the maintenance carried out only when required. This considers the condition of the project, but not its importance. In this case, continuous monitoring is introduced when sewer is at a critical condition and occasional at mid condition.

***Maintenance based on the reliability of the sewer***: This entails the priority list, the risk management and the outlines of the relationship between the asset condition and failure effect. This takes into consideration both the condition of the sewer as well as the importance of the sewer.

***Maintenance based on time***: This entails a fixed interval of time for carrying out the inspections and the maintenance. It takes into consideration the importance of the sewer but not its condition. From practical experience, this could be seen as bureaucratic but not heuristic.

***Maintenance for correction***: This is never done until a serious breakdown. It does not take into consideration the condition of the asset or its importance. An example is a category C sewer in the SRM (SRM, 2013).

AM has a great influence on the profitability and operational performance of utilities involved in the asset operation (ISO55000, 2014). Therefore, in order for any company or society to embrace AM, it must be in a position to successfully handle and operate the asset throughout its life cycle with profitable output assured with very definite safety and service standards put in place. Infrastructural AM is involved with the analysis of such assets that are vital to the whole society which include; buildings, sewerage network, power grids, water network, telecommunication systems and any other asset that may be used communally, though a service charge may apply. These are often large networks which create problems and opportunities of scale.

AM consists of a series of frameworks for designing the best processes and instigating decisions for creation, operation, conservation, inspection, regeneration, enhancement as well as discarding of such physical assets with an aim of delivering safe and economical infrastructure.

For sewers, inspection planning is the premise of effective AM to support a safe delivery and economical viable SN. It is clear that identification of both present and future sewer condition is an essential core component of AM.

In the UK, conventional CCTV survey is used to identify the present condition of a sewer. Future conditions can only be predicted by sewer deterioration models and an improved version of one of these is used later in this paper.

### Methodology

An essential aim of the research was to determine with improved precision and reliability the effective life time of SN with different materials, sizes and effluents. This is the core quantitative tool which allows the development of proactive models for AM, risk management and advising development teams on likely SN capability.

The data used in this paper was extracted from Thames Water utilities’ database. It includes 703,156 records of sewers inspected between 1989 and 2014 with a total length of 24,252 km. This assessment were done by sewer survey CCTV cameras for sewers less than a diameter of 1200mm and man entry assessment for sewers larger than 1200mm. Recorded parameters include the survey date, location, date built, manhole identification number, sewer material type, surveyed length, size, shape, use, WRC structural and service condition grades.

Fifteen senior experts were interviewed in the utility companies and their consultants with a typical experience of fifteen years each. It was necessary for the principal researcher to understand in-depth how databases had developed from legacy practices. The discussion with practitioners was very fruitful in guiding this research project and they include some co-authors and those in the acknowledgements.

The data was processed and sorted using Microsoft Power query. Most of previous work had often treated the entire network as a homogeneous population. This was unsatisfactory because the data was difficult to correlate and quite scattered if plotted. By stratifying data into cohorts such as materials, sizes, effluents, it was possible to show different life times for different subsets of the network and identify the Gaussian distributions and converging standard deviations for these cohorts as the strata were refined. (E.g. a small range of pipe sizes within a particular material category.)

Thousands of inspection records were interrogated with Tibco Spotfire software (Data analytical tool) and for each SRM grade ICG 1 to 5. At each grade, for each sub set (e.g. a Concrete (CO) sewer of 0-450 mm diameter pipe at ICG 4 in a rural road with mainly domestic effluent) the time to reach a particular ICG was combined with hundreds of similar ones. Many of these results plotted as Gaussian distributions with a mean and standard deviation.

The behaviour of the pipelines was similar to other normally distributed properties of engineering materials, although the standard deviations were higher than in the constituent materials, where factory based quality control was possible. However, reliable values of time to eventual ICG 4 or 5 were obtained for a range of materials and these were significantly different for each material. So the stratification worked and discriminated between properties. This gives a better tool for a proactive approach to repairs. Due to commercial confidentiality only data on CO can be presented here as a proof of concept. The number of CO sewers out of the 24,252 km of sewers stratified was 8,451 km. This was a major analytical exercise, over a full year and more extensive than anything in the literature.

Following on from this, a similar major stratification approach was adopted but this time around the criticality of sewers. The DM for CO was stratified into 3 different proposed criticality categories that were proposed by WRc in the SRM, to dissolve the uncertainty that has prevented utilities from embracing DMs. This is revisited in the section on risk management. The conceptualisation of the risk management approaches took several months after the DM’s tools were available.

With this primary objective achieved it was possible to start to work towards modifying reactive approaches to repairs according to WRc SRM recommendations, which are conservative for critical pipes. Knowing there was a time margin probably available that would permit a delay in repairing reactively a damaged segment so that it could be combined with nearby network repairs in an economic deployment of plant creates an improvement in budget efficiency. Such a methodology relies upon managing risks of severe failure with managed (non-reactive) repairs that eke out a budget and thereby raise the level of service experienced by most customers. With more demands put upon urban infrastructure by increasing population, aging assets and the need for economy and safety, the knowledge of likely sewer lifetimes is of practical value because it underpins developments in AM practice.

With more housing on brown field sites as a national planning objective, the likelihood of existing sewers either failing, or contributing to a proposed redevelopment, becomes significant for a project’s viability and this information needs to be available to the multidisciplinary teams of planners, architects and engineers who will be advising politicians and developers of costs and benefits of any proposal. It too relies upon reliable asset lifetime data at the bottom of this pyramid of applications.

### Sewer condition identification

Sewer CCTV survey is carried out using guidelines set out by WRc (Water Research Council). A camera attached to a sewer CCTV survey monitor is lowered into the sewer via the upstream manhole and the surveyor controls the camera as it moves through the entire length of the sewer.

Figure 4. Sewer condition scoring process (Adapted from SRM, 2004)

Whilst watching the footage, the technician applies a code according to BS EN 13508-2 to all the defects found in the entire sewer length. For example; going through a 20m sewer length, the code BAA A is applied for a vertical deformation as shown in Figure 4 with the chainage recorded. Further down the sewer length at 11m, a dropped invert is found and recorded as BAD C with the chainage, and at 15m, a collapse found is recorded as BAD D with the defect chainage. The codes are then converted to the corresponding WRC defects scores as shown in Table 1.

Table 1. Scoring of sewer defects in Figure 3 using existing scoring system. Source: Tade (2018)

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Defects | BS EN 13508-2 | WRC SCORE | Peak score | Mean score | Total score | Condition grade |
| vertical deformation | BAA A | 40 | 165 | 14.25 | 285 | 5 |
| dropped invert | BAD C | 80 |
| Collapse | BAD D | 165 |

 |

The peak score is the highest individual score found in any section of the sewer, the total score is the addition of all the individual scores found along the sewer length, the mean score is the total score divided by the length of the sewer and the structural condition score is a function of the peak score as shown below. The defect score assigned to structural defects depend upon its severity and pipe material and the internal condition grades (ICG) are calculated based on the peak defect score (Chughtai & Zayed, 2011). The ICG is assigned as shown in Table 2.

|  |  |
| --- | --- |
|  Structural internal condition grade (ICG) |     Peak Score           |
| 12345 | Less than 1010 - 3940 - 7980 - 164165+ |

Table 2.WRC condition grades (WRC, 1994)

From the discussion with practitioners of AM of SN, it was confirmed that for risk management the identification of both present and future sewer condition is an essential core component of AM. This can only be provided by understanding the consequence of the asset and reliable sewer DMs.

### **Risk Management**

In the management of risks, the key potential hazards must first be defined, their potential impacts and likelihoods analyzed, and eventually outlining the most appropriate procedures that can be applied in response to their occurrence. Analysis of risks forms a very basic component of management of such risks as it defines as well as dissolves them, whereas the risk management seeks to establish the solution to such shortcomings.

For proactive AM, there is a need to analyze risk. Risk in this context is a function of Likelihood of Failure (LOF) multiply by the consequence of failure to the utility (COF). The ICGs as in Table 2 relate to the likelihood of sewer failure (LOF). Utilities across the UK understand the COF of their SN failure but not the LOF with the level of granularity needed (Tade, 2018). In England, 75% of the high-risk sewers are in London. Most access points to the sewers are on roads and will require traffic disruption when manhole access is required. One of the consequence factors that is considered during risk analysis are busy road diversion and railway lines closure. Hence, there is a future need to investigate sewer assessment options with minimal disruption.

In an approach to analyze the SN there is need to carry out an intensive theoretical and conceptual study. This is analogous to Red Amber Green (RAG) coding in Construction Design and Management regulations (CDM, 2015).

Low event impact/ High event probability

(Reactive) (CAT **C**)

High

High risk

(Proactive) (CAT A)

Event probability(LOF)

Low risk/High event impact

(Proactive) (CAT B)

Low risk

(Reactive) (CAT C)

High

Event impact (COF)

Figure 5. Risk chart Source. Tade (2018)

Sewers will deteriorate with time and it will get to a point where replacement or repair becomes inevitable as the required level of service can no longer be guaranteed or there is an unacceptable risk of collapse. For some less critical assets, a failure can lead to a minimal service impact and therefore it may be least cost to be reactive and let an asset fail before repair or replacement. In other instances, for more critical assets, failure could lead to significant service impact – such as flooding or pollution or public health risk such as contamination or a train derailment. In these instances, investment in repair needs to be proactive (take place before failure). This echoes the CAPEX vs OPEX problem (Hackitt, 2013).

Another vital factor in selecting the most appropriate maintenance strategy to be put in place is the condition of the assets. This is based on the grounds that the condition of the asset is the key determinant of the rate of failure by the asset and its reliability (Rajani & Kleiner, 2001). This factor is, however, very variant with the life of operation of the particular asset. The successful management of risks arising as a result of failure, is the capacity to identify the critical cohorts within the SN. There is the need to establish a protocol that transparently prioritises the higher ranking assets.

The AM discipline incorporates both the analysis of conservation and replacement, as well as analysis of the system failure and economics. This field has gained a lot of recognition within the past two decades. Three reasons as to the increase in the interest have been put forward (Brint, et al., 2009). These are:

* Over the years, very comprehensive asset modeling systems have replaced the asset registers based on paper with computerized database which has enhanced a much better prediction and analysis of performance of asset for business intelligence analysis.
* Such assets are quickly aging yet their quality of service expectancy is constantly on the rise. Due to the rising population as earlier stated, the assets that are already in place are expected to serve a larger population than initially stipulated and at the same time for a longer time. There thus, comes the need for a timely maintenance of the already existent network assets (Tade, 2018).
* Even the private companies, since 1985 are expected to periodically make submission of their 5-year plans of AM (AMP) for review. In this way, every company’s investment and performance plans should be identified. This therefore, calls upon the industries to substantiate their funding for the future investment (OFWAT, 2016). To meet these expectations, the utilities must be able to prioritize and justify proactive investment in SN.

**Investment prioritization practice in the UK**

The practise for prioritising investment in SN in the UK is to analyse the criticality of the SN. A sewer could be critical or non-critical. Generally, criticality is a measure of cost which a knock-on effect created by COF. COF is a function of;

* The level of sewer importance
* Likely collateral damage from a failure or collapse of sewer
* Sewer replacement cost
* Sewer location

Clearly, there is a cost overlap between criticality and COF.

The WRc Sewer Rehabilitation Manual (SRM) provides guidance on the process of managing SN. This SRM grouped sewer’s criticality into 3 categories. These categories depend on the surface theme (type of building above such as highway, railway or hospital area), sewer depth, sewer material type and soil condition (WRC, 2001). These factors can potentially result into a very high cost of repair.

Category A (CAT A): Sewer failure will directly or indirectly have an extreme cost consequence to the utility. The reactive cost is 6 times greater than the proactive cost (WRC, 2001).

Category B (CAT B): Sewer failure will result into a moderate cost consequence to the utility. The reactive cost is between 3 to 6 times the proactive costs (WRC, 2001).

Category C (CAT C): Sewer failure will result into low consequence to the utility. The reactive cost is less than 3 times the proactive cost (WRC, 2001).

To avoid this consequential cost, the existing proactive investment frequency for sewers was provided by WRC is as in Table 3. These reactive and proactive cost factors of 3 and 6 might be regarded as almost traditional.

Table 3. Investment priorities (Adapted from WRC, 2001 and Zhao et al, 2001)



From extensive discussion with primarily the same UK experts in the waste water industry identified in the methodology section, it was found that the survey frequencies provided in the SRM are too ambiguous, having too low level of granularity for proactive investment management. To improve the granularity of the information a large, rigorous, stratified statistical analysis has been undertaken for a subset of concrete pipes to produce an improved predictive capability that supports sustainable asset risk management. These improved graphs of deterioration rates are for concrete sewers in the Thames catchment and are original research reported in this paper.

**Deterioration model for concrete sewer**

Sewer material ranges from brick, iron, vitrified clay, pitch fibre, plastic, composite materials and concrete. Ideally, it is expected that these materials will deteriorate at different rates. It was found that different properties within the concrete sewer cohort deteriorate at different rate as shown in Figure 6.



Figure 6: Stratified deterioration for concrete sewers showing the variation in deterioration Source: Tade (2018) 

= standard deviation.

It will be nothing short of reactive to manage all these different sewer material types with the same investment priorities provided in the SRM in Table 3. For this research paper, concrete material was the chosen example.

Sewer assessment data in the UK between 1989 till 2014 was collected, cleaned and sorted. 53935 manhole to manhole numbers of concrete sewers were identified. This represents a total length of 2,346km of concrete sewer with an average length of 43m. The average time for these sewers to get to each ICG was analysed to obtain the deterioration curve in Figure 6.

Figure 6. Deterioration curve for concrete sewer. Source Tade (2018)

Using standard spreadsheet software the deterioration curve can be fitted as Equation 1;

It can be seen from the deterioration curve that it will take around of 2 years for this concrete sewer type to get to ICG 5 from ICG 4. This is higher than the 0 years provided by WRC in Table 3. For a comprehensive comparison, the investment priorities provided by WRC is compared with the observed in Table 4.

Table 4. Inspection frequency comparison. Source Tade (2018)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **ICG** | **Observed Deterioration with our new DM** | **WRC CAT A** | **WRC CAT B** | **WRC CAT C** |
| 1 to 5 | 15 | 5 | 20 | Reactive |
| 2 to 5 | 8 | 3 | 15 | Reactive |
| 3 to 5 | 5 | 0 | 5 | Reactive |
| 4 to 5 | 2 | 0 | 0 | Reactive |

A critical look at Table 4 shows that there are significant discrepancies between the observed rates of condition change and the ones provided by the existing WRC framework. For CAT A with the costliest reactive investment, the implied frequency of inspection from our observations is less demanding than provided by WRc. This implies that the utility following WRc guidance would have to spend more on sewer inspection than necessary. For CAT B, the frequency of inspection provided by WRC appears to be less demanding than suggested by our observations; this implies that some sewers will be failing before assessment resulting in a reactive form of maintenance.

The justification for the different figures for CAT A provided by WRc is that there are uncertainties around sewer deterioration. Hence, it is necessary to inspect sewer condition more frequently. Nevertheless, for CAT B sewer, the frequency of inspection provided doesn’t appear to be proactive as the observed is lower than the ones provided.

Another major problem is for utilities managing a large SN where a large portion of sewers could be in ICGs 3, 4 and 5, in CAT A criticality. The research question is how will the business prioritize and justify inspection frequencies within 3 years specified by WRC in the face of scarce financial resources? Hence, there is the need to modify current priorities for AM.

**Best practice asset management of sewerage network**

There are numerous benefits that can be derived from modifying the existing application of the techniques of AM in the waste water utilities. This is to provide;

* Solutions of AM that are vital for the safety of the system.
* Timely maintenance intervention.
* Increase in the availability of the asset.
* Increased lifetime of the asset.
* Increased productivity of the asset.
* Reduced cost of the asset’s life cycle as well as being compliant with legislative measures.

AM must take into consideration all the varied kinds of factors peculiar to the SN with their respective needs, and finally applying an all-inclusive approach that gives focus to the network’s total value. Most prognostic techniques applied in the management of assets help in the making of decisions with regards to a specified threshold on the information forecasted on the individual assets by taking into consideration the time of failure. However, in a case whereby the individual asset is interdependent thus forming a network, such approaches may not be in a position of giving the most reliable result (Camci, 2009). For the SN, that seems somehow a bit more complex, its buried nature, concrete network structure, as well as the interconnections that exist amongst the components renders that a very contentious system feature. There is also a variation in material, size, depth, location and age of sewers. The unique nature as well as the properties variation that exist amongst sewers also creates a very contentious system.

The characteristic of the network, usually, becomes economically impossible to describe just by the analysis of the very separate cohort, which is very distinct when considered independently (Kastenberg, 2005). There, thus, is the need to analyze the individual characteristics of the different sewer cohort in the network to establish the vulnerability of such a network system, which will inform the decision pertaining to the maintenance, operation as well as the optimal design (Zio, 2009).

After a further analysis of the deterioration curve in Figure 6, it was found that a standard deviation of +30 to -30 years exist around the average year obtained for ICG 5. This quantifies the uncertainty around sewer deterioration. For each ICG (1 to 5) condition there would be well over 100 values and these were found all to be normally distributed with similar percentage standard deviations. One can therefore viusalise the average lifetime graph plotted in Figure 6 having parallel ones below it with multipliers of the standard deviation used to determine the distance between them reflecting the likelyhood of lower more conservative estimates of the time to reach that ICG.

In this research, it was observed that sewer degradation follows a Gaussian distribution. This means that risk management techniques used for other engineering systems such as new concrete superstructures are transferable. For example, in concrete buildings in Europe, a multiplier of 1.64 times the standard deviation when subtracted from the mean gives a design strength such that 95% of the material will exceed that value. The use of Gaussian distribution and factored standard deviation for structural design has been established in Eurocodes for several years (EN1992-1-1, 1992). Our approach is to transfer the established methodology of structural Eurocode to risk management of SN. Standard texts deal with this, Kong and Evans (1987), Chatfield (1987).

As shown is Figure 7, the uncertainty was analysed as a factor of safety (FOS) to manage risk. The average value obtained in the deterioration curve is at 50%. 50% means, 50% of the sewers analysed survived at this point and 50% has failed in some way. At 65%, 65% of the sewers analysed survived and 35% has failed at that point and at point 80%, 80% of the sewer analysed survived and 20% has failed at that point.



Figure 7. Standard deviation analysis of uncertainty around deterioration . Source Tade (2018)

…….Equation 2

Where;

 is the design strength for only 5% to fail for a structure

 is the mean strength

 is the standard deviation

If the asset manager for a sewer therefore had the risk appetite such that no more than 20% of the assest would have failed for a CAT A sewer,say, the intervention time in Equation 3 would be used, if no more than 35% for a category B sewer, Equation 4 is used and for category C where only half would have failed.

…….Equation 3

…….Equation 4

…….Equation 5

Where;

 is the intervention time for category A sewers.

 is the intervention time for category B sewers.

 is the intervention time for category C sewers.

 is the average life of sewers to get to a particular ICG 5.

As a statistically proven process, this gives a picture of the overall behaviour and is not predictive at any sewer element level. Although this gives an improved planning tool, the allocation of a CAT A status to a link of sewer will always prioritise it over a CAT B. For example, in the management of sewers in a catchment of 40 CAT A sewers, this would allow effective management. There could still be a localised failure but if a link is that critical, a wireless sensor monitor might be an option in a ‘beyond CAT A’ sewer.

To put this analysis into perspective; for a set of 8,451 concrete sewers in ICG 5, several explanatory factors such as depth, location, length, size, slope, effluent type, and soil type have resulted in different deterioration rates within the concrete material cohort. The average of this variable deterioration rates is taken and the deviation around this rate is derived to capture the uncertainty. This uncertainty is used to dissolve the risk. For example, it takes an average of E years as shown in Figure 6 for all concrete sewers to get to ICG 5 and the standard deviation (SD) is 30. For a criticality A sewer, the SD is used to estimate the time it takes 20% of the sewers to get to ICG 5. Assuming the value of E is 80 using Equation 3, utilities can start surveying at 55 years.

If the risk appetite is to pick up at least 10% of the sewers then one must be checking those using a factor of 1.28 times 30 years, equals 43 years. So, inspections need to start 12 years sooner for a 10% rate compared to 20%. Different zones of the network can be prioritised to suit the regional policy.



Figure 8. Failure rates against the time span of the network. Tade (2018)

Point w : sewer commissioning

Point w to x: Infant mortality,decreasing failure rate

Point x to y: Normal life (the useful life): Very low but constant rate of failure

Y to z: Deterioration begins increasing failure rate

Z: sewer end of life.

For yet to be surveyed sewers, the point of intervention for the different criticality categories shown on the bath tub curve in Figure 8 can be used. For example, for a CAT A sewer, sewers older than 55 years should be inspected if missing 20% of failures and responding reactively is acceptable, and for CAT B concrete sewers older than 68 yearS should be inspected.



Figure 9.Deterioration curves for stratified into 3 criticality

**Development of Framework**

As shown in Figure 10, data from the utilities database is analyzed to identify levels of criticalities. The individual criticality goes into different programmes;

* Criticality A: Into proactive inspection programme because the cost of reactive repair is very high.
* Criticality B: Into proactive inspection programme because the cost of reactive is high.
* Criticality B: Into reactive maintenance programme because the cost of proactive could be significantly more than reactive



Figure 10. Framework for proactive AM of SN, Tade (2018)

For sewers that have never been surveyed before, the programme creates material cohort deterioration models. If the material is concrete, Equation 3 and 4 are used for Cat A and Cat B sewers respectively.

Generally, in criticality A inspection program, 80% survival rate or 20% failure rate is used and the predicted ICGs combined with the COF is used to set priorities.

In criticality B inspection program, 65% survival rate or 35% failure rate is used and the predicted ICGs combined with the COF is used to set priorities.

As earlier stated, these percentages can be adjusted to suit the utility’s risk appetite.

After sewer CCTV survey, the observed and the predicted ICGs go into a recalibration model for the deterioration rates to be recalibrated. This would allow the model to adjust to any shift in the deterioration rates. The recalibrated model is used to set priorities for CCTV resurvey frequencies.

Also from the risk analysis using the COF and observed ICGs, sewers with risk levels 1, 2, and 3 go back into the database for another cycle of criticality analysis. This is because the criticality of a sewer can change over time. Sewers with risk level 4 and 5 go into proactive maintenance program for rehabilitation. All repair or maintenance programme goes back into the data base for another cycle.

All these improved procedures assist the process of AM and informing long term town planning.

**Conclusion**

The paper has developed an improved reliability for predicting the remaining lives of concrete sewer cohorts. It also improves practice by allowing the risk appetite of the asset manager to be reflected in the assignment of modified service factors to the standard deviation of the degradation curve. This more precise information permits the asset manager to prioritize inspection plans and control the risk and altered frequencies of inspections. There is anecdotal evidence from the experts consulted for other parts of the paper that in a modified way, SN follow a bath tub curve and this paper clarifies the medium and long-term characteristics once the system has been commissioned.

As shown in Table 5, there are some invaluable insights. Often, CAT A, B and C are defined as repair cost consequences of A and B as 9 times and 6 times the cost of proactive investment. This is somewhat arbitrary as is the selection of traditional WRc inspection frequencies shown in Table 4.

The paper shows that once condition 1 is observed in concrete sewers, it typically takes 15 years till a condition 5 failure occur. This means that the WRC CAT A inspection frequencies of 5, 3, 0, 0 are over anxious. It also means that the 20 and 15 for CAT B is too relaxed and need to be modified. This is a significant and rational improvement on traditionally accepted values. Clearly, some urgency is introduced for a sewer link by triggering an earlier inspection time for CAT A compared to CAT B. There will be outlier failures but the proposed practice will generate efficiencies for the sewer network as a whole. Hence, WRC inspection frequencies can be safely adjusted.

As we increase the density of occupation in some parts of London and other cities to the highest levels experienced anywhere, the old infrastructure and SNs will become an even more vulnerable public health asset needing careful asset management if the municipality is to remain sustainable. The improved quantification of the likelihood of element service failure presented here is a tool that helps eke out that element of sustainability and for a while fends off the need for capital expenditure of a magnitude that will tax political leadership. There will however in the foreseeable future be a need to revisit the funding of the infrastructure systems to afford the new investment. . Currently a deeper understanding of pipe pathology supports sustainable asset management in developing cities and buys us some respite.

AM is an important concept in the waste water sector, with some of the utilities having a positive attitude. With the aid of information technology, AM has a very significant assistance to the SN that helps a community in conveying effluent in an efficient and cost-effective way, thus improving the performance and reliability of such systems. Such positive outcomes include: optimum inspection time and reduced AM cost, availability of more information, funding towards all elements of the assets in a prioritized manner, fast decision making as well as the prediction of the varied lines of actions to be taken. It is crucial that an effective calibrated deterioration model of the system is available, and that there is an enthusiasm to use it. Thus, there is the need for the waste water companies to make AM their single source of truth and to embrace the move to improved quantified models in order for them to optimize the sustainable future for stakeholders.

### Acknowledgment

The authors will like to thank Thames Water Utilities limited most especially Martin Baggs the former CEO for giving us the opportunity to work on this project and Stephen Pattenden for his support and for giving us the opportunity to test the model. The authors also thank Chris Hinton,

Sam Glenton, Jade Petersen, Sivaraj Valappil, Michael McSweeney and Paul Woodborn of Thames Water for their support and contribution in making all necessary data, reports and training available.

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