H2Open Journal

© 2020 The Authors
46

H_2Open Journal Vol 3 No 1
doi: 10.2166/h2oj.2020.027

Performance assessment of Swedish sewer pipe networks using pipe blockage and other associated performance indicators

E. Okwori*, M. Viklander and A. Hedström

Department of Civil, Environmental and Natural Resources Engineering, Lulea University of Technology, 971 87 Lulea, Sweden

*Corresponding author. E-mail: emmanuel.okwori@ltu.se

Abstract

Sewer pipe networks are expected to operate with minimal or no interruptions. The complex nature of randomly occurring failures in sewer networks arising from blockages significantly adds to the cost of operation and maintenance. Blockages are significant due to sewage backup or basements flooding, resulting from their occurrence. Therefore, continuous performance assessment of sewer pipe networks is necessary to ensure required levels of service at an acceptable cost. This study provides insight into the performance of the sewer pipe networks by assessing the proneness of the network to blockages. Furthermore it draws inferences at a holistic strategic level of influential explanatory factors of blockage proneness, using data available in the Swedish Water and Wastewater Association's benchmarking system. Results indicate that medium sized municipalities are prone to at least 30% more blockages per km per year compared to other municipalities. A hypothesis of explanatory factors includes reduced flow volumes and flow depth. Flow velocities below self-cleaning velocity in sewer pipe networks, encouraged by sluggishness of flow are responsible for increased possibility for sediment deposition and accumulation in sewers leading to blockages. This is also exacerbated by the deposition of non-disposables (wet wipes, baby diapers, hard paper, etc.), accumulation of fats, oils and grease in sewers and increased water conservation measures.

Key words: benchmarking, wastewater

INTRODUCTION

The complex nature of interdependencies of the various components of a sewer pipe network (Venkatesh 2011), and urban challenges are some of the key frontline reasons to move towards more resilient urban infrastructure (Hedström *et al.* 2016). In this regard the performance assessment of pipe infrastructure networks has increasingly become more critical (Cardoso *et al.* 2004; Mazumder *et al.* 2018; Tscheikner-Gratl *et al.* 2020).

Existing asset management approaches for pipe infrastructure performance assessments are constantly experiencing tensions between governance policy and strategic/tactical goals of water utilities towards selecting a systematic and effective method for prioritization of maintenance (choice between redesign and rehabilitation) which ensures efficiency of outcomes. Performance indicators may be used to improve efficiency of maintenance actions and ensure desired outcomes, based on set objectives (Pinto *et al.* 2017). The use of performance indicators (PIs) as a rationale for identification of critical areas for maintenance shows how operational disturbance data in sewer pipe networks at the strategic network level can be used to establish an overview of the state of pipe

H2Open Journal Vol 3 No 1
doi: 10.2166/h2oj.2020.027

infrastructure assets. Performance indicators also serve as mechanisms for benchmarking and prioritisation. However, it has been acknowledged that performance indicators provide an estimation of the status and are therefore precursors for more detailed investigations in the critically identified areas (Alegre & Coelho 2012; Rokstad 2012).

Maintenance actions, among other reasons are performed in order to maintain the function and extend the remaining service life of an asset, by improving its condition and/or reducing its condition deterioration rate and improving performance (Grigg 2003). Maintenance operations have a critical role in ensuring the reliability of urban water infrastructures particularly sewer pipes. It is expected that effective maintenance actions reduces the frequency of service disruptions and their undesirable consequences. However due to limited resources and cost constraints, all maintenance cannot be performed simultaneously as such the most critical maintenance activities need to be prioritized. In this sense, sewer blockages are one of the main challenges faced by municipalities.

Van den Berg & Danilenko (2010) and Miszta-Kruk (2016) stated that sewer blockages serve as an indication of various problems in the sewer networks such as hydraulic deterioration, structural integrity and operation and maintenance (O&M) efficiency. Previous research which focused on this include Rodríguez *et al.* (2012) illustrating that hydraulic deterioration of sewer systems, among other factors, arises from sediment accumulation and an indicator of this process is the presence of sediment-related blockages in sewer pipe networks. (Hafskjold *et al.* 2002; Arthur *et al.* 2009; Hillas 2014), amongst others, drew conclusions that a significant number of sewer pipes in operation prior to the establishment of self-cleaning velocity requirements in standards are observed to be experiencing more blockages compared to sewer pipes designed in accordance with minimum self-cleaning velocity requirements. Conclusions drawn by Chinyama (2013), investigating the poor performance of urban sewerage systems, also supported this and showed that 68% of blockages occurred in sewers having velocity below the self-cleaning velocity. This was attributed to the difference between conditions of the flow regime design assumptions of population per household and water consumption estimated to determine the design peak discharge and the actual conditions in operation. Other studies which illustrate the link between blockages and exertions on the sewer pipe network include Blanksby *et al.* (2002), who reported that pipe defects are some of the biggest perceived causes of blockages by sewerage operators. Water UK (2017) attributed most blockages to the disposal of non-flushable wipes occurring at locations with backdrop pipes, bends, interceptor trap and low/intermittent flow. Cherqui *et al.* (2015) attributed 45% of blockages in sewer pipes to accumulation of fat, oil and grease (FOG) and 35% to be due to human behavioural patterns. Despite the importance of performance indicators for sewer pipe network and the link between blockages and other problems within the sewer pipe network. A survey by Mattsson *et al.* (2014) of six Swedish water utilities showed no monitoring of sewer blockage on the basis of performance indicators or functional criteria.

The efficiency of the operation and maintenance efforts of municipalities on sewer networks may also be assessed based on the management of blockage related failures. Existing approaches to the management of blockages apply a combination of proactive and reactive measures which have been described by authors such as Thomson (2008), DeSilva *et al.* (2011) and Fontecha *et al.* (2016). However effective blockage management should be an optimized balance between proactive and reactive maintenance to maximize service outcomes at the lowest cost within operational budgeting constraints (DeSilva *et al.* 2011). Conventionally, reactive approaches are applied to assets with a perceived low consequence of failure, usually operated till failure occurs and associated with low recurrence blockages while proactive approaches are applied when the perceived consequence and cost implications of failure are considered to be high specifically high recurrence blockages. According to Ugarelli *et al.* (2009) the expenditure on blockages are regular costs to municipalities.

Blockage management should not only be viewed as temporary relief to obstructions which require reactive actions but precursors to more in-depth problems within the sewer pipe network prompting

H2Open Journal Vol 3 No 1
doi: 10.2166/h2oj.2020.027

more detailed investigations (Arthur *et al.* 2008) towards proactive management. Furthermore, the number of blockages occurring, and frequency of return should be considered as indicators which provide insight into the magnitude of problems within the sewer pipe network (Cardoso & Matos 2005). The ability to predict the number of blockages and estimate the frequency of return and estimate consequences is necessary for effective management of blockages (Arthur *et al.* 2009). Furthermore, increased proactive corrective actions are required to reduce the occurrence of low consequence failures, and prevent high consequence failures (Anbari *et al.* 2017). These actions need to consider blockages with high return frequency and the associated problems to efficiently mitigate cumulative and frequent costs and other associated consequences.

The primary objective of this paper was to use blockages and associated performance indicators at a strategic level to assess the performance of sewer pipe networks and benchmark municipalities sewer networks based on size as an initial precursory step to more detailed investigations. Furthermore, the objective was to develop a hypothesis of factors which necessitate occurrence of blockages in the sewer networks at the strategic level which require more in-depth investigations.

Below, in the Methods section, the descriptions of the municipality classifications, performance indicators and associated factors, including a description of the methods used for assessments are detailed. The Results and discussion section illustrate results of performance indicators comparisons between municipality clusters and trends from influential factors for blockages. At the end of the paper, the conclusions are drawn, and recommendations provided.

METHODS

Performance indicators

The use of standardized PI systems are recommended compared to ad-hoc systems developed for specific objectives. The use and choice of performance indicators is also highly affected by data availability, quality and accuracy (Rohrhofer *et al.* 2008). Therefore the selection of performance indicators often requires a trade-off between standardized and ad-hoc performance indicators in order to provide useful insights in performance evaluation.

Performance indicators used for assessment of blockages in this study provide a rational basis for decision making at the strategic level for sewer pipe networks. They are based on standardised IWA recommended indicators (Cardoso & Matos 2003). Their main strengths include the following. (1) Characterization of sewer pipe network and susceptibility assessment of sectors or clusters where proactive maintenance can be implemented. (2) Indicators also allow for assessment of the impact of maintenance actions periodically, as well as assessment of maintenance impact with target or reference values. Performance indicators also do not account for the effects of location and cost of consequence of blockage failures due to the lack of data. Other data needed for analyses, such as population statistics, population density, land use and discharge, could be normalized by total pipe length of sewer network in the municipality for more symmetrical comparisons.

To facilitate the assessment of blockages, municipalities were grouped into four clusters based on population sizes, in accordance with the Swedish Association of Local Authorities and Regions (2017) (Table 1). A description of the selected performance indicators for this study is presented in Table 2.

Input data for assessment of blockages using the performance indicators listed in Table 2 were based on yearly recorded information from municipalities documented in a statistics database managed by the Swedish Water and Wastewater Association (VASS). Data from 290 municipalities are documented in VASS. In this study, seven municipalities were excluded from the analyses since relevant data were not available. Other information associated with performance indicators were collected from Statistics Sweden. Data available in VASS for the sewer pipe networks were most complete for performance

H_2Open Journal Vol 3 No 1
doi: 10.2166/h2oj.2020.027

Table 1 | Classification of municipalities for assessment

Classification	Range
Large	Greater than 200,000 people
Medium	50,000–200,000 people
Small	15,000–50,000 people
Less than small	Less than 15,000 people

Table 2 | Evaluated performance indicators adopted by Cardoso & Matos (2005)

Performance Indicator	Definition
Sewer blockage (in combined and separate sewers)	Number of blockages in sewers that occurred during the assessment period *365/(assessment period in days)/total sewer length at the reference date (*No.* km^{-1}.$Year^{-1}$)
Connection ratio (No. of inhabitants connect to the sewer network)	How much of the municipality's population is connected to the general sewer pipeline network at the date of reference (*No. inhabitants* km^{-1}*100)
Sewer renewal rate	Length of defective sewers renovated during the assessment period/total sewer length at the reference date
Operation and maintenance cost of wastewater pipeline	Running costs related to maintenance, cleaning and repair of sewer system during the assessment period/total sewer length at the reference date (*kr/km*)
Percentage pipeline network maintained (flushed/cleaned)	Length of sewers cleaned/flushed during the assessment period/total sewer length at the reference date *100 (%.)
Blockage rate	Average number of stops/average pipe length (*No. Blockages/km*)
No. of incidents of basement flooding	Number of incidents of basement flooding in sewers that occurred during the assessment period × 365/assessment period in days)/total sewer length at the reference date (*No.* km^{-1}.$Year^{-1}$)
Flow discharge	Average discharge over the assessment period/total sewer length at the date of reference (m^3.km^{-1})
Degree (ratio) of spread of sewer network	Population density (*No. people.* Km^{-2})

indicators considered in this study between the period 2007–2018 (prediction and assessment dataset (2007–2017) and validation dataset (2018)). The statistical values reported to the VASS database are sourced from municipalities across Sweden via surveys with specific questions regarding their operations on a yearly basis. The reported data are verified by VASS administrators in conjunction with local municipality administrators before being published on the website http://www.vass-statistik.se/. Most likely there are sources of uncertainties related to reporting errors from personnel at municipalities.

Statistical analysis of trends and relationships between performance indicators

A statistical analysis was carried out using Microsoft Excel to evaluate the blockage occurrence trend over the assessment period by regression lines. A positive slope indicating an upward trend implies an increase in blockages and a negative slope indicating a downward trend implies a decrease in blockages.

A partial least square discriminant analysis (PLS-DA) was performed to assess influence of performance indicators on the occurrence of blockages in sewer pipe network clusters. The PLS-DA approach discriminates variables (performance indicators) based on information that influences the dependent variable (No. blockages/km/year) to separate observations (large, medium, small and less than small). A detailed description of the PLS-DA modelling and analysis technique can found in Lee *et al.* (2018).

H2Open Journal Vol 3 No 1
doi: 10.2166/h2oj.2020.027

Furthermore the influence of the performance indicators on the number of blockage events occurring per km per year was investigated by fitting the data to an overdispersion Poisson regression model described by Cupal *et al.* (2015), using R statistical software. Furthermore, the model was used to predict specific aspects of generalized system behaviour defined by the data over the assessment period, specifically number of blockages, which is characterized by a continuous stochastic process in which events occur independently of each other at a constant rate described by Xie *et al.* (2017), known as a Poisson process. This process justifies the assumption of random behaviour of blockages underpinning the failure behaviour of blockage to not be entirely predictable and likely to deviate at different times between years (Jin & Mukherjee 2010). This process has also yielded some of the most suitable abilities to model blockage likelihood (Santos *et al.* 2017). To validate predictive aspects of generalized system behaviour, a comparison between predicted values (based on data from the assessment period) and observed values (validation dataset (2018)) was performed using a two-sample Kolmogorov-Smirnov (KS) test to evaluate if there were any statistically significant differences between the datasets. The KS test reports the maximum difference between the two cumulative distributions (D), and calculates a *p*-value from that and the sample sizes. The null hypothesis states that both groups are of identical distributions and the null hypothesis is not rejected if the *p*-value is greater than 0.05 level of significance.

RESULTS AND DISCUSSION

Performance indicators

Over the assessment period 2007–2017, a total of 56,500 blockages in the sewer pipe networks were registered and 2,800 blockages in the stormwater pipe networks across municipalities, while figures for combined sewer systems were not available. Figure 1 shows a comparison of distributions between No. blockages/km/year in the sewer and stormwater pipe networks.

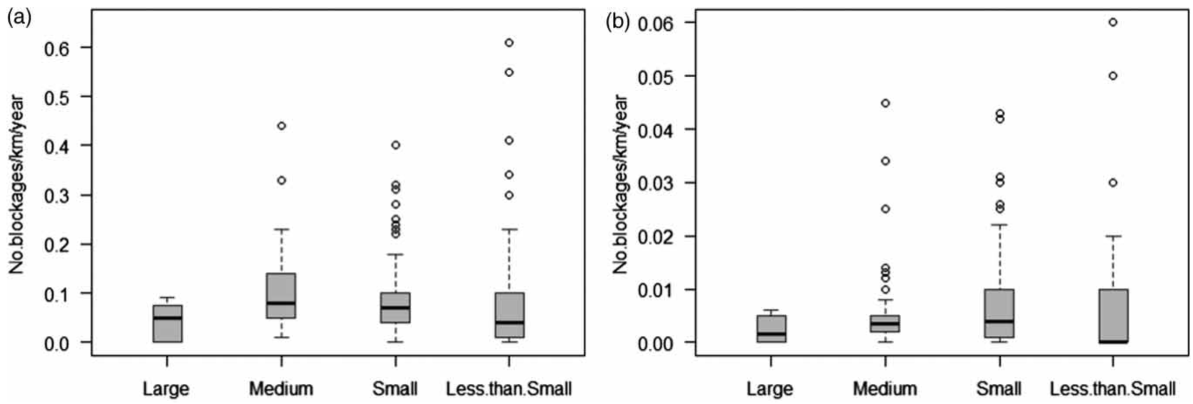

Figure 1 | Distributions and median number of blockages/km/year in relation to municipal size for (a) sewer pipe and (b) stormwater pipe networks.

The observed ratio of blockages in the stormwater pipe compared to sewer pipe networks was 1:20 over the assessment period. This was corroborated by Ugarelli *et al.* (2010), who made similar observations for blockages in the networks of Oslo, Norway. Sewer pipe networks between the 25th–50th and above percentile of medium- to small-sized municipalities were also observed to have higher blockages per km per year compared to the median value observed.

Ugarelli *et al.* (2010) reported sewer blockage rates in Oslo of 0.176 blockages/km/year and Hafskjold *et al.* (2002) of 0.096 blockages/km/year in Trondheim, both in Norway. In Wales and

H₂Open Journal Vol 3 No 1
doi: 10.2166/h2oj.2020.027

parts of western England blockage rates have been reported by Bailey *et al.* (2015) in the interval of 0.002–0.9 blockages/km/year. However, much higher blockage rates have been reported in the UK. Arthur *et al.* (2008) reported rates between 0.1 and 2.0 blockages/km/year and Hillas (2014) rates between 0.3 and 1.4 blockages/km/year. In Bogota, Colombia, a blockage rate of 1.5 has been published (Rodríguez *et al.* 2012), and corresponding values reported from four utilities in Australia were between 0.2 and 1.2 (DeSilva *et al.* 2011). It can be observed that even within countries that blockage rates reported vary by various degrees. Blockage rates obtained from Swedish municipalities range between 0.02 and 0.61, see Figures 1(a) and 2. However blockage rates have been reported to not be an appropriate metric for comparison between sewer pipe networks in utilities, cities or countries (Marlow *et al.* 2011). This is largely due to complex relationships between blockage rates and triggering mechanisms which vary between locations (Rodríguez *et al.* 2012).

Furthermore comparisons to a reference value establishes a benchmark state which can be used for assessment between sewer pipe networks (Alegre & Coelho 2012). Malm *et al.* (2012), recommended a guideline cut-off value for number of blockages per km per year in sewer pipe networks in Sweden of greater than 0.25 per km per year to be classified as having less than good endurance, and blockage rates greater than 0.5 per km per year to be considered as bad. The 75th percentile of medium-less than small municipalities can be classified as having less than good endurance or bad.

Figure 2 presents the average blockage rates geographically and Figure 3 presents distributions and average values of connection ratio (%) and population density between the municipalities.

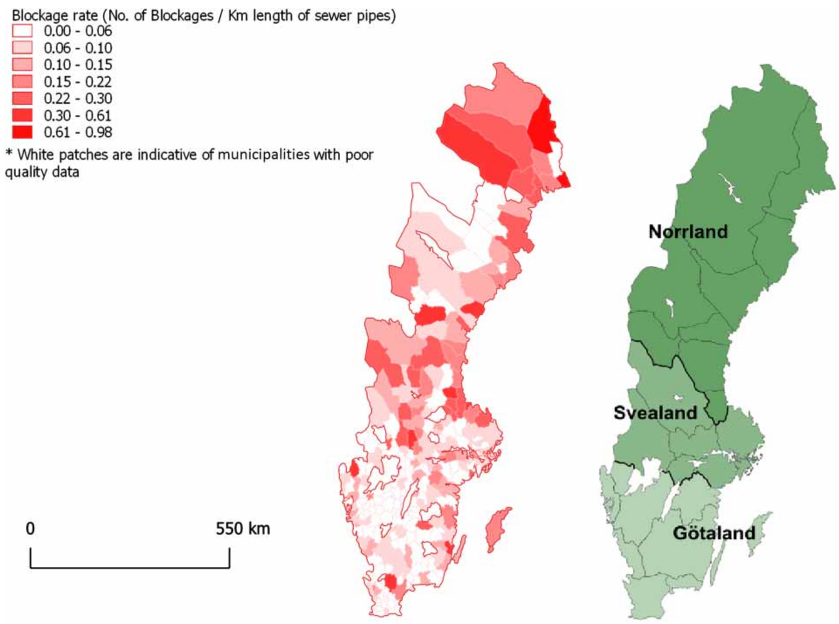

Figure 2 | Map of Swedish municipalities showing the blockage rate geographically with a corresponding geographically division of Swedish main regions (Wikimedia Commons 2009).

Observation from Figures 2, 3(a) and 3(b) show that municipalities with the higher blockage rates, above 0.25 per km per year, were observed to have less than 200 inhabitants/km connected to the sewer network as well as a connection ratio of less than 85% and population density of less than 500 km^2. Based on the above, inferences are that in sewer pipe networks, a reduction in the number of inhabitants connected per km of pipe length increases the proneness to blockage occurrence. Hedström *et al.* (2016) reported the Norrland region be experiencing two times higher average benchmark values for sewer blockages compared to the average in Sweden. Hedström *et al.* (2016) further attempted to explain these differences with depopulation trends, using a regression model but found no such statistical correlation. To further explore the relationship between

H2Open Journal Vol 3 No 1
doi: 10.2166/h2oj.2020.027

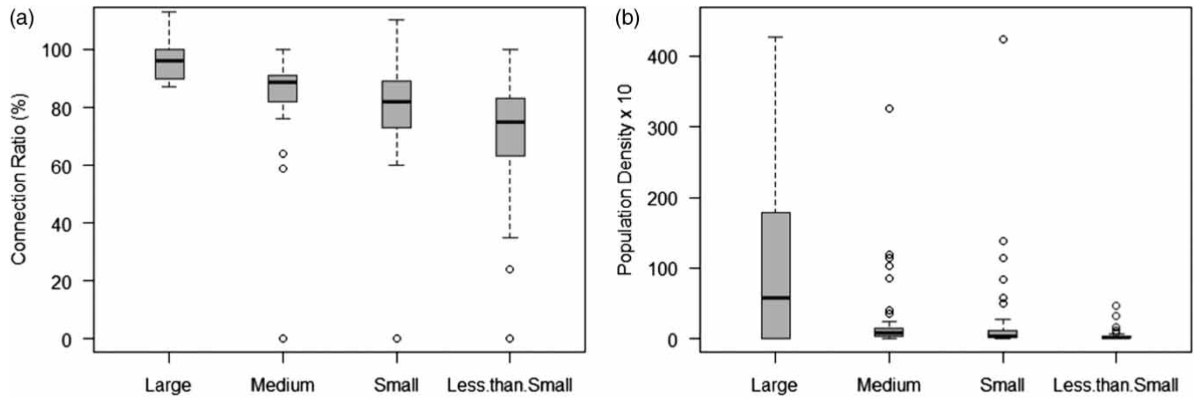

Figure 3 | (a) Connection ratio: share of municipality's population connected to the general sewer pipeline network and (b) population density.

depopulation and increased blockage likelihoods this study uses a partial least squares regression (PLS) model to explore the relationship between population decrease and increased blockages in municipal sewer networks across Sweden. A PLS regression response surface between number of inhabitants connected to the sewer network per km, population density and dependent variable No. blockages/km/year was plotted. Increased number of blockages appear to be occurring in the region of lower population density and inhabitants connected to the sewer networks, see Figure 4.

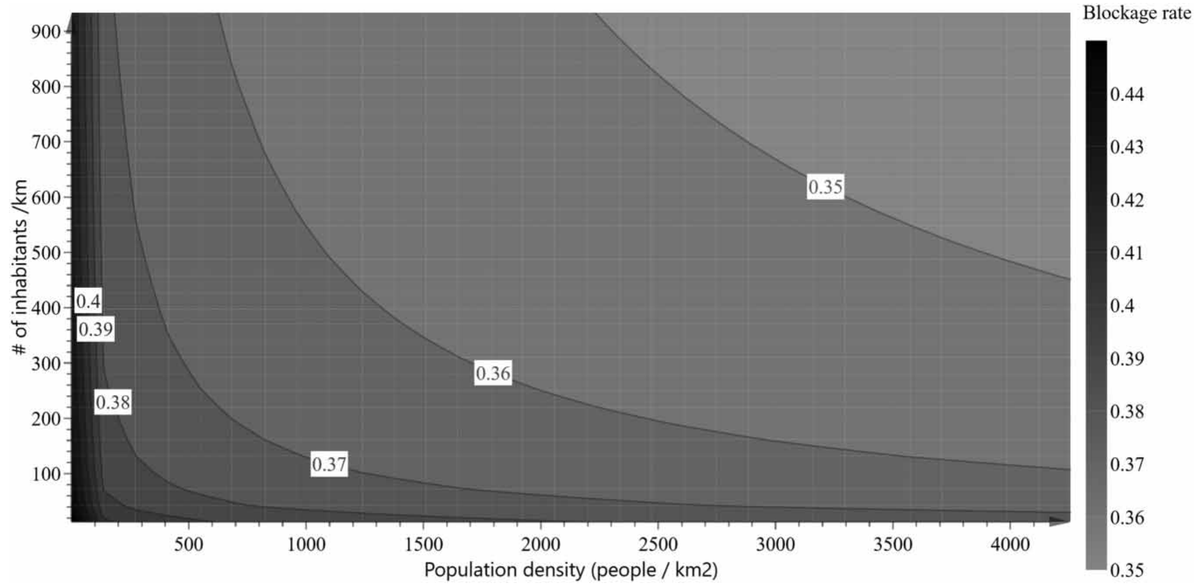

Figure 4 | Second order PLS regression response surface showing the interaction between the independent variables (numbers of inhabitants connected to the sewer pipe network and population density) and the dependent variable (No. blockages/km/year) for sewer networks in Sweden.

A working hypothesis is that networks experiencing higher rate of blockages are suspected to have flow conditions (reduced flow volumes, and sewers not achieving self-cleaning velocity) which increases the possibility for sediment deposition and solid accumulation in sewers leading to blockages. Banasiak (2008) investigated the in-sewer sediment deposit behaviour and its influence on the hydraulic performance of sewer pipes and stated that an efficient self-cleansing sewer is one having a sediment-transporting capacity that is sufficient to maintain a balance between the quantity of deposition and erosion.

Figure 5 presents the distribution and average values of percentage of sewer network maintained and sewer renewal rate.

H_2Open Journal Vol 3 No 1
doi: 10.2166/h2oj.2020.027

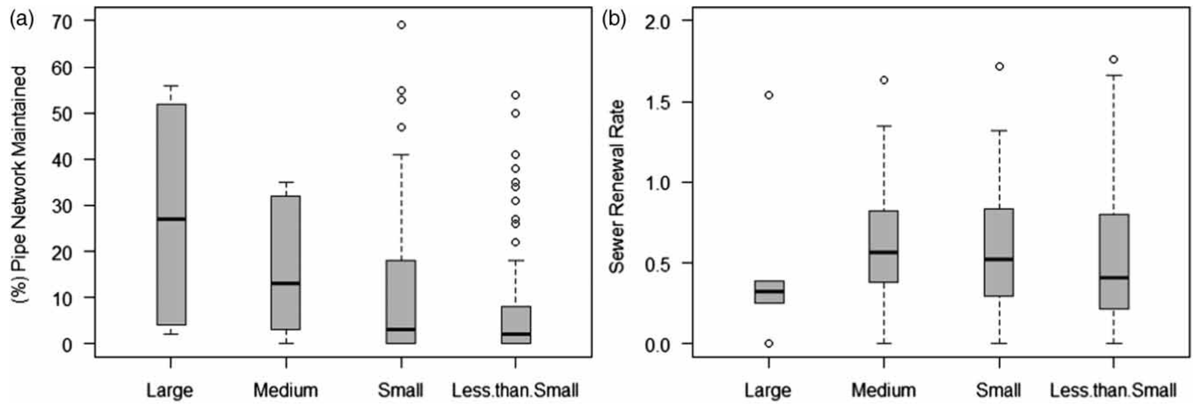

Figure 5 | Percentage of (a) pipe network maintained (% Length of pipes flushed vs total length of pipe network) and (b) sewer renewal rate distributions.

Observations from percentage of pipe network maintained indicate that large-sized municipalities maintain their sewer networks 20% more, compared to medium-sized municipalities while medium-sized municipalities 15% more compared to small and less than small municipalities. Figure 5(a) may also be considered to be a prognosis of maintenance needs. The median sewer renewal rate shows no significant difference between municipalities. Medium- to less than small-sized municipalities have lower percentages of their networks maintained and consequently experience at least 30% more blockages per km per year. This is illustrated further with the PLS response surface in Figure 6(a) and 6(c) showing the relationship between Total cost of maintenance per km, the percentage of the network maintained and No. blockages/km/year in large and small municipalities. It can be observed

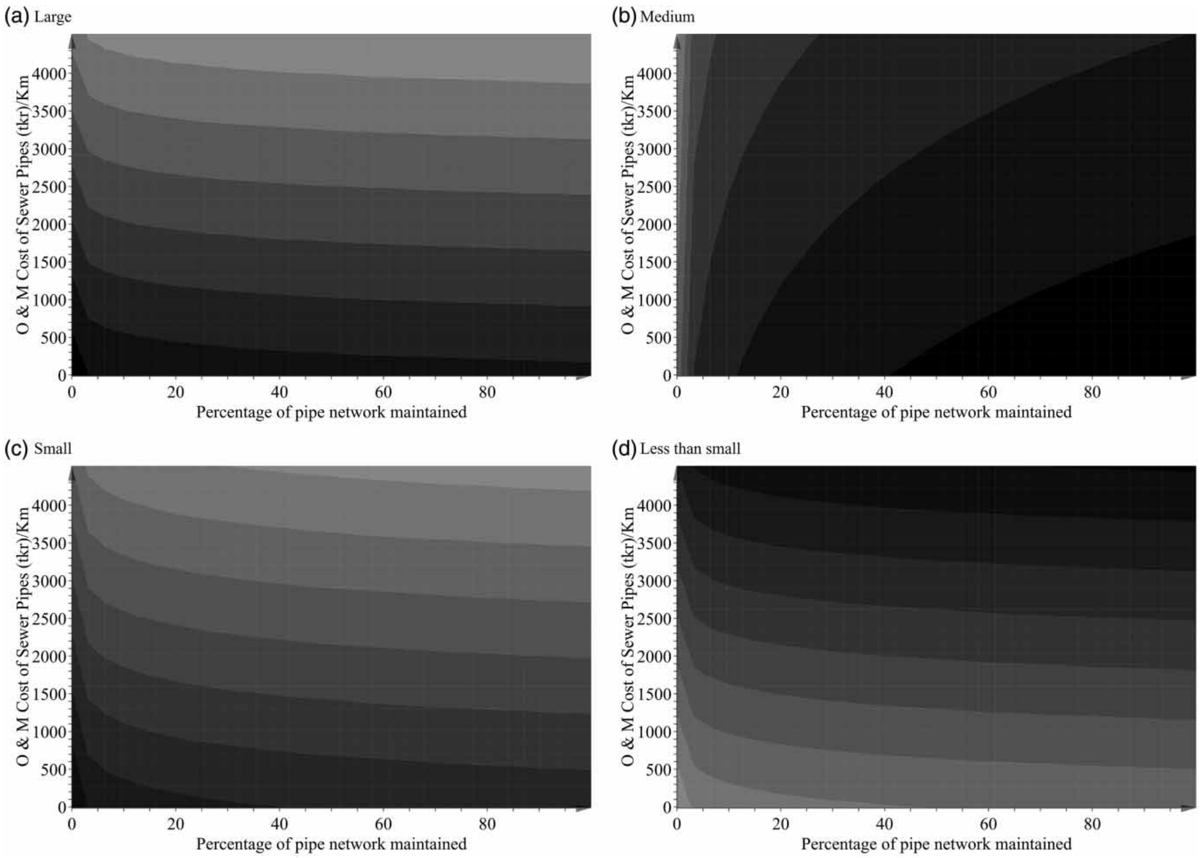

Figure 6 | PLS-regression response surface indicating the holistic relationships between blockage rates, cost of sewer pipe maintenance per km and percentage of the pipe network maintained. Darker shades indicate maximum blockage rates.

H2Open Journal Vol 3 No 1
doi: 10.2166/h2oj.2020.027

that as the spending increases with a corresponding increase in the network maintenance the No. blockages/km/year decreases. However, Figure 6(b) shows in medium-sized sewer networks, low O&M costs and higher blockage rates occur in the region where the highest percentage of the network is maintained. Figure 6(d) shows high blockage rates in regions of highest O&M cost irrespective of maintenance percentage in less than small-sized networks. This prompts the assumption that improving that balance between proactive and reactive management of blockages, to favour more proactive measures may be useful to improve blockage management in medium- and less than small-sized sewer pipe networks.

Table 3 presents operation and maintenance cost per km of the pipe network figures which provide an indication of the availability of resources in municipalities.

Table 3 | Operation and maintenance cost performance indicator assessed for different municipality classifications.

Municipality classification	Large	Medium	Small	Less than small
Performance indicator	O&M cost (tkr/km)	O&M cost (tkr/km)	O&M cost (tkr/km)	O&M cost (tkr/km)
Operation and maintenance cost	200	140	120	80
Ratio of large	1	0.7	0.6	0.4

Kr is indicative of the Swedish Krona, the official currency of Sweden; tkr – Thousand Krona.

The number of occasions of basement flooding provide an indication of the impact/consequence of blockages. An almost linear relationship was observed between the increased occurrence of basement flooding and blockages in the sewer pipe networks when the blockage rate is above 0.5. This is in line with previous findings that indicated the pipes which experienced more blockages had an increase likelihood of basement flooding (Ugarelli *et al.* 2010). Increased basement flooding likelihoods also provides an indication of sewer networks with higher consequence of failures where performance can be improved by implementation of risk-based operation and maintenance programs such as fuzzy inference systems (FIS) (Anbari *et al.* 2017).

Statistical analysis of relationships between performance indicators

Large municipalities showed a negative slope in blockage occurrence indicating a decrease in rate of blockage occurrence while all other municipality clusters showed neutral slopes implying a constant rate of blockage occurrence over the assessment period. Results from the overdispersion Poisson regression model showed that and connection ratio, and blockage rate had the most statistically significant influence on the number of blockages (No. blockages/km/year) for predictions. Refer to Table 4 for Poisson regression model output.

Table 4 | Overdispersion Poisson regression model output for total number of blockages in Swedish sewer pipe networks

Coefficients	Estimate	Std error	*P*-value
Intercept	9e-01	2e-01	2e-04
Blockage rate	4e+00	2e-01	2e-16
Percentage of pipe networks maintained	2e-03	1e-03	3e-01
Connection ratio	3e-02	3e-03	5e-16
Sewer renewal rate	3e-02	2e-02	3e-02
Operation and maintenance cost	−3e-04	1e-04	4e-03
Land use percentage	−2e-02	7e-03	2e-02
Population density	−5e-05	1e-04	7e-01
Flow discharge	2e+01	7e + 00	3e-02

Significance level (α) = 1e-02 (0.01).

H₂Open Journal Vol 3 No 1
doi: 10.2166/h2oj.2020.027

A predictive relationship was developed based on blockage rate (number of blockages/network length (km)) and the number of blockages based on coefficients listed in Table 4. This may support budgeting and the planning process in municipalities, predicting the expected numbers of blockages that can be expected to occur per year. This is illustrated in Equation (1).

$$NB = (\exp.(2.97 + 3.20(\text{blockage rate}))*L)/365 \quad (1)$$

NB is total number of blockages anticipated per year and L is the total length of sewer pipe network (km). Figure 7 presents empirical cumulative density function (ECDF) curves for predicted and observed blockages across all municipalities considered.

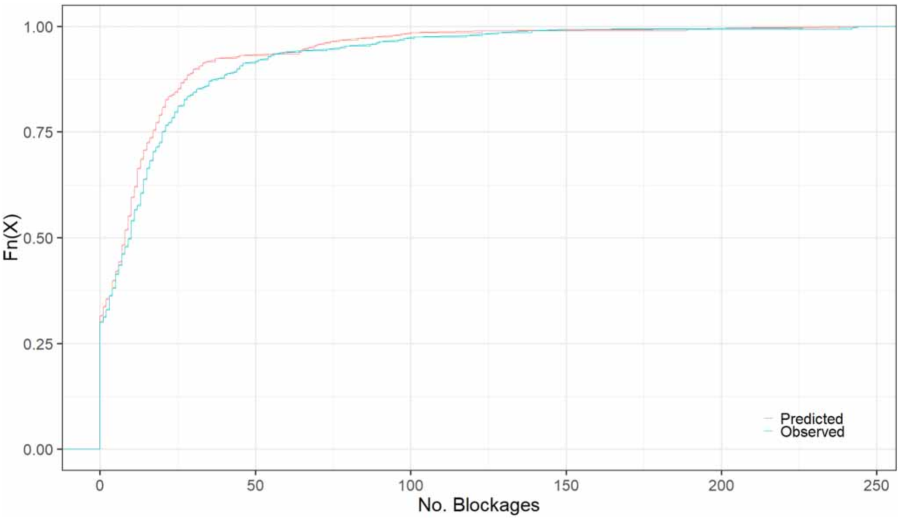

Figure 7 | K.S-test comparison between predicted and observed blockages in municipalities for the year 2018. Fn(x) defines the cumulative probability distribution quantiles for number of blockages. Maximum distance between the ECDF curves of the two samples (D) = 0.1087 and *p*-value = 0.07.

The null hypothesis could not be rejected for comparison between the two sample datasets at a 95% confidence level, which means that no significant difference is observed between predicted and observed distributions. The values for the test parameters, D and *p*-value, have been reported in Figure 7. The derived equation may be helpful for planning but may show some disparity between predicted and eventual observed blockages as blockage occurrence is mostly still characterized as random. More data are required to validate this model.

CONCLUSION

This study illustrated how performance indicators can be used for strategic performance assessment of sewer pipe networks. The main conclusion from this study was that sewer pipes are experiencing more blockages compared to stormwater pipes, indicating sewer pipes are experiencing more problems arising from performance inefficiencies such as reduced flow volumes, non-disposables being disposed in sewer pipes, increased deposition of FOG, etc., catalysed by deterioration and aging pipe infrastructure. Blockages in medium- to small-sized municipalities over the assessment period did not show an increase or decrease in occurrence.

In sewer networks where suspected reduced flow volumes in comparison to design flows result in flow velocities below self-cleaning. Recommendations after more investigation and confirmatory tests,

H$_2$Open Journal Vol 3 No 1
doi: 10.2166/h2oj.2020.027

include a temporary reduction in cross-sectional area of critical pipes to improve flow conditions and reduce blockages, the use of trenchless technologies and techniques such as re-lining and slip lining which are reversible are recommended.

Lower operation and maintenance costs per km highlights limited monetary and/or personnel resources in medium- to small-sized municipalities. Furthermore in response assumptions are that a disparity may exist between reactive vs proactive approaches to management of blockages mostly in medium and less than small-sized municipalities, more proactive initiatives may be required to improve blockage management. Redesigning certain pipes may be a sustainable method to reduce interruptions from blockages proactively at a one-time cost compared to recurring operation and maintenance costs. However this needs to be considered in terms of consequence to the whole sewer network.

Data regarding repeated blockage locations, physical properties of the pipe networks (such as age, material, diameter) at the holistic level may provide more critical insights to blockage proneness. Furthermore, the proposed equation for estimating the anticipated number of blockages may be improved by taking into account other critical factors at the tactical level (such as pipe dimeter, self-cleaning velocity, pipe sagging and spatial-temporal patterns) which may differ between municipalities.

ACKNOWLEDGEMENT

The projects Stormwater & Sewers and FORMAS 2018-01178 are acknowledged for their financial support. Gilbert Svensson and Swedish Water and Wastewater Association are also acknowledged for their support.

REFERENCES

Alegre, H. & Coelho, S. 2012 Infrastructure Asset Management of Urban Water Systems, Water Supply System Analysis. Selected Topics, Avi Ostfeld, IntechOpen, DOI:10.5772/52377. Available from: https://www.intechopen.com/books/water-supply-system-analysis-selected-topics/infrastructure-asset-management-of-urban-water-systems.

Anbari, M. J., Tabesh, M. & Roozbahani, A. 2017 Risk assessment model to prioritize sewer pipes inspection in wastewater collection networks. *Journal of Environmental Management* **190**, 91–101.

Arthur, S., Crow, H. & Pedezert, L. 2008 Understanding blockage formation in combined sewer networks. *Proceedings of the Institution of Civil Engineers: Water Management* **161** (4), 215–221.

Arthur, S., Crow, H., Pedezert, L. & Karikas, N. 2009 The holistic prioritisation of proactive sewer maintenance. *Water Science and Technology* **59** (7), 1385–1396.

Bailey, J., Keedwell, E., Djordjevic, S., Kapelan, Z., Burton, C. & Harris, E. 2015 Predictive risk modelling of real-world wastewater network incidents. *Procedia Engineering* **119** (1), 1288–1298.

Banasiak, R. 2008 Hydraulic performance of sewer pipes with deposited sediments. *Water Science and Technology* **57** (11), 1743–1748.

Blanksby, J., Khan, A. & Jack, A. 2002 Assessment of cause of blockage of small diameter sewers. In: *Proceedings of International Conference on Sewer Operation and Maintenance.* Bradford.

Cardoso, M. A. & Matos, R. 2003 *WP1, Deliverable D1 Construction of A Control Panel for Rehabilitation: Selection of A Listing of Rehab PIs*. IWA Publishing, London, UK.

Cardoso, M. A. & Matos, R. 2005 *Performance Indicators for Rehabilitation*. IWA Publishing, London, UK

Cardoso, M. A., Matos, R. S. & Alegre, H. 2004 *Performance Assessment of Water Supply and Wastewater Systems*. Taylor & Francis, London, UK.

Cherqui, F., Belmeziti, A., Granger, D., Sourdril, A. & Le Gauffre, P. 2015 Assessing urban potential flooding risk and identifying effective risk-reduction measures. *Science of the Total Environment* **514**, 418–425.

Chinyama, A. 2013 Understanding the poor performance of urban sewerage systems: a case of coldstream high density Suburbs, Chinhoyi, Zimbabwe. *Urban Planning and Design Research (UPDR)* **1** (3), 43–49.

Cupal, M., Deev, O. & Linnertova, D. 2015 The Poisson regression analysis for occurrence of floods. *Procedia Economics and Finance* **23**, 1499–1502.

DeSilva, D., Marlow, D., Beale, D. & Marney, D. 2011 Sewer blockage management: Australian perspective. *Journal of Pipeline Systems Engineering and Practice* **2** (4), 139–145.

doi: 10.2166/h2oj.2020.027

Fontecha, J. E., Akhavan-Tabatabaei, R., Duque, D., Medaglia, A. L., Torres, M. N. & Rodríguez, J. P. 2016 On the preventive management of sediment-related sewer blockages: a combined maintenance and routing optimization approach. *Water Science and Technology* **74** (2), 302–308.

Grigg, N. S. 2003 *Water, Wastewater and Stormwater Infrastructure Management*. CRC Press, Lewis Publishers, Boca Raton, FL.

Hafskjold, L. S., Kønig, A., Sægrov, S. & Schilling, W. 2002 Improved assessment of sewer pipe condition. *CityNet 19th European Junior Scientist Workshop on Process Data and Integrated Urban Water Modelling* (7465), pp. 1–8.

Hedström, A., Svensson, G. & Viklander, M. 2016 Challenges in water and wastewater transport systems in cold regions. *Advances in Particle Science and Separation: Meeting Tomorrow's Challenges*, Oslo, Norway (Ratnaweera, H., ed.). IWA, London, pp. 1–8.

Hillas, T. T. 2014 *Reducing the Occurrence of Flooding Through the Effective Management of Sewer Blockages*. University of Exeter, UK.

Jin, Y. & Mukherjee, A. 2010 Modeling blockage failures in sewer systems to support maintenance decision making. *Journal of Performance of Constructed Facilities* **24** (6), 622–633.

Lee, L. C., Liong, C. Y. & Jemain, A. A. 2018 Partial least squares-discriminant analysis (PLS-DA) for classification of high-dimensional (HD) data: a review of contemporary practice strategies and knowledge gaps. *Analyst* **143** (15), 3526–3539.

Malm, A., Horstmark, A., Jansson, E., Larsson, G., Meyer, A. & Uusijärvi, J. 2012 *Guideline for Renewal Planning of Water and Wastewater Networks* (Report No. 2011-12).

Marlow, D. R., Boulaire, F., Beale, D. J., Grundy, C. & Moglia, M. 2011 Sewer performance reporting: factors that influence blockages. *Journal of Infrastructure Systems* **17** (1), 42–51.

Mattsson, J., Hedström, A. & Viklander, M. 2014 Indicators for blockages caused by changing wastewater – how well does a municipality need to know its sewer? In: *13th International Conference on Urban Drainage*, 7–12 September 2014, Sarawak, Malaysia, pp. 1–8.

Mazumder, R. K., Salman, A. M., Li, Y. & Yu, X. 2018 Performance evaluation of water distribution systems and asset management. *Journal of Infrastructure Systems* **24** (3), 1–55.

Miszta-Kruk, K. 2016 Reliability and failure rate analysis of pressure, vacuum and gravity sewer systems based on operating data. *Engineering Failure Analysis* **61**, 37–45.

Pinto, F. S., Simões, P. & Marques, R. C. 2017 Raising the bar: the role of governance in performance assessments. *Utilities Policy* **49** (December), 38–47.

Rodríguez, J. P., McIntyre, N., Díaz-Granados, M. & Maksimović, Č. 2012 A database and model to support proactive management of sediment-related sewer blockages. *Water Research* **46** (15), 4571–4586.

Rohrhofer, K., Leroch, K. & Cate, F. M. 2008 Performance assessment of urban infrastructure services. *Performance Indicators (PIs) as a Control Mechanism for the Effective Use of Donor Funds*, Vol. 7 (E. A. Cabrera Jr & M. A. Pardo, eds). IWA Publishing, London.

Rokstad, M. M. 2012 *An Approach to Planning Data Collection for IAM in VMW*. Norwegian University of Science and Technology, Oslo, Norway.

Santos, P., Amado, C., Coelho, S. T. & Leitão, J. P. 2017 Stochastic data mining tools for pipe blockage failure prediction. *Urban Water Journal* **14** (4), 343–353.

Swedish Association of Local Authorities and Regions 2017 Classification of Swedish Municipalities 2017. Volume 1 (November 2016), 1 p.

Thomson, G. 2008 Investigation of sewer blockages due to tree roots. In: *71st Annual Water Industry Engineers and Operators' Conference*, Bendigo, pp. 71–78.

Tscheikner-Gratl, F., Caradot, N., Cherqui, F., Leitão, J. P., Ahmadi, M., Langeveld, J. G., Le Gat, Y., Scholten, L., Roghani, B., Rodríguez, J. P., Lepot, M., Stegeman, B., Heinrichsen, A., Kropp, I., Kerres, K., do Céu Almeida, M., Bach, P. M., Moy de Vitry, M., de Sá Marques, J. A. A., Simões, N. E., Rouault, P., Hernandez, N., Torres, A., Werey, C., Rulleau, B. & Clemens, F. 2020 Sewer asset management – state of the art and research needs. *Urban Water Journal* **16** (9), 663–675.

Ugarelli, R., Kristensen, S. M., Røstum, J., Sægrov, S. & Di Federico, V. 2009 Statistical analysis and definition of blockages – prediction formulae for the wastewater network of Oslo by evolutionary computing. *Water Science and Technology* **59** (8), 1457–1470.

Ugarelli, R., Venkatesh, G., Brattebø, H., Di Federico, V. & Sægrov, S. 2010 Historical analysis of blockages in wastewater pipelines in Oslo and diagnosis of causative pipeline characteristics. *Urban Water Journal* **7** (6), 335–343.

Van den Berg, C. & Danilenko, A. 2010 *The IBNET Water Supply and Sanitation Performance Blue Book*. International Bank for Reconstruction and Development/The World Bank, Washington, DC. DOI:10.1596/978-0-8213-8582-1.

Venkatesh, G. 2011 *Systems Performance Analysis of Oslo's Water and Wastewater System.* Norwegian University of Science and Technology, Trondheim, Norway.

Water UK 2017 *Wipes in Sewer Blockage Study*. WaterUK, London.

Wikimedia Commons 2009 Sverigekarta-Landsdelar,_namn_och_landskap.

Xie, Q., Bharat, C., Nazim Khan, R., Best, A. & Hodkiewicz, M. 2017 Cox proportional hazards modelling of blockage risk in vitrified clay wastewater pipes. *Urban Water Journal* **14** (7), 669–675.

First received 17 December 2019; accepted in revised form 3 February 2020. Available online 9 March 2020