Laakso, Tuija; Ahopelto, Suvi; Lampola, Tiia; Kokkonen, Teemu; Vahala, Riku

Estimating water and wastewater pipe failure consequences and the most detrimental failure modes

Published in:
Water Science and Technology: Water Supply

DOI:
10.2166/ws.2017.164

Published: 01/06/2018

Document Version
Peer reviewed version

Please cite the original version:
Laakso, T., Ahopelto, S., Lampola, T., Kokkonen, T., & Vahala, R. (2018). Estimating water and wastewater pipe failure consequences and the most detrimental failure modes. *Water Science and Technology: Water Supply*, *18*(3), 901-909. https://doi.org/10.2166/ws.2017.164

Estimating water and wastewater pipe failure consequences and the most detrimental failure modes

Short title: Water and wastewater pipe failure consequences and detrimental failure modes

Tuija Laakso (corresponding author) *, Suvi Ahopelto*, Tiia Lampola**, Teemu Kokkonen*, Riku Vahala*
* Department of Built Environment, Aalto University, P.O. Box 15200, 00076 Aalto, Finland. (E-mail of the corresponding author: tuija.laakso@aalto.fi)
** Helsinki Region Environmental Services Authority (HSY), Water Services, P.O. Box 300, 00066 HSY, Finland.

Abstract
Failures of water and wastewater networks can lead to severe consequences for human, natural and built environment. This paper presents how data on networks and their immediate environment together with graph analysis can be used to estimate the severity of pipe failure consequences. A case study concerning a large water and wastewater utility revealed that ca. 14% of the water distribution pipes and ca. 25% of the sewers had potentially severe failure consequences with regard to at least one factor considered. The most detrimental failure modes connected to these pipes were identified. An assessment of the most important information needs revealed that a number of crucial source data sets were missing. The results can be used to support asset management decisions aiming at risk alleviation, e.g. when estimating the resources needed for network maintenance, condition inspections or renovations and when planning excavation works.

Keywords
failure consequences; failure modes; water and wastewater networks

INTRODUCTION

Water and wastewater networks form a part of modern society's critical infrastructure. However, these networks are also a cause of threats - if failed, they may cause serious consequences of different kinds. This was experienced in Helsinki, Finland, in 2009, when a 400mm diameter water pipe burst in the centre of the city, causing water to flood into the subway tunnel with direct costs of about 5 M€ and parts of the subway being out of use for more than three months. Surprisingly, due to network redundancy at the location, the disaster caused almost no disturbance to water distribution.

Managing the risks that relate to the networks is one of the main tasks of water and wastewater utilities. Within engineering, risk is often defined as a combination of two factors: failure likelihood and failure severity. In recent decades, significant results have been achieved related to the modelling of pipe failures and the lifespan of different pipe cohorts (e.g. Le Gat 2000; Baur & Herz 2002; Savić *et al.* 2006; Le Gat 2008). Besides addressing the failure likelihood, assessments of failure consequences have also been reported. However, earlier work on failure consequences has predominantly explored individual impacts such as the number of people left without water following a pipe break (e.g. Diao *et al.* 2014). Utility companies, however, need to consider jointly all known risks but it often remains unclear how such risk assessments are currently carried out and how the results affect daily operations and management practices. This study aims at providing material for filling this gap.

Consequence estimation is an integral part of risk management (ISO 31000:2009). In consequence estimation, failure consequences to both the network itself as well as to the near-by environment are assessed. In water distribution systems, failures can lead to insufficient water flow or pressure, deficient firefighting capability and damage to structures. Hydraulic modelling is a common way to assess failure effects such as insufficient flow or pressure in the network (e.g. Möderl & Rauch 2011, Berardi *et al.* 2014). For example, Möderl & Rauch (2011) estimated the vulnerable points of a water distribution system through hydraulic modelling. The vulnerability of each network element was measured as the shortage of water supplied compared to the water demand. Diao *et al.* (2014) used clustering to identify critical pipes in water distribution systems without hydraulic simulations. They applied graph theory to identify pipes that had topologically strongest external connections. They assessed failure consequences as the number of people left without water. Fares & Zayed (2010) utilized a fuzzy logic -based method for risk analysis of water mains. The consequences that they covered were cost of repair, damage to surroundings or business disruption, loss of production, traffic disruption and type of serviced area, but the exact procedures for evaluating consequences were not reported.

The Sewerage Rehabilitation Manual (WRc 2001) suggests classification of sewer pipes into critical and non-critical and recommends that proactive maintenance be focused on critical pipes. The manual gives instructions on identifying critical pipes, but otherwise most literature seems to deal with ranking or prioritizing pipes (e.g. Kleiner *et al.* 2006, Berardi *et al.* 2009, Piratla & Ariaratnam 2011, Ward & Savić 2012). Ward & Savić (2012) presented a method for sewer pipe prioritization where the consequence estimation complies with the principles presented in the Sewerage Rehabilitation Manual. They covered an extensive set of criteria and reported the network lengths in each class for the 37km long network subset. Berardi *et al.* (2009) optimized expenditures by comparing the total cost of an inspection programme with the estimated direct and indirect failure costs in the case of sewer blockages or collapses. Asset features, straight distance to buildings, watercourses and vegetation are given as examples on factors considered, but the criteria are not discussed in detail. Möderl *et al.* (2009) assessed the vulnerability of a wastewater network system. They analysed the effect of each pipe failing in a drainage system and compared the importance of each pipe in different combined sewer overflow (CSO) and flooding scenarios. Syachrani *et al.* (2013) estimated the severity of sewer failure consequences based on land use type and pipe size. Land use type consisted of features such as types of buildings, capacity, and types of activities the buildings serve. Salman & Salem (2011) determined sewer failure consequences using 16 factors and combined these as a weighted sum. While they report clearly the criteria and the Consequences of Failure (CoF) scores, pipe lengths per category cannot be identified because of the weighting applied. Baah *et al.* (2015) used 11 criteria to assess the CoF for sewers. They reported the criteria and how these were applied in the analysis as well as the resulting pipe volumes per category. Like in the case of Salman & Salem (2011), they applied scores and weights to determine CoF values.

In the literature, the focus has often not been on presenting the steps applied for estimating the consequences of failure, but rather on presenting new methods. However, as the network data quality improves and the availability of spatial data sets improves, there are better options to assess failure consequences. For example, the implementation of the INSPIRE Directive (2007/2/EC) has improved the availability of open geographic data in Europe.

The aim of this paper was to identify pipes with potentially severe failure consequences in both water and wastewater networks of the studied utility and to report the process that led to their selection. This is the first phase in estimating the resources required for risk management and has an essential role in asset management. (ISO 55000:2014) Failure consequences were assessed from the perspective of possible damage to either the built environment, the natural environment or the human environment. Pipes were categorized into three classes according to the estimated severity of failure consequences. Because the focus was on pipe identification instead of prioritization, no scores or weights were applied. In addition to the identification of these pipes, the significance of different pipe failure modes was evaluated, with the objective to assess how risks related to them could be alleviated or prevented. Finally, the most important information needs were mapped.

This article is organized as follows: The Methods section presents the case utility, the data used and the classification principles applied. The resulting network lengths per category and the identified detrimental failure types are given in the Results section, followed by the Discussion, where the limitations of the study are analysed and the possibilities of further developing and improving the classification are specified. The Conclusions presents the key findings of the study together with their implications.

METHODS

The studied utility, Helsinki Region Environmental Services Authority (HSY), has ca. 3,200 km water distribution pipes and ca. 2,800 km sewers, of which the majority is foul sewers. The starting point for the consequence estimation was to assess failure consequences from as many perspectives as what the information sources available allowed at the time of the study. The procedure consisted of three stages: 1) Inventory of data sets available at the time of the study, 2) Assessment of the importance of each data set and 3) Identification of further information needs.

Pipes were classified into three classes based on the estimated severity of failure consequences: class 1 (‘very severe’), class 2 (‘severe’) and class 3 (‘not severe’). An expert group consisting of utility personnel and researchers was established for the classification procedure. The expert group first discovered what kind of data was available for the analysis and judged which data sets were relevant for pipe failure consequence assessment in both networks. The group also evaluated how pipes should be prioritized with respect to different factors. For example, the buffers were set based on expert knowledge representing the best available understanding at the time of the analysis.

The importance of different factors (shown in Tables 1 and 2) was discussed until an agreement was reached within the expert group. The classification was carried out following the precautionary principle. This meant, for example, that a pipe was assigned to Class 1 when just a single criterion indicating "very severe" consequences was met. Failure costs were not estimated, since the focus was on identification of risk factors. However, failure costs are implicitly included through the assessment of consequence severity.

Three types of data were available for the classification:

- Pipe locations and the following pipe attributes: material, diameter, installation year, pipe type (gravitational/pressure sewer).
- Information on the annual water consumption of connected properties.
- Spatial data on built and natural environment, for example data on buildings, roads, nature conservation areas and water bodies.
- Reports on the effects of pipe closure to water supply. These existed for a limited number of pipes.

As listed in Tables 1 and 2, ten criteria were considered for water pipes and 17 for sewer pipes. The analyses needed for the classification were carried out using a geographic information system (ArcGIS). The analyses covered identification of pipes of certain type (for example, of certain diameter) within an area or within a given distance (a buffer) from an object such as a building. In addition to spatial analyses, a "cut edge" graph analysis was performed for the water distribution system to reveal the pipes that served as only connections for a high number of consumers. In the cut-edge analysis, each pipe (edge) is consecutively removed from the graph and the number and size of possible subgraphs is calculated.

The classification principles and the factors considered are presented in Table 1 for water supply pipes and in Table 2 for sewers. Threshold values (e.g. for pipe sizes or buffers) are given in brackets.

Table 1. Criteria used for defining the failure consequence class for water distribution pipes.

Class 1
Water mains of crucial functional importance to the whole network
Water pipes serving critical consumers (hospitals) with no alternative path
Pipes which, according to pipe closure reports, should not be closed at all or should only be closed for a very short time
Pipes under railways with no protective pipe around them
Pipes that provide the only connection serving an area with more than 0.3 Mm^3 of water consumption per year
Pipes close to a subway entrances, buffer 50m
Class 2
All water mains not included in Category 1
Pipes under or close to buildings (pipe diameter ≥ 300mm, buffer 2m)
Pipes under main roads (pipe diameter ≥ 300mm, regional main roads, i.e. road classes I and II)
Pipes close to main gas transport lines (buffer 1m)

As can be seen from Table 1, all water mains are included in either Class 1 or Class 2. At this first stage of the analyses, hospitals were the only critical consumers considered.

All water pipes running under railway lines (SePe 2013) were considered in case where they (according to the GIS data) did not have a protective pipe around them. In the "cut-edge" analysis, the limit for pipe selection was set to 0.3Mm^3 of annual water consumption, which corresponded to approximately 10,000 inhabitants. In the case of underground facilities, only the entrances of subway stations were considered using a buffer of 50m for water pipes. Data on railways and buildings (SePe 2013) were used to find pipes that are located under or close to these structures. For water pipes, a buffer of 2m was applied and in case of buildings only pipes whose diameter exceeded 300mm were considered. Pipes with a diameter of 300mm and located under a road of type I and II were considered. The road type information followed the categorization of the Finnish Transport Agency (2013), where classes I and II are motorways and other roads connecting regions. The gas transport mains (Gasum 2013) were considered with a buffer of 1m, since these lines typically have a protective cover around them.

The criteria settled upon for the sewer system are presented in Table 2.

Table 2. Criteria used for defining the failure consequence class for sewer pipes.

Class 1
Sewer mains of crucial functional importance for the whole network
Tunnels
Sewer mains and pressure sewers that are within groundwater areas suitable for water intake (Class I and II groundwater areas)
Sewers close to primary or secondary raw water resources (lakes or rivers that act as reserve surface water sources, buffer 200m)
Pipes under railways
Pipes under significant roads (pipe diameter ≥ 600mm, regional main roads)
Unduplicated pressure pipes from critical pump stations
Class 2
Sewer mains not included in Category 1
Sewers within nature conservation areas
Pipes crossing water tunnels
Pipes going under a water body (river, lake, sea)
Pipes under buildings (pipe diameter ≥ 400mm)
Pipes close to protected brooks (buffer 20m)
Pipes close to swimming beaches (buffer 100m)
Pipes other than sewer mains which are within groundwater areas suitable for water intake (Class I and II groundwater areas)
Sewer mains within groundwater areas not suitable for water intake (Class III groundwater areas)
Sewers close to critical underground structures (subway entrances, 10m buffer)

The Finnish Environment Institute (2013) provided the data on groundwater areas and the nature conservation areas. The groundwater areas were provided in three categories: Class I includes groundwater areas important for water intake, Class II groundwater areas suitable for water intake and Class III all other groundwater areas. The surface waters (National Land Survey Finland 2013) were considered in several ways in the analysis: 1) when pipes intersected with water bodies; 2) in cases where the surface water body served as a secondary raw water resource (a buffer of 200m); for swimming beaches (a buffer of 100m); and 3) for protected brooks (a buffer of 20m). At this point, the buffers were set without an analysis of flow directions based on the expert group's judgement. The critical pump stations included those pump stations that, according to the utility's own assessment, should have a duplicate outlet but which at the time of the study were still waiting for one.

RESULTS AND DISCUSSION

Results

The data analysis revealed that 14% of the utility's water pipes and 25% of its sewers were estimated to have significant failure consequences (either Class 1 or 2). The corresponding network lengths in the Classes 1 and 2 are given in Table 3.

Table 3. Pipe lengths in Class 1 (very severe consequences) and Class 2 (severe consequences).

Pipe type	Class 1 (km)	Class 2 (km)
Water distribution pipes	89	357
Sewer pipes	182	506

Table 4 shows the total length of pipes for different criteria used for assessing the failure consequences for water pipes.

Table 4. Total length of pipes for meeting the criteria used for assessing the failure consequence class of water pipes

Criterion	Network length (km)
Water mains Class 2	307
Water mains Class 1	78
Buildings	20
Roads	20
Gas lines	18
Critical consumers	10
Closure not recommended	6
Underground structures	4
The only connection serving a large area	2
Railways	1

From Table 4 it can be seen that the most common factor causing significant failure consequences is a pipe's functional importance for the network. Water mains are all in Classes 1 or 2 where they form the largest subgroup. The remaining factors correspond to ca. 17% of the total length of pipes with significant failure consequences. One pipe can meet more than one criterion, so some pipes are listed under several criteria. For water pipes, a little less than 5% of the total length in Classes 1 and 2 met more than one criterion.

Table 5 shows the total length of sewer pipes meeting a given criterion.

Table 5. Total length of pipes meeting the criteria used for assessing failure consequence class of sewers.

Criterion	Network length (km)
Sewer mains Class 2	318
Groundwater areas Class 2	103
Main tunnels	92
Ditches	82
Sewer mains Class 1	35
Water bodies	34
Groundwater areas Class 1	31
Critical pump stations	14
Raw water resources	11
Roads	8
Nature conservation areas	8
Beaches	6
Railways	4
Buildings	4
Water tunnels	3
Underground	0.4

From Table 5 it can be seen that, similar to water pipes, the functional importance of a pipe in the network is the most common factor leading a pipe to be included in Classes 1 or 2. However, for sewers, other factors constitute a larger share (41%). This is understandable since wastewater networks could also cause environmental pollution and therefore more criteria were involved in the analysis for wastewater pipes than for water pipes. A little less than 10% of the total sewer length of pipes in categories 1 and 2 met more than one criterion.

For both water and wastewater systems, the total length of pipes in Classes 1 and 2 was relatively high. In addition to the identification of pipes with potentially severe failure consequences, an assessment was carried out on the relevance of different failure modes. This way, pipes can be further subdivided into groups when making decisions related to operation, maintenance and management activities. The analysis covered the following failure modes: pipe bursts and hidden leaks for water distribution pipes; and exfiltration, blockages, collapses and inflow and infiltration (I/I) for sewers.

Regarding water pipes, it was concluded that both pipe bursts and hidden leaks are detrimental in all different subgroups pipes in Classes 1 and 2. Hidden leaks were considered as harmful as pipe bursts, since they may lead to soil being diverted away from around the pipe, which could eventually cause a pipe burst. For this reason, no differentiation between different subgroups was made.

For sewers, the assessment results are given in Table 6.

Table 6. The effect of failure mode on failure consequence severity for wastewater pipes. Cases where the effects of a failure were assessed severe are marked with X.

Failure mode	Sewer mains Classes 1 & 2	Groundw. areas Classes 1& 2	Main tunnels	Brooks	Water bodies	Critical pump stations	Raw water resources	Roads	Nature conservation areas	Beaches	Railways	Buildings	Water tunnels	Underground structures
Exfiltration		X		X	X		X	X	X		X	X		
Collapse	X	X	X	X	X	X	X	X	X	X	X	X	X	X
I/I		X		X			X		X	X				
Blockage	X	X	X	X		X	X	X	X	X				

As expected, exfiltration was judged most detrimental in pipes located within groundwater areas, in nature conservation areas, and close to raw or other fresh water resources. Exfiltration was also judged detrimental under buildings, roads and railways due to the fact that even relatively small volumes of exfiltration may cause damage to these structures (Read and Wickridge 1997). Collapses were found to be detrimental with respect to every factor considered in the analysis. Inflow and infiltration were judged most detrimental in pipes where exceedance of capacity could lead to overflows to the environment nearby. Such pipes include pipes close to brooks or raw water resources, pipes within nature conservation areas and pipes starting from critical pump stations. Blockages were judged detrimental in sewer mains and in the same pipes where inflow and infiltration was also considered harmful.

Discussion

The results of the analyses can be used when prioritizing pipes for rehabilitation and renovation as well as when planning maintenance activities and condition assessment. For example, those pipes where inflow and infiltration was assessed to be most harmful can be selected for more intensive inflow and infiltration analyses. Similarly, CCTV (close-circuit television) inspections can be focused on pipes, where exfiltration could cause damage. The failure consequence classification and the information on the factors causing the severe consequences can be considered when giving permissions for excavations close to water or wastewater pipes. In general, pipes can be prioritized differently depending on the causer of consequence severity and the information on the most harmful failure types. The information on the consequences can also be combined with network performance indicators (see for example Marques & Monteiro, 2001). This way, it could be judged whether the level of performance is adequate for the location considering the severity of failure consequences.

The assessment of information requirements related to risk assessment revealed that a number of relevant data sets were missing. At the time of the study, no hydraulic model existed for the wastewater network and the network topology was not known. The hydraulic functioning of the drinking water network had been modelled but the results mainly provided support for distinguishing water mains from the network. A comprehensive analysis of the network hydraulics would enhance future analyses. The hydraulic significance of each pipe could be analysed using for instance the methodologies suggested by Möderl *et al.* (2009) and Möderl & Rauch (2011). However, it has to be noted that several other criteria are necessary when assessing the most severe failure consequences. For example, in the studied network an analysis on the hydraulic significance or network redundancy alone would not have identified the pipes that could cause a subway to flood.

For sewers, a better understanding of the failure consequences could be achieved through hydrodynamic modelling. For example, blockages can cause an overflow to a sensitive body of water upstream of the blocked pipe and this can only be revealed by hydrodynamic modelling. Future work on improving the classification procedure outlined here should involve a construction of a hydrodynamic sewer model and its use for identifying upstream impacts of blockages.

Important information on underground structures such as basements and parking halls was missing. Network topology was also not known, which made it impossible to estimate the extent of flooding caused by pipe failure in a trustworthy manner. Similarly, there was no information on the elevation at which the connection starts inside a property, i.e. whether the connection is below the retention water level. This information is vital when assessing the susceptibility of a property to wastewater flooding. Consequently, pipes causing risks to the underground facilities could not be identified. The accuracy of the analysis on flooding caused by water pipe bursts or sewer surcharging could be improved by incorporating network data with elevation data of facilities both under and above the ground level. This kind of analysis can be carried out following for example Gibson *et al.* (2016), where the extent of flooding caused by pipe bursts was estimated in a computationally efficient way using a regular square grid terrain model.

Future work will include incorporating new spatial data sets into the analysis and improving the accuracy of the methods applied. A larger set of critical water consumers will be considered in the upcoming analysis and graph analysis applied also for the sewer system. The utility is currently creating a hydraulic model and after it is ready, its results will be incorporated into the classification as well. The aim is to collect more data on underground facilities and to consider new infrastructure such as district heat pipelines. After the utility has gained more experience on the use of the classification, they will re-evaluate the factors considered and the classification principles applied and make changes if needed. Frequent updates will be carried out to ensure validity of the results. The analysis needed for the classification was automated with a Python script in ArcMap in order to enable a periodical update. Changes both in the network structure and the surrounding environment will take place and classification principles need to be revised.

The shares of pipes assessed to potentially have severe failure consequences, 14% and 25% of the total network length for water pipes and sewers, respectively, are relatively high. As more data becomes available, the number of criteria considered will most likely increase leading to even more pipes to be identified as having severe failure consequences. However, knowing the most detrimental failure types for each criterion will assist in allocating preventive maintenance to pipe subgroups. On the other hand, as data accuracy improves and more detailed analysis methods are applied, some of the pipes currently classified to pose a severe risk in case of a failure may be found to have less severe failure consequences. For example, data on underground facilities will likely increase the number of pipes in their immediate vicinity, but the enhanced analysis accuracy when detailed flooding analysis is carried out may reveal that some of the pipes are unlikely to cause problems in the nearby structures.

Eventually, the information on the pipes with severe failure consequences should be combined with knowledge on their condition to define the risks that they pose.

CONCLUSIONS

Failures in water or wastewater networks can cause severe consequences to the built, natural and human environments. Therefore, utility companies need to know, which elements in their networks could cause severe consequences if they fail. The identification of these elements is the first step in the process of alleviating or preventing risks related to them.

The focus of this study was on pipe identification and for this purpose, only categorization instead of the use of weighted scores was applied. Network attributes, spatial data sets and graph analysis were used to assess failure consequences. Even though the severity of failure consequences was found often to be dictated by the pipe's importance in the network, the study showed that other factors could cause detrimental consequences as well.

In addition to consequences, also the most detrimental failure modes were assessed regarding each criterion. This allows different subgroups of pipes to be managed distinctively, for example, when deciding on preventive maintenance activities. The information on fulfilled criteria can also be used in combination with performance indicators to explore whether pipe performance is acceptable considering pipe location and type.

This article presents an extensive set of criteria for failure consequence estimation. The transparent reporting of the selected criteria allows for constructive criticism by the scientific and professional communities, which is essential for further development of pipe network risk analyses. Although many data sets were available for the current analysis, crucial information needs were recognized, relating especially to underground facilities. As data availability and accuracy become better and analysis methods improve, the results can be updated leading to an iterative procedure of consequence assessment.

Some of the data sets (groundwater areas, nature conservation areas and subway entrances) and methods (graph analysis) used here in failure consequence assessments have not been reported in earlier studies. Also, the discussion of the effect of different failure modes on actual risks has not been presented elsewhere.

References

Baah, K., Dubey, B., Harvey, R. & McBean, E. 2015 A risk-based approach to sanitary sewer pipe asset management. *Science of The Total Environment*, **505**, 1011-1017. https://doi.org/10.1016/j.scitotenv.2014.10.040

Baur, R. & Herz, R. 2002 Selective inspection planning with ageing forecast for sewer types. *Water science and technology*, **46**(6-7), 389-396.

Berardi, L., Giustolisi, O., Savić, D.A. & Kapelan, Z. 2009 An effective multi-objective approach to prioritisation of sewer pipe inspection. *Water Science and Technology*, **60**(4), 841–850. https://doi.org/10.2166/wst.2009.432

Berardi, L., Ugarelli, R., Røstum, J. & Giustolisi, O. 2014 Assessing mechanical vulnerability in water distribution networks under multiple failures. *Water Resources Research* **50(**3), 2586–2599. https://doi.org/10.1002/2013WR014770

Diao, K., Farmani, R., Fu, G., Astaraie-Imani, M., Ward, S. & Butler, D. 2014 Clustering analysis of water distribution systems: identifying critical components and community impacts. *Water Science and Technology,* **70**(11), 1764–1773. https://doi.org/10.2166/wst.2014.268

Fares, H. & Zayed, T. 2010 Hierarchical fuzzy expert system for risk of failure of water mains. *Journal of Pipeline Systems Engineering and Practice*, **1**(1), 53-62. https://doi.org/10.1061/(ASCE)PS.1949-1204.0000037#sthash.yQlte3EA.dpuf

Finnish Environment Institute 2013 Groundwater areas.

Finnish Transport Agency 2013 Road network.

Gasum 2013 Gas transport mains.

Gibson, M.J., Savic, D.A., Djordjevic, S., Chen, A.S., Fraser, S. & Watson, T. 2016 Accuracy and computational efficiency of 2D urban surface flood modelling based on cellular automata. Procedia Engineering, **154**, 801-810. https://doi.org/10.1016/j.proeng.2016.07.409

INSPIRE 2007 Council Directive 2007/2/EC of 14 March 2007 on establishing an infrastructure for spatial information in the European Community (INSPIRE).

ISO 31000:2009 *Risk management – Principles and guidelines*.

ISO 55000:2014 *Asset management – Overview, principles and terminology*.

Kleiner, Y., Rajani, B. & Sadiq, R. 2006 Failure risk management of buried infrastructure using fuzzy-based techniques. *Journal of Water Supply: Research and Technology-AQUA*, **55**(2), 81-94. https://doi.org/10.2166/aqua.2006.075

Le Gat, Y. & Eisenbeis, P. 2000 Using maintenance records to forecast failures in water networks. *Urban Water*, **2**(3), 173-181.

Le Gat, Y. 2008 Modelling the deterioration process of drainage pipelines. *Urban Water Journal*, **5**(2), 97-106. http://dx.doi.org/10.1080/15730620801939398

Marques, R.C. & Monteiro, A.J. 2001 Application of performance indicators in water utilities management-a case-study in Portugal. *Water Science and Technology*, **44**(2-3), 95-102.

Möderl, M., Kleidorfer, M., Sitzenfrei, R. & Rauch, W. 2009 Identifying weak points of urban drainage systems by means of VulNetUD. *Water Science and Technology*, **60**(10), 2507–2513. https://doi.org/10.2166/wst.2009.664

Möderl, M. & Rauch, W. 2011 Spatial risk assessment for critical network infrastructure using sensitivity analysis. *Frontiers of Earth Science*, **5**(4), 414-420. https://doi.org/10.1007/s11707-011-0202-1

National Land Survey Finland 2013 Topographic database.

Piratla, K. R. & Ariaratnam, S. T. 2011 Criticality analysis of water distribution pipelines. *Journal of Pipeline Systems Engineering and Practice*, **2**(3), 91-101. https://doi.org/10.1061/(ASCE)PS.1949-1204.0000077#sthash.gK4CY5YJ.dpuf

Read, G. F. & Vickridge, I. G. 1997 *Sewers – Rehabilitation and New Construction. Repair and Renovation*. Elsevier Buttworth-Heinemann Publishing. Oxford, United Kingdom.

Savić, D., Giustolisi, O., Berardi, L., Shepherd, W., Djordjevic, S. & Saul, A. 2006 Modelling sewer failure by evolutionary computing. *Proceedings of the ICE-Water Management*, **159**(2), 111-118.

Salman, B. & Salem, O. 2011 Risk assessment of wastewater collection lines using failure models and criticality ratings. *Journal of pipeline systems engineering and practice*, **3**(3), 68-76. https://doi.org/10.1061/(ASCE)PS.1949-1204.0000100#sthash.hthMgIXy.dpuf

SePe 2013 Helsinki Regional Services Authority: Regional Basic Register.

Syachrani, S., Jeong, H. D. & Chung, C. S. 2013 Advanced criticality assessment method for sewer pipeline assets. *Water Science and Technology*, **67**(6), 1302-1309. https://doi.org/10.2166/wst.2013.003

WRc 2001 *Sewerage rehabilitation manual*. 4th edn, Swindon:WRc.

Ward, B. & Savić, D. 2012 A multi-objective optimisation model for sewer rehabilitation considering critical risk of failure. *Water Science and Technology*, **66**(11), 2410–2417. https://doi.org/10.2166/wst.2012.393