

Sewer asset management - state of the art and research needs

Review Article**Author(s):**

Tscheikner-Gratl, Franz; Caradot, Nicolas; Cherqui, Frederic; Cherqui, Frédéric; Leitão, João P.; Ahmadi, Mehdi; Langeveld, Jeroen G.; Le Gat, Yves; Scholten, Lisa; Roghani, Bardia; Rodríguez, Juan P.; Lepot, Mathieu; Stegeman, Bram; Heinrichsen, Anna; Kropp, Ingo; Kerres, Karsten; do Céu Almeida, Maria; Bach, Peter M.; Moy de Vitry, Matthew; Sá Marques, Alfeu; Simões, Nuno E.; Rouault, Pascale; Hernandez, Nathalie; Torres, Andres; Wery, Caty; Rulleau, Bénédicte; Clemens, François

Publication date:

2019

Permanent link:

<https://doi.org/10.3929/ethz-b-000394020>

Rights / license:

[Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International](#)

Originally published in:

Urban water journal 16(9), <https://doi.org/10.1080/1573062X.2020.1713382>



Sewer asset management – state of the art and research needs

Franz Tscheikner-Gratl, Nicolas Caradot, Frédéric Cherqui, Joao P. Leitão, Mehdi Ahmadi, Jeroen G. Langeveld, Yves Le Gat, Lisa Scholten, Bardia Roghani, Juan Pablo Rodríguez, Mathieu Lepot, Bram Stegeman, Anna Heinrichsen, Ingo Kropp, Karsten Kerres, Maria do Céu Almeida, Peter M. Bach, Matthew Moy de Vitry, Alfeu Sá Marques, Nuno Eduardo Simões, Pascale Rouault, Nathalie Hernandez, Andres Torres, Caty Wery, Bénédicte Rulleau & François Clemens

To cite this article: Franz Tscheikner-Gratl, Nicolas Caradot, Frédéric Cherqui, Joao P. Leitão, Mehdi Ahmadi, Jeroen G. Langeveld, Yves Le Gat, Lisa Scholten, Bardia Roghani, Juan Pablo Rodríguez, Mathieu Lepot, Bram Stegeman, Anna Heinrichsen, Ingo Kropp, Karsten Kerres, Maria do Céu Almeida, Peter M. Bach, Matthew Moy de Vitry, Alfeu Sá Marques, Nuno Eduardo Simões, Pascale Rouault, Nathalie Hernandez, Andres Torres, Caty Wery, Bénédicte Rulleau & François Clemens (2020): Sewer asset management – state of the art and research needs, Urban Water Journal, DOI: [10.1080/1573062X.2020.1713382](https://doi.org/10.1080/1573062X.2020.1713382)

To link to this article: <https://doi.org/10.1080/1573062X.2020.1713382>



© 2020 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.



Published online: 15 Jan 2020.



[Submit your article to this journal](#)



Article views: 412



[View related articles](#)



[View Crossmark data](#)

Sewer asset management – state of the art and research needs

Franz Tscheikner-Gratl^a, Nicolas Caradot^b, Frédéric Cherqui^c, Joao P. Leitão^d, Mehdi Ahmadi^e, Jeroen G. Langeveld^{f,g}, Yves Le Gat^h, Lisa Scholten^f, Bardia Roghaniⁱ, Juan Pablo Rodríguez^j, Mathieu Lepot^f, Bram Stegeman^f, Anna Heinrichsen^k, Ingo Kropp^l, Karsten Kerres^m, Maria do Céu Almeidaⁿ, Peter M. Bach^{d,o,p}, Matthew Moy de Vitry^{d,o}, Alfeu Sá Marques^q, Nuno Eduardo Simões^r, Pascale Rouault^b, Nathalie Hernandez^f, Andres Torres^f, Caty Werey^s, Bénédicte Rulleau^h and François Clemens^{f,t}

^aDepartment of Civil and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, Norway; ^bKompetenzzentrum Wasser Berlin, Berlin, Germany; ^cUniversity of Lyon, INSA Lyon, Villeurbanne, France; ^dSwiss Federal Institute of Aquatic Science & Technology (Eawag), Dübendorf, Switzerland; ^eDepartment of Building and infrastructure, SINTEF, Oslo, Norway; ^fFaculty of Civil Engineering and Geoscience, Department of Water management, Delft University of Technology, Delft, The Netherlands; ^gPartners4UrbanWater, Nijmegen, The Netherlands; ^hIrstea Bordeaux – ETBX, Cestas, France; ⁱSchool of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran; ^jDepartamento de Ingeniería Civil y Ambiental, Universidad de los Andes, Bogotá, Colombia; ^kDr.-Ing. Pecher und Partner Ingenieurgesellschaft mbH, Berlin, Germany; ^l3S Consult GmbH, Dresden, Germany; ^mAachen University of Applied Sciences – FH Aachen, Aachen, Germany; ⁿDepartment of Hydraulics and Environment, LNEC, Lisbon, Portugal; ^oInstitute of Civil, Environmental and Geomatic Engineering, ETH Zürich, Zurich, Switzerland; ^pDepartment of Civil Engineering, Monash University, Clayton, Australia; ^qINESC Coimbra, Department of Civil Engineering, University of Coimbra, Coimbra, Portugal; ^rFaculty of Engineering, Pontificia Universidad Javeriana, Bogotá, Colombia; ^sIrstea, UMR GESTE, Enges, Strasbourg, France; ^tDepartment of Hydraulic Engineering, Deltares, Delft, The Netherlands

ABSTRACT

Sewer asset management gained momentum and importance in recent years due to economic considerations, since infrastructure maintenance and rehabilitation directly represent major investments. Because physical urban water infrastructure has life expectancies of up to 100 years or more, contemporary urban drainage systems are strongly influenced by historical decisions and implementations. The current decisions taken in sewer asset management will, therefore, have a long-lasting impact on the functionality and quality of future services provided by these networks. These decisions can be supported by different approaches ranging from various inspection techniques, deterioration models to assess the probability of failure or the technical service life, to sophisticated decision support systems crossing boundaries to other urban infrastructure. This paper presents the state of the art in sewer asset management in its manifold facets spanning a wide field of research and highlights existing research gaps while giving an outlook on future developments and research areas.

ARTICLE HISTORY

Received 27 May 2019
Accepted 3 January 2020

KEYWORDS

Urban drainage; inspection; deterioration modelling; data management; decision support; costs

Introduction

Modern sewer infrastructure faces major challenges in fulfilling public expectations concerning the functionality of the urban drainage infrastructure – the maintenance and rehabilitation of aging networks along with the adaptations needed to cope with a changing environment (e.g. climate change and/or urban development in the context of population increase/decrease). The focus of operating companies in places with long-lived sewer infrastructure is, therefore, shifting from new design and construction to redesign and asset management. We understand sewer asset management, following the definition of Marlow, Beale, and Burn (2010), as ‘a combination of management, financial, economic, engineering and other practices applied to (physical) assets with the objective of maximizing the value derived from an asset stock over a whole life cycle, within the context of delivering appropriate levels of service to customers, communities and the environment, and at an acceptable level of risk’, that reaches beyond spatial, temporal and organizational decision-making scales.

The management of these assets also represents an important economic consideration. Sewer infrastructure is extremely

capital-intensive and fixed costs constitute up to 80% of the total costs of a utility (Hukka and Katko 2015). The estimation of appropriate investment levels for wastewater infrastructures is challenging due to the assets’ characteristics: long asset life, cumbersome condition assessment of the assets, differences between accountancy and real value and the difficulty of assessing costs of deferred investments (Westerhoff et al. 2003). Investment needs for urban water supply and drainage infrastructure combined is set at 0.75% of the gross domestic product (Cashman and Ashley 2008).

In Austria, Neunteufel et al. (2012) estimated a yearly reinvestment need of 490 to 830 million €. In reality, 2017 investments of about 362 million € were made (KPC 2017), well below these assumptions but above the 0.07% rehabilitation rate in 2012 (Kleidorfer et al. 2013). In Germany, Berger et al. (2016) highlighted that ~20% of the sewer network requires short or mid-term rehabilitation. The annual investment for sewer rehabilitation of approximately 4 billion €, representing a rehabilitation rate of ~1.1%, contrasts with an estimated 7 billion € capital need (Scheller and Schneider 2016). In the Netherlands, a yearly amount of

800 million € is spent on rehabilitation and/or replacement of sewers, i.e. affecting 1% of the network annually, which is still short of the expected need (Oosterom and Hermans 2013). In France the current annual investments are at the Dutch level, lacking 1.4 billion € per year (Lesage 2013).

The overall condition of the French sewer network remains mostly unknown, as it is the case in most cities where only a small part of the existing network has already been inspected. This lack of information inhibits the development of efficient sewer rehabilitation strategies (Ahmadi et al. 2014a; Harvey and McBean 2014). In practice, proactive management strategies are mainly based on the companies or municipalities employees' experience: their intuition and tacit knowledge of the system play an essential role in decision-making (van Riel et al. 2016, 2017).

The aim of this paper, based on the experiences of a working group on Urban Drainage Asset Management (UDAM – <https://udam.home.blog/>) of the IWA and IAHR Joint Committee on Urban Drainage, is to present the state of the art in sewer asset management in its manifold facets, while highlighting views of future developments and research areas. The structure of this discourse is akin to sewer asset management approaches: we begin with the topic of inspection, using the data from inspections to assess the condition to be used in a risk-based approach. All these data must be stored and manipulated to be usable for the operator and other decision-makers. From these data, we derive appropriate models for investment and operational decisions. Finally, we broaden the focus to a more systems engineering approach (Wasson 2016), looking at the possibilities of interactions, interdependencies and synergies with the other urban infrastructures, that share the same physical space.

Inspection techniques

Closed Circuit Television (CCTV) inspection techniques remain the most applied method for condition and operability assessment of sewer systems. Notwithstanding the undisputed quality increase in obtained footage over the last decades, the CCTV concept for sewer inspection has been repeatedly criticised (e.g. Dirksen et al. 2013). The main issues identified are twofold:

- Limited type of information acquired:
 - Only a snapshot of the condition without information on deterioration process or cause.
 - No direct information on the actual hydraulic capacity of inspected conduits or networks.
 - No information on the material properties and the geometry to estimate the structural strength and stability.
 - No information about the quantity of in- and exfiltration.
 - Only prior defined (e.g. EN 13508-2 2011) defects are reported.
- Low accuracy and repeatability:
 - Relatively large percentage of false negatives and false positives in defect identification, due to dependence on human observation of images.

- Numerical classification, representing good to poor condition, may vary between individual inspectors up to two steps.

Efforts to minimise the human factor, namely the recent research development on applying automated image processing techniques using pattern recognition and machine learning (e.g. Kumar et al. 2018; Meijer et al. 2019; Myrans, Everson, and Kapelan 2018), show encouraging results (accuracies of around 90%), particularly in their ability to reduce the percentage of false negatives. However, the issue of correct classification remains a challenge. This is mainly because the classification procedure applied in the standards depends on semantic descriptions rather than rigorously defined quantifiable measures.

Another issue, with respect to sewer inspection in general, is the fact that inspection schedules are often based on operator experience and intuition, customer complaints or on pre-selections based on either age, material or operational conditions that are believed to have adverse effects on the state of the assets. This may result in biased data and inefficient inspection programs (Roghani et al. 2019), making extrapolation from available data to a whole system extremely uncertain.

Alternative inspection techniques

As cheap alternatives for CCTV inspection (providing the same information), recently developed acoustic (e.g. Horoshenkov, Long, and Tait 2010) and manhole camera zoom techniques (e.g. Plihal et al. 2016) have been proposed. However, since these technologies are not included in standards yet, the application in practice is still limited.

Ring laser scanning methods have been applied to detect and quantify the inner geometry of sewer pipes to measure deformations (Hartley and Zisserman 2003), with rather poor accuracy. Recent developments report an increase in accuracy due to the application of camera movement compensation methods, tested under lab-conditions only (Clemens et al. 2015; Lepot, Stanić, and Clemens 2017c). The technology is promising as it provides detailed information of the 3D geometry of pipes that may be used to quantify material loss, deformation and the dimensions of obstacles and intruding lateral connections. Based on such data, the possibility to extract wall-roughness values of corroded pipes has been shown (Clemens et al. 2015). However, the translation of shape, position texture of obstacles and sediment beds into hydraulic loss characteristics are still an open issue.

Multiple methods have been developed to assess infiltration/exfiltration (I/E) in the last decades (e.g. Bertrand-Krajewski et al. 2006; Harris and Dobson 2006). Recent research focuses on the application and further development of Distributed Temperature Sensing (DTS), tracer methods and electro tomography. DTS can be used to detect and locate infiltration (Hoes et al. 2009; Nienhuis et al. 2013), providing, however, only a rough estimate. The placement of a fibre-optic cable into the pipeline bed to monitor high-frequency temperature differences because of exfiltration is yet to be tested in urban drainage.

Bertrand-Krajewski et al. (2006) developed and improved tracer methods to quantify infiltration (e.g. the stable isotope method) and exfiltration (e.g. QUEST-C). Current research is focussing on the application and further development of tracer methods to detect and quantify exfiltration (Rieckermann et al. 2007; Stegemann et al. 2018). In lab-scale experiments, the application of Infra-Red cameras has been tested (Lepot, Makris, and Clemens 2017a). This method seems to be able to detect infiltration, but the detection limit is relatively high. Electrical Resistivity Tomography (ERT) and self-potential methods (Thompson, Kulesa, and Luckman 2012) could be promising since they potentially may be applied for long-term monitoring of the effect of infiltration and exfiltration in the soil.

Sedimentation of sewers causes potentially large reductions of hydraulic capacity (Van Bijnen, Korving, and Clemens 2012), but CCTV only reveals what 'can be seen' by optical means and does not provide any direct quantification. When dry conditions can be established, the application of accurate laser scanning techniques may be applied (Lepot, Stanić, and Clemens 2017c). These conditions could until now only be achieved in a laboratory setting. Another promising technique is the application of sonar (Lepot et al. 2017b), which is less accurate than laser-scanning but seems to be more robust and applicable in practice.

An important limitation of most inspection techniques is the fact that a pipe is only inspected from the inside. This implies that some defects (e.g. outer wall corrosion) cannot be detected at all. Depending on pipe material and its location, cracks along the pipe perimeter (e.g. a longitudinal crack on the bottom of a pipe) may go undetected during visual inspection (even after draining and cleaning prior to visual inspection). There are techniques such as Ground Penetrating Radar (GPR) (Hao et al. 2012), that show promise to identify voids around the pipes and pipe collapses.

In current practice, the most widely applied method for obtaining information on material properties is taking samples for lab analysis. However, the material properties of concrete pipes, especially older ones, tend to be very inhomogeneous. This renders the number of samples, necessary to obtain usable statistical information, prohibitive for practical application (Stanić et al. 2017). No practical applicable non-invasive methods for obtaining data on material's properties for sewer pipes have been reported yet.

The idea for robotising pipe inspection has been discussed for at least two decades (Kirkham et al. 2000; Kuntze and Haffner

1998) along with the idea of mounting multiple sensors to obtain information from different sources (e.g. infra-red and visible spectrum, sonar, temperature, laser). These platforms are believed to provide mutually combinable data to detect the presence of infiltration, cracks, loss of wall thickness due to corrosion, deformation of the geometry and possibly even the presence of bacterial activity through stimulated emission of visible light under ultra-violet radiation. The big challenges for such integrated platforms are their practical applicability, data post-processing, interpretation of obtained information and costs.

Condition and performance assessment

Condition assessment is a vital component of any asset management strategy, that precedes the performance assessment of the asset, to pursue a risk-based approach. Usually, condition assessment of collection systems is undertaken with limited resources and potentially with an incomplete inventory or incomplete characterisation of related systems' attributes (Oliveira et al. 2007). The investigation techniques have been previously presented and data quality and availability will be discussed in the next section. Therefore, we will focus here on protocols used to assess the condition and combination of condition with other indicators to obtain an assessment of performance.

Table 1 presents an inventory of existing protocols to classify pipe condition into several possible states depending on the level of complexity and the stakes considered. A condition class as such cannot be regarded as an objective metric related to functionality, as it is based on CCTV with no direct link to physical measurable characteristics. It is merely a structured and standardized method to aggregate opinions.

The *comprehensive* condition represents the simplest assessment, where physical integrity gets a score corresponding to the need for rehabilitation and its urgency. Due to its simplicity, this assessment does not allow for a deeper understanding of why and how rehabilitation should be done. The objective is to assess functionality of the asset at the time of inspection (present function fulfilment).

Structural condition refers to the capacity of the pipe to fulfil its structural role maintaining its shape and bearing capability. The classification of the *integrity (structural)* of a sewer is the basis for the wear margin or remaining service life (Vanier and

Table 1. Existing protocols to assess the condition of a sewer pipe.

Type	Description	References
Comprehensive	Overall assessment of pipe's need for rehabilitation based directly on observed defects or combining the conditions below	Chughtai and Zayed (2011), EN 752 (2017), Kley et al. (2013), WRc (2013), Zhao, McDonald, and Kleiner (2001)
Structural	Assessment of pipe physical condition by considering defects leading to deterioration and ultimately the collapse of the pipe	Ahmadi et al. (2014c), Chughtai and Zayed (2011), EN 752 (2017), Khazraeializadeh, Gay, and Bayat (2014), Kley et al. (2013), WRc (2013), Zhao, McDonald, and Kleiner (2001)
Integrity (structural)	Assessment of structural condition with reference to strategic rehabilitation planning to determine remaining service life and structural integrity values of sewers (currently not standardised)	DWA-Themen T4 (2012), Kley et al. (2013)
Operational	Assessment of defects leading to an increase of operational interventions necessary on the pipe	Ahmadi et al. (2014c), ATV-M 143-2 (1999), Chughtai and Zayed (2011), EN 13508-2 (2011), EN 752 (2017), NASSCO (2016), WRc (2013), Zhao, McDonald, and Kleiner (2001)
Environmental	Assessment of defects leading to pollution of water (groundwater or surface water)	DWA-M 149-7 (2016), EN 752 (2017)
Hydraulic or serviceability	Assessment of defects that will perturbate the flow	Ahmadi et al. (2014c), Arbeitshilfen Abwasser (2018), EN 752 (2017), Micevski, Kuczera, and Coombes (2002), ÖWAV-RB 22 (2015)
Malfunctions	Consequences of defects on facility operations, e.g. ongoing corrosion, blockage, excessive spillage, sand silting, etc.	Ahmadi et al. (2014c), Kley et al. (2013), Le Gauffre et al. (2007)

Rahman 2004) as well as the allocation of a reasonable rehabilitation type (renewal, renovation or repair) for damaged sewers. A simple example illustrates the difference between a classification based on structural condition and an integrity-oriented one, which focuses more on the overall condition of a sewer: A sewer with a single severe damage (causing a poor structural condition rating) may require immediate (repair) action to restore function, but its overall integrity is still good. Consequently, there is no need for a complete replacement of the sewer pipe in the immediate future. On the other hand, a sewer pipe without severe single defects, but irreparable degradation along the whole pipe length requires renovation or replacement.

Operational, environmental and hydraulic conditions consider physical deterioration that will, respectively, lead to operational incidents, environmental impact, infiltration, exfiltration or flooding. Such conditions may be interconnected but may lead to different rehabilitation strategies. *Malfunctions* represent the consequences of defects in facility operations. Some malfunctions may be observed using CCTV inspection or alternative types of investigation procedures, while others can only be estimated based on occurring defects (Le Gauffre et al. 2007).

From condition to risk-based approach

Condition assessment should not be the only factor for prioritisation of pipe rehabilitation. From an economic perspective, pipes to be rehabilitated should be in poor condition, contribute to an existing and important impact or cause an increase in risk. It is, therefore, necessary to combine conditions with other factors in this risk-based approach. Risk can be defined as the combination of the consequences of failure and the likelihood or probability that such a failure will occur (ISO 24765 2017; ISO 55000 2014). Consequences can include social, economic, and environmental impacts that occur because of a pipe failure. If an asset failure triggers severe consequence, but has a low probability of failure, this can result in a moderate risk of failure. Those assets with the potential to significantly impact the delivering of network objectives are called 'critical assets' (ISO 55000 2014) and should never fail in an ideal situation. Nevertheless, there is always some likelihood of failure. This implies the necessity to accept some level of risk as its elimination is neither feasible nor affordable. The degree of risk should, however, be kept as low as reasonably practicable (Frangopol 2011).

The extensive research on the field of risk-based approaches has brought the method and tools to the operational field. Table 2 presents an overview of references dedicated to risk-based approaches, combining the assessment (or prediction) of condition with other indicators. The last decade has also seen the emergence of software (e.g. Debères et al. 2011; Halfawy, Dridi, and Baker 2008) dedicated to risk-based approach, combining pipe condition or CCTV reports (when the tool has a pipe assessment protocol) with a broad range of indicators related to the surroundings of the pipe (often extracted from the city's geospatial information system). There is some complexity involved in determining the direct costs of repair or replacement activities, due to the method selection process. Even more uncertainty, difficulty, and subjectivity are encountered during the estimation of indirect costs of sewer failure in

monetary terms as they are intangible in nature (Salman and Salem 2012). One major impediment of the adoption of such methods and tools is the lack of data, although approaches with valuations from survey data have been tested (Rozan, Rulleau, and Wery 2017). Still, data management remains a major concern for operational and research activities.

Sewer asset data management

The amount of data relevant to asset management and its variety are expected to grow due to factors such as increasing regulatory requirements, the emergence of new low-cost sensors, increasing digitalization and the potential of social media platforms to report different types of problems. The diversity of data sources brings not only new opportunities but also new challenges with respect to data management. Water utilities must deal with large volumes of data in near real-time and thus current data-management platforms will require significant changes and improvements.

Organisational characteristics and size of management utilities of urban water systems can vary significantly, from small (local) to large (regional and international) sewer operators which can be private, public, or public-private partnerships or anything in between. Among other factors, this will influence data availability and quality, as well as on the capability of processing the data.

Several types of data can be used to support asset management, and attempts have been made to structure and make the various data sets outlined previously compatible, especially at the national level; examples being the Swiss Water Association (VSA) data model (VSA-DSS 2014) or the Dutch Gegevenswoordenboek Stedelijk Water (RIONED 2017). These types of data models consist of a relational database structure specification, for instance for system data, and should facilitate the link with other relevant data sets (e.g. Organisation and Environment data). Another important feature of the data model is to enable the connection of databases of operation and maintenance data, for example, databases of sewer inspection reports or customer complaints. Data models tend to be very detailed, attempting to cover various potential uses of data. Therefore, due to its completeness, some data models become complex and water utilities end up not leveraging their full capabilities, or use them at all, preferring to develop simpler custom data models suited to their, limited, specific needs.

There are several international standards focussed on managing asset data, specifically. For example, ISO 55000 (2014) for the data aspects to be considered and EN 13508-2 (2011), that provides a coding system for observations made during sewer visual inspection activities. Several authors refer to minimum data requirements to develop an effective asset management strategy (e.g. Carvalho et al. 2018; Rokstad and Ugarelli 2016) or the 'optimal' data set (e.g. Ahmadi et al. 2014a; Tschekner-Gratl et al. 2013). Minimum data sets focus on the characteristics of the sewer infrastructure (e.g. sewer pipes and manholes) as well as data from management and operational processes. Acquiring additional data is usually associated with managing different data owners and navigating varying data quality. This should be contemplated when devising data collection plans, since it creates additional challenges in the workflow.

Table 2. Risk-based approaches regarding sewer asset management.

Reference	Impacts/risk considered	Decision support method	Case study
Anbari, Tabesh, and Roozbahani (2017)	Wastewater inflow to river, lake or water distribution network, Overflow, Service disruption	Weighted average and fuzzy inference	Tehran, Iran
Baah et al. (2015)	Roadway type, intersecting a railway, proximity to hospital or school, proximity to river, proximity to park or recreational areas	Weighted sum using a geographical information system (ArcGIS)	"Mid-sized community located in southern Ontario", Canada
Debères et al. (2011)	Groundwater and soil quality, deterioration, operating costs, flooding, traffic and urban disturbance	Outranking method (ELECTRE TRI) and a simple procedure called "thresholds method"	Caen-la-Mer, France
Egger and Maurer (2015)	Rainfall variability, sewer deterioration, preference uncertainty, socio-economic and land use development, groundwater contamination, sewer failure and collapse, flooding weighted by location, cost increase	Multi-criteria decision analysis (MCDA)	2 small-town cases in Kanton of Zurich, Switzerland
Elsawah, Bakry, and Moselhi (2016)	Type of soil, number of road lanes, land use, function of the pipe	Risk matrices	Montreal, Canada
Ennaouri and Fuamba (2013)	Type of soil, traffic, groundwater, exfiltration, infiltration, hydraulic capacity	Analytic hierarchy process (AHP)	Saint-Hyacinthe, Canada
Hahn et al. (2002)	Human health, Environmental, Commerce, and traffic impacts	Bayesian belief network	Input from a US national group of experts from both the public and private sectors
Halfawy, Dridi, and Baker (2008)	Sewer type, sewer function, land use, road classification	Simple Weighing	City of Regina, Canada
Korving et al. (2009)	Cost of environmental damage due to combined sewer overflows, investment costs	Optimization	De Hoven catchment, The Netherlands
Kuliczowska (2016)	Water table level, intensity of road traffic, backflow or overflow of wastewater	Simple Weighing	Poland
Rozan, Rulleau, and Werey (2017)	Intangible goods, inhabitants' preferences	Assessment of inhabitants' willingness to pay	Strasbourg, France
Salman and Salem (2012)	Proximity to water sources, pipe function, landslide potential, roadway type, building type	Weighted scoring and fuzzy inference	Cincinnati, USA
Tscheikner-Gratl et al. (2014)	Flood risk and opportunities connected to urban development	Weighted scoring system	"Medium-sized Alpine city", Austria

Although the value of the Open Data paradigm is widely accepted (Carrara, Radu, and Vollers 2017), there are relatively few examples of Open Data in sewer asset management. Aside from the potential benefits, there are also several barriers for Open Data (Janssen, Charalabidis, and Zuiderwijk 2012). Some of these barriers may be particularly challenging for asset data, such as the unclear potential for value creation or the relatively small audience size interested in, and capable of, using such data. Other barriers include the intrinsic value of data and data security issues.

Various stakeholders involved should also take advantage of new technologies to improve data accessibility. One such recent development is cloud data hosting, which would allow utilities to share data more efficiently within their organisation and provide controlled access to relevant information to other stakeholders. This approach could provide the opportunity to create a large and common accessible database that could be shared among utilities and researchers in the field. It would also contribute to data loss protection and, in theory, ensure that an adequate data structure exists, to mitigate the issue of lacking historical data.

Data quality challenges

The process of acquiring data is costly and complex, which often explains why data are limited in quantity and quality (Ana et al. 2009). Nevertheless, irrespective of data requirements and acquisition method(s), there will always be some level of error and

bias. Other relevant data issues include missing and implausible data, lack of information about rehabilitation works and decisions underlying these, poorly documented models, insufficient measurements and calibration data, and lack of environmental data (Egger et al. 2013).

Limitations in data quality and quantity are major impediments to condition-based maintenance and to the wide use of predictive models. Necessary data include information on asset characteristics during operational life (e.g. date and depth of installation, material, backfill, condition, failure events, and interventions), but such elements are usually missing from the utilities' databases. Further complications can arise regularly when there are discrepancies between design drawings and final constructed assets, which impact asset management solutions (Farrelly and Bach 2018).

When such information is available, it often covers only the most recent years or is inconsistently collected due to changes in industry reporting standards over time or lack of adherence to protocols. In addition, data management and storage by urban drainage operators usually results in overwriting historical data with the most recent information. This leads to a lack of robust historical information about network development, condition, operation and maintenance. Much historical data may also neither be digitalised nor stored in relational databases, making their use extremely challenging. To tackle these data quality issues, methods for infilling missing data/metadata using alternative data sources (e.g. construction dates and pipe

specifications) should be further investigated (e.g. Tschekner-Gratl et al. 2016a).

Shortcomings and possible improvements of CCTV inspections have been discussed in the section about inspection techniques. When currently using data provided by sewer utilities, attention is required on the following elements:

- Inspections are mainly performed for four specific purposes: (1) checking the quality of pipe installation or renovation at asset handover, (2) diagnosis in case of proven malfunction (odour, overflow, ground subsidence), (3) checking sewer condition before roadway renovation, and (4) random (or sectoral) survey of pipe conditions.
- Due to the availability of resources, only a sample of network segments can be covered within the observation window.
- Inspection and renovation data are only available in numerical format from a given year onwards (often after 1990).

Consequently, available inspection data are very likely to be subject to three data quality issues: (1) selective survival bias, (2) recruitment bias, and (3) information censoring.

Of all those issues, the selective survival bias seems to be a critical issue for the future development of deterioration models. Current models are expected to underestimate the real condition of the network because the observed pipes used for model calibration are only those that ‘survived’ until the date of inspection. Since the models are calibrated using data concerning pipes that were in place at the date of inspection, they will inevitably underestimate the probability to be in a poor state, and consequently, overestimate the duration of useful life of pipes. Egger et al. (2013) proposed to combine the deterioration model with a probabilistic replacement model that characterises the probability that a pipe was not replaced, i.e. the chance that a pipe is still in service.

Sewer deterioration modelling

Over the last 30 years, a myriad of tools has been developed or applied by researchers, companies and municipalities, thanks to the potential of computational modelling. Modelling outcomes can support utilities in developing short-term rehabilitation programs by estimating the current sewer condition of uninspected sewers and forecasting the future condition of the network in planning long-term investment needs. The main tools for this are sewer deterioration models for structural deterioration, infiltration, exfiltration and blockages.

Modelling of sewer structural deterioration

Existing sewer deterioration models can be classified into three basic groups: deterministic, statistical and artificial intelligence (AI) models. For a detailed review of modelling approaches, the authors refer to Ana and Bauwens (2010), Kley et al. (2013), Marlow et al. (2009), Rokstad and Ugarelli (2015) and Tschekner-Gratl (2016).

Deterministic models aim at understanding the physical mechanisms that drive sewer deterioration. Even sophisticated

deterministic models are often too simplistic to reflect the complexity of the deterioration process and the scarcity of available data needed to simulate deterioration mechanisms decreases the applicability of such models (Rajani and Kleiner 2001).

To overcome the difficulty of deterministic simulation, statistical models have been developed to simulate the structural condition of sewer pipes from a set of explanatory covariates. The main statistical approaches developed are survival analysis, Markov-chain, logistic regression and discriminant analysis. Survival analysis and Markov-chain are the most common types of statistical deterioration models on a network level (e.g. Caradot et al. 2017; Duchesne et al. 2013; Egger et al. 2013; Le Gat 2008; Micevski, Kuczera, and Coombes 2002; Rokstad and Ugarelli 2015). Prior to model calibration, pipes are generally grouped in cohorts, i.e. homogenous groups of sewer pipes sharing similar features, e.g. same material and type of effluent. Regression methods have been successfully used to determine the probability of failure of individual pipes (e.g. Ahmadi et al. 2014b; Chughtai and Zayed 2008; Elmasry, Hawari, and Zayed 2017; Fuchs-Hanusch et al. 2015; Salman and Salem 2012; Tschekner-Gratl et al. 2016b).

Compared to statistical models, machine learning models do not require assumptions about the model structure, they are purely information-driven. Model outputs are classified from a set of input variables by learning from the available data. Their advantage is their ability to identify complex and non-linear relationships between explanatory variables and sewer condition states by ‘learning’ the deterioration behaviour of pipes from inspection data (Scheidegger et al. 2011). Therefore, the knowledge gained on the available inspection data is generalised to non-inspected pipes. Main machine learning methods used as deterioration models are Random Forest (e.g. Harvey and McBean 2014; Laakso et al. 2018; Rokstad and Ugarelli 2015), Support Vector Machines (e.g. Hernández et al. 2018; Mashford et al. 2011; Sousa, Matos, and Matias 2014), and Neural Networks (e.g. Jiang et al. 2016; Sousa, Matos, and Matias 2014; Tran, Ng, and Perera 2007).

The comparison of modelling approaches and performances is not straightforward. This is due to the number and variety of modelling methods, the different type and size of the networks, the different degree of data availability (CCTV and explanatory factors) and the variety of metrics used to assess modelling performance. Model performance can be assessed at two different levels, depending on modelling objective (Ana and Bauwens 2010):

- At the network level, the objective is to simulate the evolution of the condition distribution of the network over time to support long-term strategic rehabilitation planning. The metrics indicate to which extent the model can predict the condition distribution of the entire network, i.e. the proportion of pipes in each condition at a given age.
- At the pipe level, the objective is to identify pipes in critical condition to support inspection and tactical replacement strategies. The metrics verify to which extent the model can correctly predict the inspected condition class of each single pipe.

Few studies evaluated the performance of deterioration models to simulate the condition distribution of the network (Caradot et al. 2017, 2018; Duchesne et al. 2013; Hernández et al. 2018; Ugarelli et al. 2013). They indicated that survival analysis and Markov models outperform a simple random model for predicting the condition distribution of the network, especially in the case of low data availability. Caradot et al. (2018) also showed that statistical models have a clear advantage against machine learning models at the network level when extrapolating beyond the observation window.

Many studies (see Table 3) assessed model performance at the pipe level. Main metrics found are statistical ones (e.g. chi-square statistic, Goodness-of-fit, Root Mean Square Error, Coefficient of determination) and a list of indicators derived from the confusion matrix, including ROC and Lorenz curves (Lorenz 1905). This includes:

- True Positive Rate (TPR), i.e. the percentage of pipes observed in poor condition and correctly predicted in poor condition.
- Positive Predictive Value (PPV), i.e. the percentage of pipes predicted in poor condition, which have been observed in poor condition.
- False-Positive Rate (FPR), i.e. the percentage of pipes observed in good condition and wrongly predicted in poor condition.

It is difficult to outline clear conclusions regarding the best modelling approach at the pipe level as modelling performance is a trade-off between several indicators. Model performance varies considerably between the case studies: to give an order of magnitude, the average PPV is 57% and the average TPV is 64%. However, the benchmark of several models obtained in the same cities showed that the machine learning model seems to outperform statistical models to identify pipes in critical conditions.

Modelling of infiltration, exfiltration and blockages

Several methods have been proposed and applied for quantifying sewer infiltration rates, as already highlighted in the inspection section (Bertrand-Krajewski et al. 2006). The most

commonly used minimal flow approximation is quite simple and practical but has considerable inaccuracies because of its subjective assumptions. On the other hand, mass flux-based analysis has proven to be useful but requires long-term continuous water quality and quantity monitoring, thus its application is limited if several urban sub-catchments are under analysis (Bareš, Stránský, and Sýkora 2012).

Some existing models on exfiltrating of raw wastewater to the pipe surroundings (e.g. Ly and Chui 2012; Vizintin et al. 2009) are primarily focused on the dynamics of the leakage point and typically require unavailable information on aspects such as leak location, leak size, thickness of clogged layer, and hydraulic conductivity of pipe bedding material thus precluding its practical application in most cases (Roehrdanz et al. 2017). Consequently, recent research has proposed simplified methods that do not require prior knowledge of leaking defect locations, based on exfiltration probability scores (Lee et al. 2015) to predict where pipes are likely leaking and contaminating groundwater, thus allowing implementation of water resource protection as planning criterion for sewer asset management (Roehrdanz et al. 2017).

Besides sewer infiltration and exfiltration rates, sediment deposits constitute another important system deterioration factor. Research focused on identifying pipe attributes that are the key variables for the blockage phenomena (e.g. Ugarelli et al. 2009), estimating the time intervals between blockages to identify potential trends in the failure rates (e.g. Jin and Mukherjee 2010) and in preventive maintenance scheduling optimization to minimize costs (e.g. Fontecha et al. 2016). Although promising, these model applications are mainly limited by data availability.

Simulation of asset management strategies implementing costs

Most approaches propose a framework to integrate the simulation of sewer deterioration with additional features such as vulnerability, impact and risk assessment or life cycle cost analysis. Methods taking costs into account aim at defining cost-effective rehabilitation programs. Tactical decisions related to the budgetary effort to be annually devoted to sewer rehabilitation on the midterm (often one decade) must

Table 3. Predictive performance of deterioration models on a pipe level.

Source	Model	Condition assessment	Case Study	Sample size (Training/Test)	PPV	TPR	FPR
Caradot et al. (2018)	RF	DWA	Berlin, Germany	97,547 (60/40)	42%	67%	26%
Salman and Salem (2012)	MLR	PACP	Cincinnati, USA	11,373 (80/20)	53%	73%	29%
	LR			11,373 (80/20)	55%	45%	22%
Hernández et al. (2018)	RF	NS-058	Bogotá, Colombia	4,633 (70/30)	53%	57%	17%
	LR			4,633 (70/30)	60%	38%	7%
	MLR			4,633 (70/30)	-	71%	21%
	LDA			4,633 (70/30)	-	70%	20%
	SVM			4,633 (70/30)	52%	67%	22%
Laakso et al. (2018)	RF	Finnish guidelines	-, Finland	6,700 (70/30)	-	80%	53%
Harvey and McBean (2014)	RF	WRC	Guelph, Canada	1,825 (80/20)	30%	89%	25%
Sousa, Matos, and Matias (2014)	ANN	WRC	Costa do Estoril, Portugal	745 (80/20)	67%	71%	18%
	SVM			745 (80/20)	69%	60%	19%
	LR			745 (80/20)	62%	39%	16%
Mashford et al. (2011)	SVM	-	Adelaide, Australia	1,441 (75/25)	88%	74%	1%
Fuchs-Hanusch et al. (2015)	LR	ISYBAU	-, Austria	4,577 (62/38)	-	60%	35%

Model abbreviations: RF (Random Forest), MLR (Multinomial logistic Regression), LR (Logistic Regression), LDA (Linear Discriminant Analysis), SVM (Support Vector Machine), ANN (Artificial Neural Network).

comply both with strategic objectives related to the performance of the service on the long term (i.e. several decades) as well as operational constraints, which short-term rehabilitation planning must consider. Planning of annual rehabilitation works consists of allocating the available budget to sewer segments:

- based on condition or performance assessment (as described in the second section),
- affected by land management operations that compulsorily involve the segment decommissioning or its change of location,
- or involved in possible coordination, either externally (see the following section) or internally with adjoining sewer segments, to implement sufficiently sized rehabilitation projects.

The question of cost definition and its implementation into the decision-making process is for all these considerations a tricky but essential one.

Costs and benefits

From an economic and financial perspective, both direct and indirect costs and benefits are to be considered when failures of the sewer network occur. Failures and their consequences have significant economic consequences for the sewer system operators. They relate to direct expenses linked to the failure (repair/rehabilitation costs for instance) as well as indirect expenses incurred in carrying out various operating activities (e.g. depreciation on vehicles). These are called 'internal costs'. In addition, street flooding can lead to traffic disruption and damaged homes and public facilities as well as water exfiltration can cause disturbance to residents such as growth of mould in cellars, and odour issues. The question of these indirect or 'social costs' (sometimes called 'externalities'), as defined by Cromwell et al. (2002), which consist in *'inconvenience to customers, disruption of roadway traffic, damage to properties or goods, disruption of business activity, disruption of parallel utilities, human injury [and] impose costs to consumers as well as on society in general'* in addition to impacts on the natural environment, becomes increasingly relevant in recent years (Marlow et al. 2011). The monetarisation of these externalities requires the assessment and definition of tangible, which are quantifiable, and intangible costs, which are more qualitative in nature and not readily quantifiable. One of the first works in this field puts a value on some impacts of malfunctions (Rozan, Rulleau, and Wery 2017), but further researches are required.

Knowing the costs of repairing a failure as part of their operating costs is important for utilities and accounting data provide an idea of the direct cost of a precise task (e.g. repair or renovation techniques) for upcoming operational and tactical planning. In the same way, an objective and accurate assessment of maintenance costs (e.g. flushing or removing a blockage) helps allocating human and machine time and resources. Wery et al. (2017) used job-order costing with homogeneous sections (Vanderbeck 2012), dealing with human and mechanical power (crossing labour time with salary or fuel expenses), to assess cost-splitting between several (sub-)

municipal departments for maintaining green stormwater management measures. This method combines direct and indirect expenses taken from accounting activities and allows to assess the utility cost-effectiveness and to propose possible improvements.

Since externalities lie outside of the market transaction, their price is not directly observable and valuation methods to determine their monetary value are necessary. Cost-based techniques measure the value of impacts based on past events and reconstitute the cost from existing data. In sewer networks' asset management literature, they are often based on other infrastructures. Gilchrist and Allouche (2005) used data from road works studies to estimate the cost of delayed travel time and traffic jams. Similarly, Wery, Janel, and Weber (2003) provided profit/loss ratios usable to activity disruption due to water delivery cut for each specific activity sector or flooding. Regarding protection costs, considering the costs for protection from flooding due to sewer network malfunctions could be an alternative.

Preference-based techniques, like the well-known contingent valuation method (Johnston et al. 2017), are based on people's preferences. Exploring resident's preferences towards sewer network asset management is seldom done, whereas these methods provide important insights for decision-making by (1) providing information about agents' preferences and thus help to design better accepted policies, (2) identifying the variables that influence these preferences (e.g. risk perception), and (3) facilitating better support among users who feel involved in issues (Genius, Menegaki, and Tsagarakis 2012; Rozan, Rulleau, and Wery 2017).

The above-mentioned approaches for internal and external costs and benefits estimation can be used as stand-alone methods or combined in more comprehensive decision-support tools, as indicators in a multi-criteria decision analysis (MCDA) or input for cost-benefit analyses (CBA). In this way, they aid informed decision-making regarding the construction of new sewer systems or sewer maintenance and rehabilitation prioritisation.

Decision making in sewer asset management

The implementation of an advanced asset management policy provides many benefits for a utility. It implies that the utilities construct and update their databases regarding the assets and services provided, as well as the assets' condition. Further, it requires prioritization of the necessary maintenance and rehabilitation activities by considering the performance levels of the infrastructures and by minimizing the assets' failure risks. This involves high-level decision-making activities where the trade-offs of management decisions should be considered. Informed decision-making decreases the probability of catastrophic system failures, major budget surprises and claims from non-performant systems, thus reducing the long-term costs of operations.

However, existing frameworks (e.g. Sægrov 2006) do not take into consideration the whole decision-making practices in daily routines (van Riel et al. 2016). Unaided decision-making relies on many heuristics that affect which information is processed and how, the preference construction process and ultimately the resulting choice. The limited knowledge

about actual operational decision-making impedes determining or improving the cost-effectiveness of urban drainage because decision transparency is required to assess whether decision-making can be improved. Moreover, asset management requires multi-actor negotiation and coordination, as it spans across operational, tactical, and strategic levels within or across organizations. Most of the existing studies are performed on the utility level and little attention has been paid to linking the different decision-making levels to policy or to user preferences. At this level, the perspectives vary from assigning more capital investment to boost the infrastructure's performance to implementing more robust regulatory approaches requiring utilities to define sustainable investment strategies or to emphasize more the role of regulators in requiring a more realistic business plan from utilities (Vinnari and Hukka 2010).

The conversion of existing frameworks and their outcomes into concrete decisions in the utilities is not always straightforward. Decision-making processes, in general, and also in sewer asset management, can be characterised as a series of compromises and negotiations considering the multi-actor characteristics of related issues (Geldof and Stahre 2006). Other influential criteria or the main decision-making factors need to be considered in this complex multi-actor decision-making process. The focus thus far has not been on supporting the process, however, but rather on developing criteria and assessment models that focus on system performance. This can lead to decreasing decision transparency, uptake and potentially cost-effectiveness of the decisions made.

MCDAs aggregation and evaluation modes have been widely applied in sewer asset management (Ana et al. 2009; Carriço et al. 2012; Egger and Maurer 2015). Still, dedicated methods, considering the decision support process and elicitation and inclusion of decision-maker preferences to support decisions, which exist in disciplines, such as operations research and decision analysis, are hardly used in urban drainage. For example, MCDA (see Greco, Ehrgott, and Figueira (2016) for a recent overview), offers an 'umbrella of methods' (Belton and Stewart 2002) that align and integrate indicator assessment and preference modelling into a structured decision support process.

Multi-infrastructure rehabilitation

Sewers are only one of the many urban infrastructures. Amongst others, water and gas distribution networks, district heating, electricity and data communication cables are other underground infrastructures. Roads, parking spaces and urban green are infrastructures on the surface, which interact with, especially, stormwater management. Each of these infrastructures can be assessed at three levels:

- *components level*, usually the focus of inspection and deterioration models.
- *network level*, usually the focus of assessment of system dynamics involving hydraulic modelling and monitoring.
- *urban fabric*, representing the physical form of towns and cities, which supports and structures the underground infrastructures.

Each of the infrastructures has its spatial scale of principal units, e.g. sewer catchment or drinking water district and temporal scales of processes involved in these different systems, e.g. service life of components and networks. Unlike many other infrastructures, sewers also have a direct link to the urban environment during peak storms resulting in urban flooding. Sewers act together with streets of the urban fabric as dual drainage systems. Recent research (van Riel et al. 2016, 2017) has demonstrated that infrastructure managers take different decisions when acting solo or cooperating, even though this may result in an overall increase in costs. Sewers are amongst the most capital-intensive infrastructures on a per length unit cost basis, with the least flexibility in space due to constraints in gradients and the maximum length of house connections. Consequently, most operators of infrastructures can act as an asset manager, while sewer operators also must act as system performance manager.

If the sewer system performs well and requires no upgrading, one can minimise interference with other utilities (e.g. applying trenchless methods). This will enlarge the service life of sewers (although probably less than replacement), without having to pay for the repair and improvement of other infrastructures, such as roads. The drawback of focusing on relining is that the 'upper' part of the sewer system, i.e. the gully pots and house connections, are also not replaced, which will, over time, cause a lot of smaller issues. In this respect, it is important to note that the upper part is responsible for >95% of sewer failures (Post et al. 2016). Another possibility is to wait for other infrastructure managers to act and then join a free ride. This strategy allows the sewer operator to act strategically and minimise costs. Finally, a decent rehabilitation plan and a strategy for replacement of all infrastructures together with all utilities involved can be outlined. This is a strategy where sewer asset management becomes 'urban area management' and where the (often relatively large) budget for sewers is also used to maintain and upgrade urban areas. This strategy, of course, requires knowledge about possible interaction of infrastructures, remaining service life per infrastructure, and risks of damaging other infrastructures during sewer works. This strategy may only work when all utilities are equally aware and transparent about ageing of their infrastructure.

If the sewer system performs moderately to poor with respect to CSOs and hydraulic performance the sewer asset manager needs to take the lead for hydraulic improvement measures. For very local measures, such as building a CSO tank, this may not require a strategy to interact with other utilities, although it should be noticed that effective hydraulic and environmental management of a sewer system is obtained through comprehensive analysis of the global system rather than local behaviour evaluation (Todeschini, Papiri, and Ciapponi 2018). For this reason, the interaction between sewer operators and other utility managers may become even more necessary. For large scale disconnecting of impervious area or transitioning from combined to separate sewers, the sewer operator will have to take the initiative, allowing other utility managers to cheaply replace their infrastructures.

If urban flooding requires significant improvement measures in the sewer and in the urban area, multi-utility involving all relevant actors needs to take place. In this situation, the

overall urban development will dominate the process, limiting the scope for optimising multi-utility rehabilitation. Nonetheless, urban rehabilitation also opens opportunities for restructuring the urban infrastructure to avoid future problems.

Applications of multi-infrastructure rehabilitation in literature

The approach of Carriço et al. (2012) may be used for an integrated approach on a strategic level. The approach of Nafi and Kleiner (2010) focuses on water distribution networks, implementing other infrastructure mainly as a source of cost savings due to coordination. Carey and Lueke (2013) considered three infrastructure networks (roads, sewers and water distribution) but focused on the economic outcome and monetary savings. Another shortcoming is the usage of randomly generated network conditions instead of real existing ones. Marzouk and Osama (2015) applied a fuzzy-logic approach for optimum replacement time of different infrastructure networks (roads, sewers, water, gas and electric cables) on a hypothetical numerical example without geographical component.

Osman (2015) presented a temporal coordination algorithm applying it for the road, sewer and water distribution network of a real-world case study. Inanloo et al. (2016) quantified vulnerabilities and potential impacts on the traffic flow of pipeline networks service failures. Tschekner-Gratl et al. (2015, 2016b) showed a methodology for the integrated prioritisation of different infrastructures. This methodology was adjusted to missing or only recently begun data management and in consequence poor or at best mediocre data quality. Its main aim was to rank, and thereby prioritise, economically viable areas for the rehabilitation of the different networks or for individual networks. van Riel et al. (2017) developed a serious gaming research tool that incorporates both the concepts of information quality and human interaction. Players manage drinking water, gas, sewer and street infrastructures. However, no geographical links were drawn which limits the results in the influence of information quality on rehabilitation decisions, for single- and multi-actor decision-making.

An approach for comparative sustainability assessment of technical alternatives for sewer, water and district heating networks expansion was conducted by Pericault et al. (2018) on a case study considering the preferences of local stakeholders. A similar approach was applied by Bruaset, Rygg, and Sægrov (2018) using a life cycle factor based on cohort survival functions as a proxy for the value of the total expected service life of pipe groups. This resulted in significantly reduced lifetime costs compared to replacement without coordination.

Examples from the literature have primarily focused on optimisation of the rehabilitation at the network level, while also much literature exists of the necessary optimisation and balancing of grey, blue and green infrastructures. Multi-utility network rehabilitation may not necessarily be the first option in this context, depending on the budget and societal implications of such approaches and the importance of the sewer system in such optimisation efforts compared to the other infrastructures. The tipping point for these multi-infrastructure approaches, however, is yet to be determined by future

research, as other asset management decisions that may have nothing to do with the state of the sewer and rather with other considerations may have an overpowering impact.

Conclusion

With aging sewer systems and pressing adaptation decisions at hand, the importance of sewer asset management will increase. The potential of modern techniques to overcome the limitations of visual inspections is substantial, and it is expected that within 5–10 years, the technologies currently developed will be mature and ready for practical applications. Focus should be laid on non-invasive methods for quantifying material's properties, cheap and practical applicable methods for determining the in-situ hydraulic capacity and methods for a continuous status survey of ALL elements in a sewer system. Also, the quest for finding an applicable physical deterioration model instead of the statistical ones, after understanding the physical processes behind the deterioration of sewer pipes, will be an ongoing one.

In other data-intensive disciplines, such as bioinformatics and medical sciences, technical advancements in data collection, storage, transfer and analysis have revolutionised the workflow, creating new opportunities for learning and finding solutions about the processes. In comparison, the value of data for underground urban drainage infrastructure management has not yet been fully realised – clearly, a paradigm shift is necessary: for example, storing and ensuring access to historical data is essential to manage urban drainage infrastructure in a more informed way. The opportunities offered by new technologies (databases and algorithmic processes) and the solutions adopted by other data-intensive sectors should be explored, especially when confronting future challenges in which the need for linking different data sets and platforms can make a difference, i.e. breaking down the professional 'silos' inside the water utilities and among the various stakeholders.

Deterioration models are useful tools to identify pipes in critical condition and long-term investment planning. Survival analysis and Markov models are found to be the most reliable and used approach to simulate sewer deterioration at the network level. Machine learning approaches and statistical regression are found to be the most reliable tools at the pipe level to identify pipes in critical condition. The uncertainties of sewer deterioration modelling have not been investigated in detail so far. First investigations have shown uncertainties in the condition assessment of pipes and their significant impact, but further work is needed to carefully quantify each source of uncertainty, assess more precisely their cumulated propagation in the deterioration models and find practical solutions to mitigate their impact on asset management decisions.

A common limitation of multi-criteria decision analysis applications in sewer asset management is that usually only aggregation and evaluation models are used. As with multi-criteria analysis and indicator assessment, the need for consideration of the decision support process and elicitation and inclusion of decision-maker preferences is often overlooked. These are crucial for successful decision support and another promising area of research in sewer asset management. Also costs and benefits valuations (both direct and indirect)

considering the organisation of the utility and the preferences of the users or inhabitants have still to be developed.

More research should also focus on the possibilities of multi-utility asset management. The few existing approaches have shown promising results. However, they are often based on assumptions on cost-effectiveness of collaboration, e.g. that the additional cost for this coordination, negotiation and shared decision-making will be lower than the savings due to better integration, which has yet to be proven. An integrated economic view on these approaches including further knowledge about internal and external costs or even an interdisciplinary multi-utility life cycle assessment of our infrastructure could help with this issue. Furthermore, interdependencies between the different infrastructures will need further investigation. Finally, studies about rehabilitation management schemes have always the inherent shortcoming of only being representative for the utilized case study and face, therefore, difficulties when generalizing their findings. Also, validating of such approaches proves to be challenging, because no non-influenced comparative scenario exists. Sharing of existing case studies or the construction of benchmarking scenarios should be encouraged.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Franz Tschekner-Gratl  <http://orcid.org/0000-0002-2545-6683>
 Joao P. Leitão  <http://orcid.org/0000-0002-7371-0543>
 Juan Pablo Rodríguez  <http://orcid.org/0000-0001-5647-4385>
 Alfeu Sá Marques  <http://orcid.org/0000-0001-6859-6662>
 Nuno Eduardo Simões  <http://orcid.org/0000-0002-4500-7981>

References

- Ahmadi, M., F. Cherqui, J. C. De Massiac, and P. Le Gauffre. 2014a. "From Sewer Inspection Programmes to Rehabilitation Needs: Research and Results Related to Data Quality and Availability with the Support of Numerical Experiment." *European Journal of Environmental and Civil Engineering* 18: 1145–1156. doi:10.1080/19648189.2014.893212.
- Ahmadi, M., F. Cherqui, J. C. De Massiac, and P. Le Gauffre. 2014b. "Influence of Available Data on Sewer Inspection Program Efficiency." *Urban Water Journal* 11: 641–656. doi:10.1080/1573062X.2013.831910.
- Ahmadi, M., F. Cherqui, J. C. de Massiac, C. Wery, S. Lagoutte, and P. Le Gauffre. 2014c. "Condition Grading for Dysfunction Indicators in Sewer Asset Management." *Structure and Infrastructure Engineering* 10: 346–358. doi:10.1080/15732479.2012.756916.
- Ana, E. V., and W. Bauwens. 2010. "Modeling the Structural Deterioration of Urban Drainage Pipes: The State-of-the-Art in Statistical Methods." *Urban Water Journal* 7: 47–59. doi:10.1080/15730620903447597.
- Ana, E. V., W. Bauwens, M. Pessemer, C. Thoeys, S. Smolders, I. Boonen, and G. de Gueldre. 2009. "An Investigation of the Factors Influencing Sewer Structural Deterioration." *Urban Water Journal* 6: 303–312. doi:10.1080/15730620902810902.
- Anbari, M. J., M. Tabesh, and A. Roozbahani. 2017. "Risk Assessment Model to Prioritize Sewer Pipes Inspection in Wastewater Collection Networks." *Journal of Environmental Management* 190: 91–101. doi:10.1016/j.jenvman.2016.12.052.
- Arbeitshilfen Abwasser. 2018. *Arbeitshilfen Abwasser - Planung, Bau und Betrieb von abwassertechnischen Anlagen in Liegenschaften des Bundes*. Berlin, Germany: Bundesministerium des Innern, für Bau und Heimat.
- ATV-M 143-2. 1999. *Optische Inspektion -inspektion, Instandsetzung, Sanierung und Erneuerung Von Abwasserkanälen und -leitungen* [Visual Inspection - Inspection, Renovation, Replacement and Rehabilitation of Sewers]. Hennef, Germany: Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V.
- Baah, K., B. Dubej, R. R. Harvey, and E. A. McBean. 2015. "A Risk-Based Approach to Sanitary Sewer Pipe Asset Management." *Science of the Total Environment* 505: 1011–1017. doi:10.1016/j.scitotenv.2014.10.040.
- Bareš, V., D. Stránský, and P. Sýkora. 2012. "Evaluation of Sewer Infiltration/Inflow Using COD Mass Flux Method: Case Study in Prague." *Water Science and Technology* 66: 673–680. doi:10.2166/wst.2012.229.
- Belton, V., and T. Stewart. 2002. *Multiple Criteria Decision Analysis - An Integrated Approach*. 1st ed. Kluwer Academic Publishers. doi:10.1007/978-1-4615-1495-4.
- Berger, C., C. Falk, F. Hetzel, J. Pinnekamp, S. Roder, and J. Ruppelt. 2016. "State of the Sewer System in Germany - Results of the DWA Survey 2015." *KA Korrespondenz Abwasser, Abfall* 63: 15–17.
- Bertrand-Krajewski, J.-L., M. A. Cardoso, B. Ellis, T. Frehmann, M. Giulianielli, W. Gujer, P. Krebs, Z. Pliska, J. Pollert, and K. Pyl. 2006. "Towards a Better Knowledge and Management of Infiltration and Exfiltration in Sewer Systems: The APUSS Project." *Water Practice and Technology* 1. doi:10.2166/wpt.2006021.
- Bruaset, S., H. Rygg, and S. Sægrov. 2018. "Reviewing the Long-term Sustainability of Urban Water System Rehabilitation Strategies with an Alternative Approach." *Sustainability* 10: 1987. doi:10.3390/su10061987.
- Caradot, N., M. Riechel, M. Fesneau, N. Hernández, A. Torres, H. Sonnenberg, E. Eckert, N. Lengemann, J. Waschnewski, and P. Rouault. 2018. "Practical Benchmarking of Statistical and Machine Learning Models for Predicting the Condition of Sewer Pipes in Berlin, Germany." *Journal of Hydroinformatics* 20: 1131–1147. doi:10.2166/hydro.2018.217.
- Caradot, N., H. Sonnenberg, I. Kropp, A. Ringe, S. Denhez, A. Hartmann, and P. Rouault. 2017. "The Relevance of Sewer Deterioration Modelling to Support Asset Management Strategies." *Urban Water Journal* 14: 1007–1015. doi:10.1080/1573062X.2017.1325497.
- Carey, B. D., and J. S. Lueke. 2013. "Optimized Holistic Municipal Right-of-way Capital Improvement Planning." *Canadian Journal of Civil Engineering* 40: 1244–1251. doi:10.1139/cjce-2012-0183.
- Carrara, W., C. Radu, and H. Vollers. 2017. "Open Data Maturity in Europe 2017." *European Commission, Directorate-General of Communications Networks, Content & Technology*.
- Carriço, N., D. I. C. Covas, M. Céu Almeida, J. P. Leitão, and H. Alegre. 2012. "Prioritization of Rehabilitation Interventions for Urban Water Assets Using Multiple Criteria Decision-aid Methods." *Water Science and Technology* 66: 1007–1014. doi:10.2166/wst.2012.274.
- Carvalho, G., C. Amado, R. S. Brito, S. T. Coelho, and J. P. Leitão. 2018. "Analysing the Importance of Variables for Sewer Failure Prediction." *Urban Water Journal* 15: 338–345. doi:10.1080/1573062X.2018.1459748.
- Cashman, A., and R. M. Ashley. 2008. "Costing the Long-term Demand for Water Sector Infrastructure." *Foresight* 10: 9–26. doi:10.1108/14636680810883099.
- Chughtai, F., and T. Zayed. 2008. "Infrastructure Condition Prediction Models for Sustainable Sewer Pipelines." *Journal of Performance of Constructed Facilities* 22: 333–341. doi:10.1061/(ASCE)0887-3828(2008)22:5(333).
- Chughtai, F., and T. Zayed. 2011. "Integrating WRc and CERIU Condition Assessment Models and Classification Protocols for Sewer Pipelines." *Journal of Infrastructure Systems* 17: 129–136. doi:10.1061/(ASCE)IS.1943-555X.0000052.
- Clemens, F. H. L. R., N. Stanić, W. Van der Schoot, J. G. Langeveld, and M. Lepot. 2015. "Uncertainties Associated with Laser Profiling of Concrete Sewer Pipes for the Quantification of the Interior Geometry." *Structure and Infrastructure Engineering* 11: 1218–1239. doi:10.1080/15732479.2014.945466.
- Cromwell, J. E., H. Reynolds, N. Pearson, and M. Grant. 2002. *Costs of Infrastructure Failure*. Denver, CO: AWWA.
- Debères, P., M. Ahmadi, J. C. De Massiac, P. Le Gauffre, F. Cherqui, C. Wery, and K. Nirsimloo. 2011. "Deploying a Sewer Asset Management Strategy Using the INDIGAU Decision Support System." In *4th Leading-Edge Conference on Strategic Asset Management (LESAM)*. Mülheim, Germany: International Water Association.

- Dirksen, J., F. H. L. R. Clemens, H. Korving, F. Cherqui, P. Le Gauffre, T. Ertl, H. Plihal, K. Müller, and C. T. M. Snaterse. 2013. "The Consistency of Visual Sewer Inspection Data." *Structure and Infrastructure Engineering* 9: 214–228. doi:10.1080/15732479.2010.541265.
- Duchesne, S., G. Beardsell, J.-P. Villeneuve, B. Toumbou, and K. Bouchard. 2013. "A Survival Analysis Model for Sewer Pipe Structural Deterioration." *Computer-Aided Civil and Infrastructure Engineering* 28: 146–160. doi:10.1111/j.1467-8667.2012.00773.x.
- DWA-M 149-7. 2016. *Zustandserfassung und -beurteilung von Entwässerungssystemen außerhalb von Gebäuden - Teil 7: Beurteilung der Umweltrelevanz des baulichen/betrieblichen Zustands* [Condition assessment and classification of urban drainage systems outside of buildings]. Hennef, Germany: Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V.
- DWA-Themen T4. 2012. *Leitfaden zur strategischen Sanierungsplanung von Entwässerungssystemen außerhalb von Gebäuden* [Guideline on strategic rehabilitation planning of urban drainage systems outside of buildings]. Hennef, Germany: Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V.
- Egger, C., and M. Maurer. 2015. "Importance of Anthropogenic Climate Impact, Sampling Error and Urban Development in Sewer System Design." *Water Research* 73: 78–97. doi:10.1016/j.watres.2014.12.050.
- Egger, C., A. Scheidegger, P. Reichert, and M. Maurer. 2013. "Sewer Deterioration Modeling with Condition Data Lacking Historical Records." *Water Research* 47: 6762–6779. doi:10.1016/j.watres.2013.09.010.
- Elmasry, M., A. Hawari, and T. Zayed. 2017. "Defect Based Deterioration Model for Sewer Pipelines Using Bayesian Belief Networks." *Canadian Journal of Civil Engineering* 44: 675–690. doi:10.1139/cjce-2016-0592.
- Elsawah, H., I. Bakry, and O. Moselhi. 2016. "Decision Support Model for Integrated Risk Assessment and Prioritization of Intervention Plans of Municipal Infrastructure." *Journal of Pipeline Systems Engineering and Practice* 7: 04016010. doi:10.1061/(ASCE)PS.1949-1204.0000245.
- EN 13508-2. 2011. *Condition of Drain and Sewer Systems outside Buildings – Part 2: Visual Inspection Coding System*. Brussels, Belgium: European Committee for Standardization.
- EN 752. 2017. *Drain and Sewer Systems Outside Buildings*. Brussels, Belgium: European Committee for Standardization.
- Ennaouri, I., and M. Fuamba. 2013. "New Integrated Condition-assessment Model for Combined Storm-Sewer Systems." *Journal of Water Resources Planning and Management* 139: 53–64. doi:10.1061/(ASCE)WR.1943-5452.0000217.
- Farrelly, M., and P. M. Bach. 2018. "Response to the DELWP Issues Paper for the Improving Stormwater Management Advisory Committee." June.
- Fontecha, J. E., R. Akhavan-Tabatabaei, D. Duque, A. L. Medaglia, M. N. Torres, and J. P. Rodríguez. 2016. "On the Preventive Management of Sediment-Related Sewer Blockages: A Combined Maintenance and Routing Optimization Approach." *Water Science and Technology* 74: 302–308. doi:10.2166/wst.2016.160.
- Frangopol, D. M. 2011. "Life-Cycle Performance, Management, and Optimisation of Structural Systems under Uncertainty: Accomplishments and Challenges." *Structure and Infrastructure Engineering* 7: 389–413. doi:10.1080/15732471003594427.
- Fuchs-Hanusch, D., M. Günther, M. Möderl, and D. Muschalla. 2015. "Cause and Effect Oriented Sewer Degradation Evaluation to Support Scheduled Inspection Planning." *Water Science and Technology* 72: 1176–1183. doi:10.2166/wst.2015.320.
- Geldof, G. D., and P. Stahre. 2006. "On the Road to A New Stormwater Planning Approach: From Model A to Model B." *Water Practice and Technology* 1. doi:10.2166/wpt.2006005.
- Genius, M., A. N. Menegaki, and K. P. Tsagarakis. 2012. "Assessing Preferences for Wastewater Treatment in a Rural Area Using Choice Experiments." *Water Resources Research* 48. doi:10.1029/2011WR010727.
- Gilchrist, A., and E. N. Allouche. 2005. "Quantification of Social Costs Associated with Construction Projects: State-of-the-art Review." *Tunnelling and Underground Space Technology* 20: 89–104. doi:10.1016/j.tust.2004.04.003.
- Greco, S., M. Ehr Gott, and J. R. Figueira. 2016. *Multiple Criteria Decision Analysis - State of the Art Surveys*. 2nd ed. New York, NY: Springer-Verlag. doi:10.1007/978-1-4939-3094-4.
- Hahn, M. A., R. N. Palmer, M. S. Merrill, and A. B. Lukas. 2002. "Expert System for Prioritizing the Inspection of Sewers: Knowledge Base Formulation and Evaluation." *Journal of Water Resources Planning and Management* 128: 121–129. doi:10.1061/(ASCE)0733-9496(2002)128:2(121).
- Halfawy, M. R., L. Dridi, and S. Baker. 2008. "Integrated Decision Support System for Optimal Renewal Planning of Sewer Networks." *The Journal of Computing in Civil Engineering* 22: 360–372. doi:10.1061/(ASCE)0887-3801(2008)22:6(360).
- Hao, T., C. D. F. Rogers, N. Metje, D. N. Chapman, J. M. Muggleton, K. Y. Foo, P. Wang, et al. 2012. "Condition Assessment of the Buried Utility Service Infrastructure." *Tunnelling and Underground Space Technology* 28: 331–344. doi:10.1016/j.tust.2011.10.011.
- Harris, R. J., and C. Dobson. 2006. "Sewer Pipe Infiltration Assessment: Comparison of Electro-Scan, Joint Pressure Testing, and CCTV Inspection." In *Pipelines 2006*. doi:10.1061/40854(211)61
- Hartley, R., and A. Zisserman. 2003. *Multiple View Geometry in Computer Vision, 2nd Ed.* Cambridge, UK: Cambridge University Press.
- Harvey, R. R., and E. A. McBean. 2014. "Predicting the Structural Condition of Individual Sanitary Sewer Pipes with Random Forests." *Canadian Journal of Civil Engineering* 41: 294–303. doi:10.1139/cjce-2013-0431.
- Hernández, N., N. Caradot, H. Sonnenberg, P. Rouault, and A. Torres. 2018. "Support Tools to Predict the Critical Structural Condition of Uninspected Pipes for Case Studies of Germany and Colombia." *Water Practice and Technology* 13: 794–802. doi:10.2166/wpt.2018.085.
- Hoes, O. A. C., R. P. S. Schilperoord, W. M. J. Luxemburg, F. H. L. R. Clemens, and N. C. van de Giesen. 2009. "Locating Illicit Connections in Storm Water Sewers Using Fiber-optic Distributed Temperature Sensing." *Water Research* 43: 5187–5197. doi:10.1016/j.watres.2009.08.020.
- Horoshenkov, K. V., R. J. Long, and S. J. Tait. 2010. Improvements in and relating to apparatus for the airborne acoustic inspection of pipes. Patent WO/2010/020817.
- Hukka, J. J., and T. S. Katko. 2015. "Resilient Asset Management and Governance for Deteriorating Water Services Infrastructure." *Procedia Economics and Finance* 21: 112–119. doi:10.1016/s2212-5671(15)00157-4.
- Inanloo, B., B. Tansel, K. Shams, X. Jin, and A. Gan. 2016. "A Decision Aid GIS-based Risk Assessment and Vulnerability Analysis Approach for Transportation and Pipeline Networks." *Safety Science* 84: 57–66. doi:10.1016/j.ssci.2015.11.018.
- ISO 24765. 2017. *Systems and Software Engineering - Vocabulary*. Geneva, Switzerland: International Organization for Standardization.
- ISO 55000. 2014. *Asset Management - Overview, Principles and Terminology*. Switzerland: Geneva.
- Janssen, M., Y. Charalabidis, and A. Zuiderwijk. 2012. "Benefits, Adoption Barriers and Myths of Open Data and Open Government." *Information Systems Management* 29: 258–268. doi:10.1080/10580530.2012.716740.
- Jiang, G., J. Keller, P. L. Bond, and Z. Yuan. 2016. "Predicting Concrete Corrosion of Sewers Using Artificial Neural Network." *Water Research* 92: 52–60. doi:10.1016/j.watres.2016.01.029.
- Jin, Y., and A. Mukherjee. 2010. "Modeling Blockage Failures in Sewer Systems to Support Maintenance Decision Making." *Journal of Performance of Constructed Facilities* 24: 622–633. doi:10.1061/(ASCE)CF.1943-5509.0000126.
- Johnston, R. J., K. J. Boyle, W. Adamowicz, J. Bennett, R. Brouwer, T. A. Cameron, W. M. Hanemann, et al. 2017. "Contemporary Guidance for Stated Preference Studies." *Journal of the Association of Environmental and Resource Economists* 4: 319–405. doi:10.1086/691697.
- Khazraeializadeh, S., L. F. Gay, and A. Bayat. 2014. "Comparative Analysis of Sewer Physical Condition Grading Protocols for the City of Edmonton." *Canadian Journal of Civil Engineering* 41: 811–818. doi:10.1139/cjce-2014-0077.
- Kirkham, R., P. D. Kearney, K. J. Rogers, and J. Mashford. 2000. "PIRAT - a System for Quantitative Sewer Pipe Assessment." *The International Journal of Robotics Research* 19: 1033–1053. doi:10.1177/02783640022067959.
- Kleidorfer, M., M. Möderl, F. Tschekner-Gratl, M. Hammerer, H. Kinzel, and W. Rauch. 2013. "Integrated Planning of Rehabilitation Strategies for Sewers." *Water Science and Technology* 68: 176–183. doi:10.2166/wst.2013.223.
- Kley, G., I. Kropp, T. Schmidt, and N. Caradot. 2013. *SEMA D1.1 - Review of Available Technologies and Methodologies for Sewer Condition Evaluation*. Berlin, Germany: Kompetenzzentrum Wasser Berlin.
- Korving, H., J. M. van Noortwijk, P. H. A. J. M. van Gelder, and F. H. L. R. Clemens. 2009. "Risk-based Design of Sewer System

- Rehabilitation." *Structure and Infrastructure Engineering* 5: 215–227. doi:10.1080/15732470601114299.
- KPC (Kommunalkredit Public Consulting). 2017. *Zahlen & Fakten: Umweltinvestitionen des Bundes 2017* [Facts and Number: Federal environmental investments]. Vienna, Austria: Kommunalkredit Public Consulting GmbH.
- Kuliczowska, E. 2016. "Risk of Structural Failure in Concrete Sewers Due to Internal Corrosion." *Engineering Failure Analysis* 66: 110–119. doi:10.1016/j.engfailanal.2016.04.026.
- Kumar, S. S., D. M. Abraham, M. R. Jahanshahi, T. Iseley, and J. Starr. 2018. "Automated Defect Classification in Sewer Closed Circuit Television Inspections Using Deep Convolutional Neural Networks." *Automation in Construction* 91: 273–283. doi:10.1016/j.autcon.2018.03.028.
- Kuntze, H. B., and H. Haffner. 1998. "Experiences with the Development of a Robot for Smart Multisensoric Pipe Inspection." In *Proceedings - IEEE International Conference on Robotics and Automation*, 1773–1778. doi:10.1109/ROBOT.1998.677423
- Laakso, T., T. Kokkonen, I. Mellin, and R. Vahala. 2018. "Sewer Condition Prediction and Analysis of Explanatory Factors." *Water* 10: 1239. doi:10.3390/w10091239.
- Le Gat, Y. 2008. "Modelling the Deterioration Process of Drainage Pipelines." *Urban Water Journal* 5: 97–106. doi:10.1080/15730620801939398.
- Le Gauffre, P., C. Joannis, E. Vasconcelos, D. Breyse, C. Gibello, and -J.-J. Desmulliez. 2007. "Performance Indicators and Multicriteria Decision Support for Sewer Asset Management." *Journal of Infrastructure Systems* 13: 105–114. doi:10.1061/(ASCE)1076-0342(2007)13:2(105).
- Lee, D. G., P. R. Roehrdanz, M. Feraud, J. Ervin, T. Anumol, A. Jia, M. Park, et al. 2015. "Wastewater Compounds in Urban Shallow Groundwater Wells Correspond to Exfiltration Probabilities of Nearby Sewers." *Water Research* 85: 467–475. doi:10.1016/j.watres.2015.08.048.
- Lepot, M., K. F. Makris, and F. H. L. R. Clemens. 2017a. "Detection and Quantification of Lateral, Illicit Connections and Infiltration in Sewers with Infra-Red Camera: Conclusions after a Wide Experimental Plan." *Water Research* 122: 678–691. doi:10.1016/j.watres.2017.06.030.
- Lepot, M., T. Pouzol, X. Aldea Borrueal, D. Suner, and J.-L. Bertrand-Krajewski. 2017b. "Measurement of Sewer Sediments with Acoustic Technology: From Laboratory to Field Experiments." *Urban Water Journal* 14: 369–377. doi:10.1080/1573062X.2016.1148181.
- Lepot, M., N. Stanić, and F. H. L. R. Clemens. 2017c. "A Technology for Sewer Pipe Inspection (Part 2): Experimental Assessment of A New Laser Profiler for Sewer Defect Detection and Quantification." *Automation in Construction* 73: 1–11. doi:10.1016/j.autcon.2016.10.010.
- Lesage, M. 2013. *Rapport D'évaluation De La Politique De L'eau En France* [Evaluation Report on the Water Related Politics in France]. Paris, France: Mission d'évaluation de la politique de l'eau.
- Lorenz, M. O. 1905. "Methods of Measuring the Concentration of Wealth." *Publications of the American Statistical Association* 9: 209–219.
- Ly, D. K., and T. F. M. Chui. 2012. "Modeling Sewage Leakage to Surrounding Groundwater and Stormwater Drains." *Water Science and Technology* 66: 2659–2665. doi:10.2166/wst.2012.496.
- Marlow, D. R., D. J. Beale, and S. Burn. 2010. "A Pathway to A More Sustainable Water Sector: Sustainability-based Asset Management." *Water Science and Technology* 61: 1245–1255. doi:10.2166/wst.2010.043.
- Marlow, D. R., P. Davis, D. Trans, D. J. Beale, and S. Burn. 2009. *Remaining Asset Life: A State of the Art Review, Final Report*. Alexandria, VA: Water Environment Research Fundation (WERF).
- Marlow, D. R., L. Pearson, D. H. MacDonald, S. Whitten, and S. Burn. 2011. "A Framework for considering Externalities in Urban Water Asset Management." *Water Science and Technology* 64: 2199–2206. doi:10.2166/wst.2011.789.
- Marzouk, M., and A. Osama. 2015. "Fuzzy Approach for Optimum Replacement Time of Mixed Infrastructures." *Civil Engineering and Environmental Systems* 32: 269–280. doi:10.1080/10286608.2014.1002715.
- Mashford, J., D. R. Marlow, D. H. Tran, and R. May. 2011. "Prediction of Sewer Condition Grade Using Support Vector Machines." *The Journal of Computing in Civil Engineering* 25: 283–290. doi:10.1061/(ASCE)CP.1943-5487.0000089.
- Meijer, D., L. Scholten, F. Clemens, and A. Knobbe. 2019. "A Defect Classification Methodology for Sewer Image Sets with Convolutional Neural Networks." *Automation in Construction* 104: 281–298. doi:10.1016/j.autcon.2019.04.013.
- Micevski, T., G. Kuczera, and P. Coombes. 2002. "Markov Model for Storm Water Pipe Deterioration." *Journal of Infrastructure Systems* 8: 49–56. doi:10.1061/(ASCE)1076-0342(2002)8:2(49).
- Myrans, J., R. Everson, and Z. Kapelan. 2018. "Automated Detection of Faults in Sewers Using CCTV Image Sequences." *Automation in Construction* 95: 64–71. doi:10.1016/j.autcon.2018.08.005.
- Nafi, A., and Y. Kleiner. 2010. "Scheduling Renewal of Water Pipes while considering Adjacency of Infrastructure Works and Economies of Scale." *Journal of Water Resources Planning and Management* 136: 519–530. doi:10.1061/(ASCE)WR.1943-5452.0000062.
- NASSCO. 2016. *Pipeline Assessment Certification Program (PACP)*. Frederick, MD, USA: National Association of Sewer service Companies.
- Neunteufel, R., T. Ertl, A. Spindler, A. Lukas, R. Perfler, D. Schwarz, M. Zessner, and R. Haberl. 2012. *Technische Herausforderungen in Der Siedlungswasserwirtschaft* [Technical Challenges for the Water Industry]. Vienna, Austria: Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Sektion VII Wasser.
- Nienhuis, J., C. De Haan, J. G. Langeveld, M. Klootwijk, and F. H. L. R. Clemens. 2013. "Assessment of Detection Limits of Fiber-Optic Distributed Temperature Sensing for Detection of Illicit Connections." *Water Science and Technology* 67: 2712–2718. doi:10.2166/wst.2013.176.
- Oliveira, D., W. Guo, L. Soibelman, and J. H. Garrett Jr.. 2007. "Spatial Data Management and Analysis in Sewer Systems' Condition Assessment: An Overview." In *International Workshop on Computing in Civil Engineering*, 391–398. Pittsburgh, PA. doi:10.1061/40937(261)48.
- Oosterom, E., and R. Hermans. 2013. *Riolering in Beeld - Benchmark Rioleringszorg 2013 (Urban Drainage in Focus - Benchmark)*. Utrecht, The Netherlands: Stichting RIONED.
- Osman, H. 2015. "Coordination of Urban Infrastructure Reconstruction Projects." *Structure and Infrastructure Engineering* 12: 108–121. doi:10.1080/15732479.2014.995677.
- ÖWAV-RB 22. 2015. *Betrieb Von Kanalisationsanlagen* [Operation of Urban Drainage Systems]. Vienna, Austria: Österreichischer Wasser- und Abfallwirtschaftsverband.
- Pericaul, Y., E. Kärrman, M. Viklander, and A. Hedström. 2018. "Expansion of Sewer, Water and District Heating Networks in Cold Climate Regions: An Integrated Sustainability Assessment." *Sustainability* 10: 3743. doi:10.3390/su10103743.
- Plihal, H., F. Kretschmer, M. T. Bin Ali, C. H. See, A. Romanova, K. V. Horoshenkov, and T. Ertl. 2016. "A Novel Method for Rapid Inspection of Sewer Networks: Combining Acoustic and Optical Means." *Urban Water Journal* 13: 3–14. doi:10.1080/1573062X.2015.1076857.
- Post, J., I. Pothof, M.-C. Ten Veldhuis, J. G. Langeveld, and F. H. L. R. Clemens. 2016. "Statistical Analysis of Lateral House Connection Failure Mechanisms." *Urban Water Journal* 13: 69–80. doi:10.1080/1573062X.2015.1057175.
- Rajani, B., and Y. Kleiner. 2001. "Comprehensive Review of Structural Deterioration of Water Mains: Physically Based Models." *Urban Water* 3: 151–164. doi:10.1016/S1462-0758(01)00033-4.
- Rieckermann, J., V. Bareš, O. Kracht, D. Braun, and W. Gujer. 2007. "Estimating Sewer Leakage from Continuous Tracer Experiments." *Water Research* 41: 1960–1972. doi:10.1016/j.watres.2007.01.024.
- RIONED. 2017. *Gegevenswoordenboek Stedelijk Water* [Data Dictionary Urban Water]. Ede, The Netherlands: GWSW. <https://www.riool.net/gegevenswoordenboek-stedelijk-water>.
- Roehrdanz, P. R., M. Feraud, D. G. Lee, J. C. Means, S. A. Snyder, and P. A. Holden. 2017. "Spatial Models of Sewer Pipe Leakage Predict the Occurrence of Wastewater Indicators in Shallow Urban Groundwater." *Environmental Science & Technology* 51: 1213–1223. doi:10.1021/acs.est.6b05015.
- Roghani, B., F. Cherqui, M. Ahmadi, P. Le Gauffre, and M. Tabesh. 2019. "Dealing with Uncertainty in Sewer Condition Assessment: Impact on Inspection Programs." *Automation in Construction* 103: 117–126. doi:10.1016/j.autcon.2019.03.012.
- Rokstad, M. M., and R. M. Ugarelli. 2015. "Evaluating the Role of Deterioration Models for Condition Assessment of Sewers." *Journal of Hydroinformatics* 17: 789–804. doi:10.2166/hydro.2015.122.
- Rokstad, M. M., and R. M. Ugarelli. 2016. "Improving the Benefits of Sewer Condition Deterioration Modelling through Information Content

- Analysis." *Water Science and Technology* 74: 2270–2279. doi:10.2166/wst.2016.419.
- Rozan, A., B. Rulleau, and C. Wery. 2017. "Assessing Preferences for Sewer Network Asset Management in France." *International Journal of Environmental Technology and Management* 21: 163–182. doi:10.1504/IJETM.2017.089644.
- Sægrov, S. 2006. *Care-S: Computer Aided Rehabilitation of Sewer and Storm Water Networks*. London, UK: IWA Publishing. ISBN: 9781780402390.
- Salman, B., and O. Salem. 2012. "Risk Assessment of Wastewater Collection Lines Using Failure Models and Criticality Ratings." *Journal of Pipeline Systems Engineering and Practice* 3: 68–76. doi:10.1061/(ASCE)PS.1949-1204.0000100.
- Scheidegger, A., T. Hug, J. Rieckermann, and M. Maurer. 2011. "Network Condition Simulator for Benchmarking Sewer Deterioration Models." *Water Research* 45: 4983–4994. doi:10.1016/j.watres.2011.07.008.
- Scheller, H., and S. Schneider. 2016. *KfW-Kommunalpanel 2016* [KfW - Municipal Panel]. Frankfurt a. M., Germany: KfW Bankengruppe.
- Sousa, V., J. P. Matos, and N. Matias. 2014. "Evaluation of Artificial Intelligence Tool Performance and Uncertainty for Predicting Sewer Structural Condition." *Automation in Construction* 44: 84–91. doi:10.1016/j.autcon.2014.04.004.
- Stanić, N., J. G. Langeveld, T. Salet, and F. H. L. R. Clemens. 2017. "Relating the Structural Strength of Concrete Sewer Pipes and Material Properties Retrieved from Core Samples." *Structure and Infrastructure Engineering* 13: 637–665. doi:10.1080/15732479.2016.1187631.
- Stegemann, B., J. G. Langeveld, T. Bogaard, and F. H. L. R. Clemens. 2018. "Detection of Exfiltration in Sewer Systems with Tracers." In *UDM 2018: New Trends in Urban Drainage Modelling*, edited by G. Mannina, 820–824. Basel, Switzerland: Springer Nature Switzerland AG. ISBN: 978-3-319-99867-1.
- Thompson, S., B. Kulesa, and A. Luckman. 2012. "Integrated Electrical Resistivity Tomography (ERT) and Self-potential (SP) Techniques for Assessing Hydrological Processes within Glacial Lake Moraine Dams." *Journal of Glaciology* 58: 849–858. doi:10.3189/2012JoG11J235.
- Todeschini, S., S. Papiri, and C. Ciaponi. 2018. "Placement Strategies and Cumulative Effects of Wet-weather Control Practices for Intermunicipal Sewerage Systems." *Water Resources Management* 32: 2885–2900. doi:10.1007/s11269-018-1964-y.
- Tran, D. H., A. W. M. Ng, and B. J. C. Perera. 2007. "Neural Networks Deterioration Models for Serviceability Condition of Buried Stormwater Pipes." *Engineering Applications of Artificial Intelligence* 20: 1144–1151. doi:10.1016/j.engappai.2007.02.005.
- Tscheikner-Gratl, F. 2016. *Integrated Approach for Multi-utility Rehabilitation Planning of Urban Water Infrastructure*. 1st ed. Innsbruck, Austria: Innsbruck University Press. ISBN: 978-3-903122-05-5.
- Tscheikner-Gratl, F., M. Hammerer, W. Rauch, C. Mikovits, and M. Kleidorfer. 2013. "Integrated Rehabilitation Management for Different Infrastructure Sectors." *gwf-Wasser|Abwasser Special 1*: 50–56.
- Tscheikner-Gratl, F., C. Mikovits, W. Rauch, and M. Kleidorfer. 2014. "Adaptation of Sewer Networks Using Integrated Rehabilitation Management." *Water Science & Technology* 70: 1847–1856. doi:10.2166/wst.2014.353.
- Tscheikner-Gratl, F., R. Sitzenfrei, W. Rauch, and M. Kleidorfer. 2016a. "Enhancement of Limited Water Supply Network Data for Deterioration Modelling and Determination of Rehabilitation Rate." *Structure and Infrastructure Engineering* 12: 366–380. doi:10.1080/15732479.2015.1017730.
- Tscheikner-Gratl, F., R. Sitzenfrei, W. Rauch, and M. Kleidorfer. 2016b. "Integrated Rehabilitation Planning of Urban Infrastructure Systems Using a Street Section Priority Model." *Urban Water Journal* 13: 28–40. doi:10.1080/1573062X.2015.1057174.
- Tscheikner-Gratl, F., R. Sitzenfrei, C. Stibernitz, W. Rauch, and M. Kleidorfer. 2015. "Integrated Rehabilitation Management by Prioritization of Rehabilitation Areas for Small and Medium Sized Municipalities." In *World Environmental and Water Resources Congress 2015: Floods, Droughts, and Ecosystems - Proceedings of the 2015 World Environmental and Water Resources Congress*, 2045–2057. doi:10.1061/9780784479162.201
- Ugarelli, R. M., S. M. Kristensen, J. Røstum, S. Sægrov, and V. Di Federico. 2009. "Statistical Analysis and Definition of Blockages-prediction Formulae for the Wastewater Network of Oslo by Evolutionary Computing." *Water Science and Technology* 59: 1457–1470. doi:10.2166/wst.2009.152.
- Ugarelli, R. M., I. Selseth, Y. Le Gat, J. Røstum, and A. H. Krogh. 2013. "Wastewater Pipes in Oslo: From Condition Monitoring to Rehabilitation Planning." *Water Practice and Technology* 8: 487–494. doi:10.2166/wpt.2013.051.
- Van Bijnen, M., H. Korving, and F. H. L. R. Clemens. 2012. "Impact of Sewer Condition on Urban Flooding: An Uncertainty Analysis Based on Field Observations and Monte Carlo Simulations on Full Hydrodynamic Models." *Water Science and Technology* 65: 2219–2227. doi:10.2166/wst.2012.134.
- van Riel, W., J. Post, J. G. Langeveld, P. M. Herder, and F. H. L. R. Clemens. 2017. "A Gaming Approach to Networked Infrastructure Management." *Structure and Infrastructure Engineering* 13: 855–868. doi:10.1016/j.watres.2011.07.008.
- van Riel, W., E. van Bueren, J. G. Langeveld, P. M. Herder, and F. H. L. R. Clemens. 2016. "Decision-making for Sewer Asset Management: Theory and Practice." *Urban Water Journal* 13: 57–68. doi:10.1080/1573062X.2015.1011667.
- Vanderbeck, E. 2012. *Principles of Cost Accounting*. 16th ed. Mason, OH, USA: South-Western College Pub.
- Vanier, D. J., and S. Rahman. 2004. *MIIIP Report: A Primer on Municipal Infrastructure Asset Management*. NRC - National Research Council Canada. doi:10.4224/20377283.
- Vinnari, E. M., and J. J. Hukka. 2010. "An International Comparison of the Institutional Governance of Water Utility Asset Management and Its Implications for Finland." *Water Policy* 12: 52–69. doi:10.2166/wp.2009.115.
- Vizintin, G., P. Souvent, M. Veselić, and B. Cencur Curk. 2009. "Determination of Urban Groundwater Pollution in Alluvial Aquifer Using Linked Process Models considering Urban Water Cycle." *Journal of Hydrology* 377: 261–273. doi:10.1016/j.jhydrol.2009.08.025.
- VSA-DSS. 2014. *Datenstruktur Siedlungsentwässerung* [Data Structure Urban Water]. Glattbrugg, Switzerland: VSA.
- Wasson, C. S. 2016. *System Engineering Analysis, Design, and Development: Concepts, Principles, and Practices*. Hoboken, NJ, USA: John Wiley & Sons, Inc. ISBN: 9781118442265
- Wery, C., F. Cherqui, N. Le Nouveau, R. Garnier, T. D. Fletcher, S. Barraud, and P. Le Gauffre. 2017. "Research and Operational Needs to Improve the Asset Management of Stormwater Control Measures." In *7th IWA Leading-Edge Conference on Strategic Asset Management of Water and Wastewater Infrastructures (LESAM)*, Trondheim, Norway.
- Wery, C., J.-L. Janel, and E. Weber. 2003. "Renouvellement des réseaux d'eau potable : Analyse des coûts (Renewal of drinking water systems - cost analysis)." *La Houille Blanche* 3: 73–76. doi:10.1051/lhb/2003053.
- Westerhoff, G. P., D. Gale, J. R. Gilbert, S. A. Haskins, and P. D. Reiter. 2003. *Evolving Water Utility: Pathways to Higher Performance*. 1st ed. Denver, CO, USA: American Water Works Association. ISBN:978-1583212394.
- WRc (Water Research Center). 2013. *Manual of Sewer Condition Classification*. 5th ed. Wiltshire, U.K: Water Research Center.
- Zhao, J. Q., S. E. McDonald, and Y. Kleiner. 2001. *Guidelines for Condition Assessment and Rehabilitation of Large Sewers*. Institute for Research in Construction. Ottawa, Canada: National Research Council Canada.