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STATE-OF-THE-ART PAPER

Risk-based prioritisation of inspections and rehabilitation of wastewater pipes

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Abstract

Reinvestments in wastewater pipe networks pose financial challenges due to high costs in combination with the complexity of rehabilitation prioritisation. Lack of pipe data and unknown pipe conditions are some factors contributing to the complexity. In Sweden, many of the wastewater pipe networks were constructed in the 1960s and 1970s and are now approaching the end of their technical life. With large investments anticipated in the coming decades, water utilities have the potential to reduce costs by identifying and prioritising high-risk wastewater pipes for rehabilitation. In this study, a risk-based decision model is presented to facilitate the strategic rehabilitation of wastewater pipe networks. The model is based on a two-tiered approach: the first tier identifies high-priority pipes for Closed-Circuit Television (CCTV) inspections, while the second tier utilises the CCTV-inspection results to estimate the probability of failure and update the risk assessment. A multi-criteria decision analysis model was utilised to prioritise wastewater pipe rehabilitation as well as CCTV-re-inspections. Hence, the model represents a novel integration of local CCTV-grades when establishing re-inspection frequencies and prioritisation of wastewater pipe rehabilitation prioritisation. Within six months, the model was implemented in the wastewater pipe network in Kungsbacka municipality, Sweden. The model enabled the development of an inspection plan and rehabilitation prioritisation, representing a significant step towards cost-effective and efficient wastewater pipe network management.

Keywords Asset management · Wastewater pipe network · Rehabilitation · Risk-based model · Multi-criteria decision analysis · CCTV inspections · Risk assessment

Introduction

Urban water infrastructure provides essential services to society, such as wastewater collection and treatment, and drinking water purification and distribution [1, 2]. In Sweden, the urban water pipe network was rapidly expanded in the 1960s and 1970s [3] and constitutes a large part of the urban water infrastructure assets (83% of the total urban water infrastructure value) [4]. In most developed countries [5, 6], including Sweden [4], the combination of ageing, deterioration, and procrastination in reinvestments forces water utilities to increase the rate of renewal and rehabilitation of existing pipes to maintain safe and high-quality asset- and urban water management. It has been estimated that in order to maintain an adequate level of services from the urban water infrastructure, the spending on rehabilitation in Sweden needs to increase by almost 50% during the next two decades, increasing from M€ 1524 to 2190

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annually[1] [4]. Both drinking water pipes and wastewater pipes are essential for providing urban water services. However, in this study focus was on the latter.

Utilities face the question of which pipes should be prioritised for rehabilitation to use available economic resources efficiently and maximise the infrastructure level of service. In many cases, the prioritisations are based on, e.g. theoretical estimations of the pipe survival time or time until failure based on pipe parameters (e.g. material, age, diameter, soil properties) [7] related either to individual pipes or pipe cohorts [8]. It is also possible to assess the pipe condition to better estimate the need for rehabilitation [9]. Pipes are buried, making rehabilitation prioritisation based on inspection and condition assessment a difficult and often costly task. Wastewater pipes are generally easier to inspect relative to drinking water pipes, using e.g. closed circuit television systems (CCTV), zoom cameras, and digital scanning [9–11]. In Sweden, the assessment of wastewater pipe condition is based on CCTV-inspections where CCTV-operators estimate a structural and an operational CCTV-grade[2] representing the pipe condition based on the visual defects [12]. The CCTV-grade is a grading system similar to systems used in, e.g. the US, and UK [9]. Different types of uncertainties have been reported related to CCTV-inspections, e.g. subjective visual condition grades, different interpretations by the operator [13–15]. Reported drawbacks are that the inspection only detects interior visual defects, omitting any external defects and the method cannot investigate any mechanical strength or defects in the surrounding bedding [16].

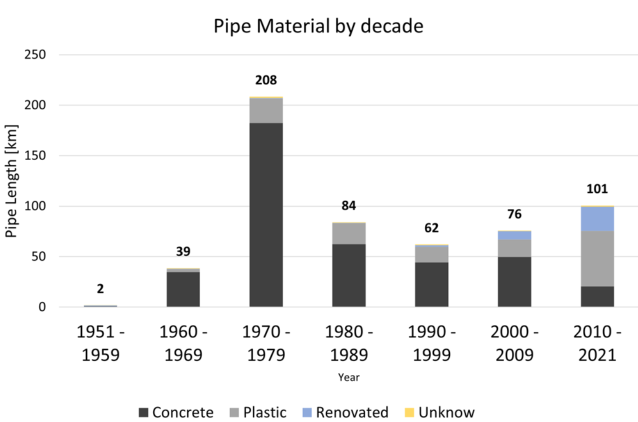

Fig. 1 Kungsbacka municipality's material of wastewater pipes installed for each decade. A colour version of the figure is available in the online version of this paper

[1] MSEK 16,000 and 23,000 recalculated using €1 = SEK 10.5 as an average of 2020 based on the statistics from Riksbanken, Sweden's central bank (https://www.riksbank.se/sv/statistik/sok-rantor--valutakurser/arsgenomsnitt-valutakurser/?y=2012&m=12&s=Dot&f=y, accessed 2022-03-23).

[2] In Swedish: Kortbetyg.

Risk-based methods for prioritising rehabilitation, combining both the probability of failure (POF) and the consequence of failure (COF) to estimate the risk of failure (ROF) have been promoted [17–19]. Risk is typically perceived as a combination of the probability and consequences of hazardous events that may occur [20]. POF has in previous studies been evaluated using, e.g. deterioration modelling, expert-based multi-criteria decision analysis (MCDA), binomial and multinomial regression, Bayesian Networks (BNs), and artificial neural networks (ANNs) [21–23]. The most common approach for evaluating COF has been MCDA to identify economic, social and environmental consequences of wastewater pipe failure [18, 24]. However, these methods and applications are often utility-tailored and apply advanced programming for implementation, making it difficult to generalise them and apply them in other locations. Thus, there is a need for a structured approach to utilising CCTV-grades in risk assessment to prioritise wastewater pipe rehabilitation. The approach should be easy to implement using a minimum of resources to be applicable for utilities not possessing large financial resources or lacking the competence to run more advanced models.

The aims of this paper were to: (1) develop a hands-on risk-based decision model for prioritising CCTV-inspections and utilise the structural CCTV-grade to prioritise pipe rehabilitation, and (2) demonstrate the applicability of the presented model in a case study in Kungsbacka municipality, Sweden. The main work was conducted through a master's thesis [25], in collaboration between Kungsbacka municipality and Chalmers University of Technology. In this paper, we streamline the implementation, adaptation and applicability of the model and provide a framework highlighting a two-tiered approach. This approach includes the novel integration of the Swedish CCTV-grades when establishing re-inspection frequencies and prioritisation of wastewater pipe rehabilitation.

Method

Case study area

Kungsbacka is a Swedish municipality located in Halland County, on the west coast of Sweden, with a population of 85,801 in 2022 [26]. There are five wastewater treatment plants in Kungsbacka, with 65,000 people connected in total [27]. The wastewater and stormwater systems are separated. An overview of the pipe material in the wastewater network in Kungsbacka (in total 571 km) is presented in Fig. 1.

Model development

Available methods for risk assessment of wastewater pipes were identified in the literature and evaluated in dialogue with representatives from Kungsbacka municipality, with respect to their applicability to Swedish small- to mid-sized municipalities. The most applicable method, based on locally available data for most Swedish medium-sized municipalities, was identified to be MCDA utilising the weighted sum method (WSM) to represent the POF and COF. The decision model was set up using a two-tiered approach. Prioritisation of CCTV-inspections was assessed in Tier I, and the need for and prioritisation of rehabilitation of the wastewater pipes was evaluated in Tier II. In Tier II, the structural CCTV-grades from inspections in Tier I (Fig. 2) were utilised. This approach was chosen so that municipalities with no or few CCTV-inspections can apply the model directly. The approach made it possible to include local data using only a limited workgroup at the case study municipality, providing a structure for a rapid implementation of the model.

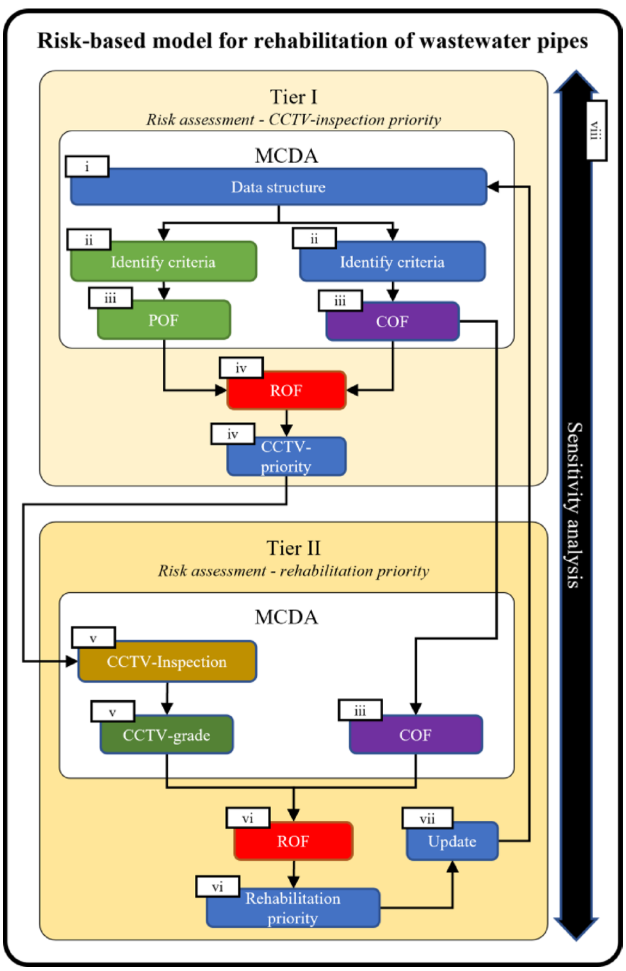

Fig. 2 Illustration of the risk-based model for rehabilitation of wastewater pipes. A colour version of the figure is available in the online version of this paper

In Tier I, the POF and COF were combined into the ROF using a risk matrix approach to enable prioritisation of CCTV-inspections[3]. In the second tier, the POF was based on the structural grade from the CCTV-inspection and combined with the COF to establish the rehabilitation prioritisation. In summary, the risk-based decision model is a combination of existing methods, with novel additions including the approach to utilise the Swedish CCTV-grading scheme as part of prioritising wastewater pipe rehabilitation.

Model overview

The developed risk-based model and the implementation process are illustrated in Fig. 2.

Tier I was divided into the following steps. First (i), the available pipe characteristic data within the water utility is structured (e.g. pipe material, age, length, diameter, pipes where failure would significantly impact economic, social, or environmental factors and available CCTV-inspection within the wastewater pipe network). Second (ii), local utility knowledge is utilised (e.g. through workshops with decision makers, strategic and operational personnel or other elicitation processes) to identify and categorise the available data into criteria and sub-criteria that affect POF and COF and establish sub-criterion values (SCV) and importance scores (IS). The SCV (values 1–5, where 5 corresponds to the highest probability and consequence) can be established using the approaches presented in this paper (if appropriate for the specific case implementation), local utility data and knowledge, or by other approaches presented in the literature. The IS (between 1 and 10, where 10 represents the highest importance) is preferably established using local knowledge in combination with theoretical relationships related to probabilities and consequences of wastewater pipe failures. Based on the IS, the normalised weights (W_j) for the different criteria (j) are calculated as:

$$W_i = \frac{IS_i}{\sum_{i=1}^{n} IS_i} \tag{1}$$

where n is the number of criteria, IS_i is the IS for criterion i. In the third step (iii), COF scores and POF scores are calculated based on the criteria identified in step two (ii). COF scores (*Score COF*) for each unique pipe ID within the wastewater pipe network are calculated as:

[3] Note that COF refers to a consequence grade, not an actual quantified consequence, and analogous, the POF does not refer to an actual probability, but a likelihood grade with respect to the occurrence of risk events.

$$Score\ COF = \sum_{j=1}^{n} SCV_{COF-j} \times W_{COF-j}, \quad for\ j = 1,\ 2,\ 3, \ldots, n. \tag{2}$$

where W_{COF-j} is the weight associated with the *j*-th criterion, SCV_{COF-j} is the individual pipe SCV for the *j*-th criterion, and *n* is the number of criteria related to COF. The POF score (*Score POF*) for each unique pipe ID is calculated as:

$$Score\ POF = \sum_{k=1}^{m} SCV_{POF-k} \times W_{POF-k}, \quad for\ k = 1,\ 2,\ 3, \ldots, m. \tag{3}$$

where W_{POF-k} is the weight associated with the *k*-th criterion, SCV_{POF-k} is the individual pipe SCV for the *k*-th criterion, and *m* is the number of criteria related to POF.

The COF scores and POF scores are converted into COF and POF grades using the approach presented in this paper (Table 3) or, if needed, adapting to reflect the specific local conditions. The fourth (iv) and final step of Tier I includes a possible weighing of the risk matrix and the combination of COF and POF to estimate the ROF to be used in the CCTV-inspection prioritisation. In this Tier I and in Tier II, the ROF is considered to be a risk grade, or ranking of the risk, rather than an absolute risk estimate.

In Tier II, the initial step (v) is to inspect the prioritised pipes and assign a structural and operational CCTV-grade to each unique pipe ID (or the subset of wastewater pipes that have been inspected). The next step (vi) is to combine the structural grade from the CCTV inspections with COF to set up a rehabilitation and re-inspection priority (in this paper based on the novel rehabilitation prioritisation and re-inspection scheme in Table 4). This re-inspection scheme may be adapted to local conditions if necessary. Any new CCTV-inspections and possible rehabilitation should be updated in the database to update structural CCTV-grade and categories affected by the new pipe that has been installed (vii). Finally (viii), a sensitivity analysis should be performed either using the approach applied in this paper (investigating the impact of changing weights for one category at a time) [19] or other appropriate methods. In addition, a basic scenario analysis of altering the weights of the risk matrix was conducted.

Table 1 Consequence criteria, associated buffer zone, importance score, weight (W_i), sub-criteria and sub-criteria values (SCV) for the consequence of failure (COF)

Criteria (buffer)[a]	IS[c]	W_i	Sub-criteria	SCV
Diameter	5	0.11	x>=1000 mm	5
			1000<x<=600 mm	4
			600<x<=400 mm	2
			x<400 mm	1
Burial depth=>4 m	2	0.05	–	5
Adjacent to buildings (1 m)	4	0.09	–	5
Close to motor- & highways (20 m)	4	0.09	–	5
Close to priority highways (12 m)[b]	5	0.11	–	5
Close to railway tracks (30 m)	7	0.16	–	5
Close to waterbodies (10 m)	7	0.16	–	5
Close to water protection area (10 m)	10	0.23	–	5

[a]Buffer of various meters was used in GIS to set up conditions for which pipes were adjacent or close to roads, buildings, waterbodies and water protection areas

[b]Priority highways refer to roads frequently used by emergency vehicles

[c]For the criterion diameter, the highest IS (5) within the group was set to represent the criterion

Results—model application

The risk-based model was implemented in Kungsbacka municipality. The MCDA identification, categorisation, evaluation of criteria and sub-criteria related to the COF and POF and establishing the IS, were made during workshops with decision making and operational personnel from Kungsbacka municipality providing adequate local knowledge.

Data structure (Step i)

Initially, the available data on pipe characteristics (material, length, diameter, age, burial depth) and proximity to infrastructure and environmentally important areas (roads, rails, water protection areas, water bodies, buildings, and emergency vehicle standard routes) were structured. The used dataset consisted of 15,044 unique pipe IDs with a total length of 571.3 km. Further, 2471 CCTV-inspections were available. Pipes with missing data (Supplementary Table S1) have been excluded from the analysis. A parallel process of data collection of urban water infrastructure characteristics is essential for including all pipes in these types of analyses and a fundamental task in the digitalisation of urban water management [28].

Identification of criteria, sub-criteria, and calculation of COF and POF (Step ii and iii)

To evaluate COF as part of the MCDA, eight consequence criteria (pipes adjacent to; buildings, motorways, highways, priority highways, railway tracks, water protection areas, water bodies; pipes with burial depth greater than four meters, and pipe diameter) were identified (Table 1). To evaluate POF, four criteria were identified that accelerate the deterioration process of wastewater pipes; material (plastic, renovated, concrete pipes installed before 1970, and concrete pipes installed after 1970), age (based on installation date), pipe diameter, and the length of the pipe (Table 2). Before the workshops, the SCV scale (1–5) was defined and preliminary SCV values were derived from the literature review. All workshop participants received this information in advance, together with instructions on how the model would be applied. During the meeting, a facilitated moderation approach was used, with a workshop leader guiding the discussion criterion-by-criterion, ensuring that all participants could contribute and that the same scoring procedure was applied consistently. The group jointly discussed whether any SCV values needed to be adjusted to reflect local conditions. In addition, each criterion was assigned an IS from 1 to 10 based on a group consensus. To support consistency, the resulting scores were subsequently cross-checked against the values suggested by the literature review (Tables 1 and 2). The *SCV* and criteria weights to evaluate COF are presented in Table 1. Criteria with binary sub-criteria were assigned an SCV of 5. The *SCV* for *diameter* was equal to the *IS* for each sub-criterion.

The assessment was also partially influenced by the results from the regression analysis, which showed a significant relationship between deterioration parameters and condition-assessed CCTV inspections. The SCV and the weighting of criteria to evaluate POF are presented in Table 2. The SCV for the material criteria were based on relative scoring in earlier reviews of MCDA applications [19, 29]. Age impact on pipe deterioration was assumed to be non-linear [e.g. 19] adopting a continuous exponential curve with a cut of where all pipes older than 70 years received an SCV of 5. A maximum age threshold of 70 years was applied because no pipes older than this existed in Kungsbacka's network. The threshold therefore limits the model to the observed age range and avoids uncertain extrapolation for ages where no data are available. Longer pipe sections are typically more exposed to ground movements, and long pipes, especially in combination with small diameters, were assumed to be more prone to bending and related structural distress resulting in a higher SCV. Pipes longer than 100 m were assigned an SCV of 5, and for pipes shorter than 100 m, the length was divided by 20 to calculate the SCV. For pipe diameter, four categories were used, each with a related SCV. The approaches related to criteria, sub-criteria, SCV and weighing were decided upon during the workshops.

The COF and POF scores were successfully evaluated for 97.3% of the pipes within the wastewater pipe network. The scores were converted into COF and POF grades (Table 3). Since not all COF criteria were assigned to each pipe (not all pipes are close to, e.g. water protection areas and railway tracks), the resulting COF scores were generally low and did not span the full range of the possible values. Therefore, Jenks natural breaks classification method was applied to the COF scores, as in earlier studies [17, 18]. Jenks natural breaks divide data into classes where the variation within classes is as small as possible and the variation between classes is as high as possible. Calculations for Jenks natural breaks were conducted with the RStudio package BAMMtools [30]. The conversion of POF score to POF grades was evaluated using a test pipe. In the test, a newly installed plastic pipe, i.e., the material with the highest SCV with an age of zero years, with the most typical diameter, 225 mm, and a common length of 20 m, was evaluated. The test pipe POF scoring was equal to 2. Hence, this was set as a baseline scenario for POF grade 1. The POF grades 2, 3, 4 and 5 were set to range evenly distributed up to five.

Table 2 Probability criteria, associated buffer zone, importance score, weight (W_i), sub-criteria and sub-criteria values (SCV) for the probability of failure (POF)

Criteria (unit)	IS	W_i	Sub-criteria	SCV
Material (-)	5	0.28	Concrete =< 1970	4
			Concrete > 1970	2
			Plastic	5
			Renovated	1
Age (yrs)	10	0.56	x >= 70 years	5
			x < 70 years	$(Age^{1.5})/117.3$
Length (m)	1	0.06	x >= 100	5
			x < 100	(Pipe length)/20
Diameter (mm)	2	0.11	0 < x < 250	5
			250 <= x < 500	3.75
			500 <= x < 750	2.5
			750 <= x	1.25

Table 3 Converting COF and POF scores into COF and POF grades

Impact	COF score[a]	COF grade	Counts
Low (L)	0–0.114	1	11,970
Moderate (M)	0.114–0.228	2	398
Moderate-to-high (MH)	0.228–0.682	3	1861
High (H)	0.682–1.364	4	303
Very high (VH)	> 1.364	5	186
Impact	**POF score**	**POF grade**	**Counts**
Low (L)	0–2.0	1	5347
Moderate (M)	2.0–2.75	2	4643
Moderate-to-high (MH)	2.75–3.5	3	3564
High (H)	3.5–4.25	4	1050
Very high (VH)	4.25–5.0	5	29

[a]Jenks natural breaks were used to categorise the COF into 5 grades

Evaluation of ROF and prioritisation of CCTV inspections (Step iv)

To combine COF and POF grades into ROF classes, a 5 × 5 risk matrix (weighted to enhance COF impact on ROF) was defined in dialogue with Kungsbacka municipality during the workshops (Fig. 3). Hence, the possible combinations of COF and POF grades (Table 3) were evaluated individually to assess the ROF class and, thus, the CCTV inspection prioritisation to which they belong. The number of pipes within each ROF classification in the Kungsbacka case study is reported in Fig. 3. Colour categories represent risk levels and CCTV inspection prioritisation. For example, high risk is indicated as red and is the highest CCTV inspection prioritisation, whereas green represents low risk and low priority. Pipes that have already been inspected can be removed from the prioritisation list unless the inspection is very old.

In Fig. 4, the risk categorisation is presented in the wastewater network in Kungsbacka municipality using a GIS-software.

New CCTV-inspections and structural grades (Step v)

The new CCTV-inspections were graded with a structural (1–3) and operational (1–3) grade, where 3 was the worst condition and the best [12]. In this analysis, the structural grades were used to replace the POF, as they strongly relate to pipe failure. Pipes with Structural Grade 0 did not have any defects at all, and this grade was added to the original 1–3 grades.

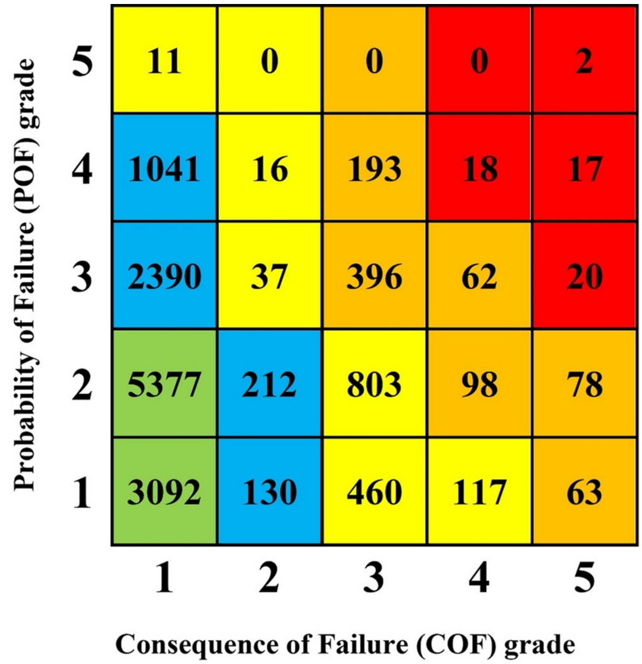

Fig. 3 The risk of failure classification. Risk categorisation according to the following colours: Red [1] = Very high (57), Orange [2] = High (890), Yellow [3] = Moderate-to-High (1444), Blue [4] = Moderate (3773), Green [5]=Low (8469). Numbers within squared brackets show the CCTV inspection priority for that category and numbers within round brackets summarise all pipes in that category. A colour version of the figure is available in the online version of this paper

Fig. 4 GIS representation of a subset of the risk categorisation of wastewater pipes. A colour version of the figure is available in the online version of this paper

Table 4 Rehabilitation priority and re-inspection plan for the risk-based model

Structural grade (KB)	COF	Rehabilitation priority	"or"	Next inspection	Count
3	2–5	Immediate	–	–	20
3	1	Immediate	or	0–2 yrs	92
2	4–5	High	or	6 yrs	27
2	3	Moderate-to-high	or	6–10 yrs	46
2	1–2	Moderate	or	10–15 yrs	437
0–1	3–5	Not required	->	15–20 yrs	401
1	1–2	Not required	->	20–25 yrs	684
0	1–2	Not required	->	25 yrs	1064
Sum					**2771**

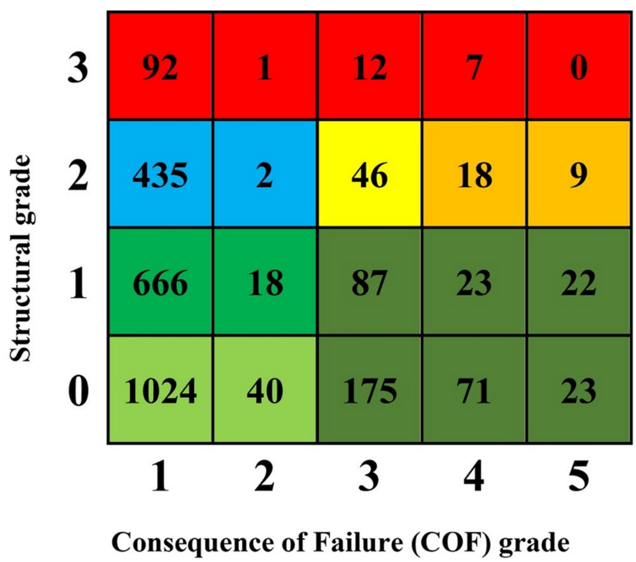

Fig. 5 Risk matrix used for prioritisation of pipe rehabilitation. Categorisation according to the following colours: Red = Immediate (112), Orange = High (27), Yellow = Moderate-to-High (46), Blue = Moderate (437), Green (three different shades) = Not required (2149). Numbers within round brackets summarise all pipes in that category of rehabilitation priority. A colour version of the figure is available in the online version of this paper

Rehabilitation prioritisation and planning of next inspection (Step vi)

Rehabilitation prioritisation assumes that the CCTV condition assessment structural grade represents the pipe's condition [9, 32, 33] and that pipes in bad condition should be either rehabilitated or re-inspected more frequently. The rehabilitation prioritisation and next inspection schedule developed in this study were inspired by several available protocols [9, 15, 32, 33] and the final approach was a novel combination with Swedish structural CCTV-grade (KB) [12] presented in Table 4.

Rehabilitation priorities and pipe classification were based on the combination of the structural CCTV-grade (0–3) from CCTV inspection and the COF classification from the MCDA analysis in a 4 × 5 risk matrix (Fig. 5).

Updating of data and sensitivity analysis (Steps vii and viii)

In the final step, a sensitivity analysis was performed to describe the influence of changes in criteria weights on the model output, similar to what Vladeanu [19] applied to an MCDA AHP model. The COF is very sensitive to changes in the weight of the *Diameter*, where a 50% decrease changes the results by 40.6%. The POF is most sensitive to changes in *Age*, where a 50% lower weight changes the results by 13.7%. The full sensitivity analysis is presented in Supplementary Tables S4 and S5.

Discussion

Model development

To provide a rapid implementation of the risk-based decision model, an MCDA utilising a WSM was used both for the POF and the COF. The accuracy of the MCDA methods used to evaluate POF and COF is difficult to evaluate. However, the most critical step is evaluating the criteria with associated weights, and if using experts, weights and criteria should strive against consistency. In this study, the WSM was applied, but other MCDA methods may be more appropriate depending on the local settings. Tscheikner-Gratl, Egger [29] evaluated different MCDA methods, and the results between methods did not differ significantly, thus choosing a less demanding approach should be appropriate for utilities lacking resources. This may be the case for many water utilities in Sweden. Vladeanu [19] suggested using sensitivity analysis to evaluate how the results vary when the criteria weight varies.

Difficulties in using the CCTV-grade have been reported, and Rokstad and Ugarelli [34] stated that the Norwegian 5-grade CCTV-system provided a too negative result compared to the reality, and the grading system was suggested to be altered. CCTV does not provide perfect information and uncertainties related to e.g. the CCTV image interpretations and continued analysis have been shown to affect decisions related to the rehabilitation of wastewater pipes [35]. Further. Since CCTV inspections are not tailored to spot infiltration and inflow into wastewater pipes, there is a risk that some of these problems may be neglected. Currently, there is no standard for grading infiltration and inflow, thus it is difficult to include in the risk assessment. Other inspection techniques may be needed to complement the CCTV inspection. Results from these techniques and the inclusion of uncertainties could be part of a further development of the risk-based decision model presented in this paper. Furthermore, the limitations of CCTV inspection—e.g., subjective, operator-dependent visual condition grading and the fact that the inspection only detects internal, visually observable defects—are acknowledged in this paper. Nevertheless, CCTV inspection remains the most common and, in practice, most effective method for assessing the actual structural condition of wastewater pipes for most Swedish water utilities.

In this model setup, a local sensitivity analysis was applied, i.e. changing inputs on-at-a-time. The local sensitivity analysis was selected to maintain the model's main strength of easy applicability to be available for resource-scarce organisations. Further development of the model may include developing global sensitivity analysis to better capture interactions and nonlinearities. Furthermore, by applying a Bayesian approach, the model may be adapted to allow for updating when new input data become available.

The simplicity of the model and the assumptions made can affect the decision basis. First, the Swedish structural grade could be improved by updating how the grade is determined. The method is relatively old and there is a need to modernise it. Furthermore, the expert assessments in this work are based on the competence and experience of a single municipality. Ideally, reference values—such as POF values—should be developed for Swedish conditions in a broader context, where more experts can contribute and review them. To be able to acknowledge any geographical proximity between individual pipes as part of the prioritisation of rehabilitation and would perhaps provide the most valuable development of the model, when balancing between adding complexity without losing simplicity. It would enable a cost-efficient approach rehabilitating several close-by pipes in a single project.

Model application–case study

The risk of introducing bias when excluding pipes cannot be entirely ruled out. However, after discussions with the municipality, our assessment was that the missing information was neither concentrated in any specific part of the network nor associated with pipes of particular diameters or materials. The risk-based decision model for rehabilitation and CCTV inspection identified 57 un-inspected pipes in the Kungsbacka wastewater pipe network that were classified as very high in the inspection prioritisation. Additionally, 20 of the inspected pipes were classified to be rehabilitated immediately, and 92 were judged to either be rehabilitated immediately or re-inspected within 2 years. These results provide a clear and structured prioritisation for the utility. It is also easy to expand any rehabilitation plan if resources allow, continuing the established prioritisation. Using Jenks natural breaks is making the results adapted to the local situation. However, to normalise the POF or COF to provide classification over the entire range of the ROF matrix is not necessary, utilities can benefit from knowing that there are no pipes with high COF or POF. Jenks natural breaks was considered a suitable method in this study for dividing this heterogeneous score distribution into five COF categories, from low to high COF. The categories should thus be regarded as relative (low–high) for the analysed dataset and are not necessarily directly transferable to other municipalities without adaptation. Since the local settings heavily impact the COF, the choice of using Jenks natural breaks should be evaluated for each case. However, the suggested method for COF can still be generally applied, acknowledging the choice of using/not using the Jenks natural breaks and being aware that the actual COF-grade cannot be transferred between case studies.

Most studies are case studies [e.g. 17, 36], i.e., the methods have been developed using the data from specific cities, municipalities, or regional water utilities to build up the models. The accuracy has then been validated using, e.g. training and test data, classification tables, r-squared etc. Hence, there is no evidence that a case-specific deterioration model could be used in another arbitrary wastewater pipe network. In some areas, there are regulatory requirements regarding the frequency of CCTV inspections [16]. Furthermore, no studies have described if there has been a previous strategy for CCTV-inspections. If there has been a strategy, or if only already defective pipes have been inspected, the inspected pipes' properties can be biased.

Changing the thresholds of the SCV for the different criteria would affect the results (i.e., the ranking and resulting risk classification). In this project, no sensitivity analysis was performed for the SCV thresholds; however, sensitivity analyses were carried out for POF and COF as described in Sect. 3.6 and a scenario analysis of the risk matrix weights was also applied. Results from the sensitivity analysis of the POF and COF indicated that the most sensitive criteria for COF and POF were pipe diameter and age, respectively. Changes in the weight of the COF resulted in higher changes in the results relative to changes in the POF weights. The risk matrix was designed to be weighted towards COF based on a dialogue with Kungsbacka municipality. The weights of the risk matrix were not investigated regarding their sensitivity. However, a brief scenario analysis of an inverted matrix (heavier weights on probability) and an equally weighted matrix was conducted. The inversion of the weighted matrix showed the biggest change in pipes, altering risk classes. Looking at the two most severe risk classes, the number of Very high-risk (Red) pipes decreased from 57 to 37, and the number of High-risk (Orange) pipes decreased from 890 to 698 when inverting the matrix. If removing the weights, using a matrix with equal weights, the changes in the number of Very high- and High-risk class pipes were 0 and an increase of 27 respectively, when comparing to the original weights (emphasis on consequences). Putting weights on the risk matrix is subjective, and in this case study, we can see that using weights that emphasise the consequences will result in more pipes being classed as high-risk pipes.

Results from a multinomial logistic regression model (Supplementary material) indicated significant relationships between deterioration parameters and CCTV-grades. Interesting findings were that the plastic pipes were graded higher (in worse conditions) in terms of structural condition compared to concrete pipes. This shows the potential of regression models and may motivate utilities to use parts of the results, even though the final accuracy of the condition classification in this case was inadequate. The results from the regression model were part of the motivation to give plastic pipes the highest SCV score. All data indicated that plastic was in worse condition than concrete and renovated pipes, which can appear counterintuitive since concrete pipes have been outrivalled by plastic (mainly PE and PP) pipes, during the last decades.

One hypothesis why plastic pipes perform worse than concrete pipes in terms of structural condition is that PE and PP pipes creep under loads [37]. Vertical loads might be too high depending on the burial depth, and if side structure support is lacking, the installation errors may also impact [38]. Creep for plastic pipes does not necessarily impact the structural condition. Suppose the high structural grade is mainly based on the defect deformation. In that case, one explanation could be that CCTV-grades and condition assessment protocols are more customised for defects in rigid pipes. Hence, if vertical deformation is present in rigid pipes, there will most definitely be defects such as cracks, the same deformations in plastic pipes could be ductile deformations that do not influence the structural integrity [39].

Conclusions

CCTV inspections are expensive, and water utilities need to use resources efficiently. This risk-based decision model for inspection prioritisation and rehabilitation of wastewater pipes is a straightforward applied approach that utilises information from CCTV inspections to prioritise wastewater pipe rehabilitation. To develop the model further, it would be interesting to see if a different kind of expert elicitation method would be suitable to find better values for the MCDA. Additionally, if the model could be adapted to a user-friendly interface, the applicability and use of the model would increase, and it would also be possible to include the omitted regression analysis as an automatic initial step to be discussed during workshops.

The main limitations and strengths of the model both lies in the simplicity of the methods used for estimating the probability and consequence of failure in the MCDA. It is, e.g. on the one hand limiting to assume a linear relationship between pipe length and the magnitude of probability of failure, on the other hand, if the model is not used by the water utilities due to the lack of knowledge, time and resources, that is a limitation in the applicability of the model. It is a balance between utilising the most advanced technical models to represent the pipe system and the applicability and availability of the model to water utilities. This study provides a bridge between research and the practical application by water utilities. The study was conducted in a Swedish municipality, but the approach to combine local CCTV-gradings with international schemes for CCTV-inspection frequencies and rehabilitation prioritisation is considered to be general and easily applicable in other countries as well.

The following conclusions were drawn based on the development of the risk-based decision model and the case study implementation:

- The presented risk-based decision model provides a structured approach that is easy to implement for identifying high-risk wastewater pipes using minimal resources.
- Probability and consequence of failure were evaluated based on a multi-criteria decision analysis using a qualitative weighted sum method with the advantage of being simple to implement and taking the competence and experience within the water utility into consideration.
- Any water utility can adopt the full-scale risk-based model. Within only half a year, it was successfully implemented to assess the wastewater pipe network in the Swedish case study municipality Kungsbacka.
- The case study showed that 97.3% of the pipes within the wastewater pipe network could be evaluated in

terms of risk of failure and providing a CCTV inspection priority.

- A novel approach for rehabilitation and re-inspection priority of CCTV inspected pipes was established using structural CCTV-grades and the consequence of failure grades.

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Declarations

Conflict of interest The authors declare that they are not aware of any conflict of interest.

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