Deterioration of our sewer infrastructure as an opportunity for adaptation

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ABSTRACT

The aging of public infrastructure networks should not only been seen as a threat leading to large investment costs but also as an opportunity to adapt the systems to a changing environment. This study shows the impact of such influences (e.g. shrinking and growing cities) on urban drainage networks. We present different development scenarios and show for each scenario different adaptation possibilities. Thereby, the decision making for adaptation is done by focusing on those network parts, which require rehabilitation anyway. We use a ‘Priority model’ to identify areas of required rehabilitation by joining deterioration models and the history of failures with other influencing factors of the environment, like connected inhabitants or number of house connections, the rehabilitation needs of other networks (street, water supply) and the vulnerability of network elements. We test for the different scenarios if adaptation to a changing environment (i.e. climate change and urban development) is possible when adaptation measures are combined with regular rehabilitation. Such an integrated view should help to prevent wrong decisions in infrastructure asset management and planning and to reduce required investment costs or at least optimize the usage of the available funds.

Alternde Entwässerungssysteme als Chance für die Zukunft

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ZUSAMMENFASSUNG

Die Alterung unserer öffentlichen Infrastruktur sollte nicht nur als Bedrohung welche mit hohen finanziellen Belastungen einhergeht wahrgenommen werden, sondern auch und vor allem als Chance zur Anpassung unserer Systeme an eine sich ändernde Umwelt. Diese Arbeit zeigt die Wirkung dieser Veränderungen (z.B. Stadtwachstum bzw. –schrumpfung) auf Kanalnetze. Dazu werden verschiedene Entwicklungsszenarien präsentiert und es wird gezeigt wie diese angepasst werden können. Dabei wird der Fokus in der Anpassung auf jene Netzwerkelemente gelegt welche ohnedies der Rehabilitation bedürfen. Um diese Elemente und Bereiche zu ermitteln wird ein Priorisierungsmodell verwendet welches auf Kombination von Alterungsmodellen, Schadenshistorie Umgebungseinflüssen (wie z.B. angeschlossenen Einwohner oder Anzahl der Hausanschlüsse), dem Sanierungsbedarf benachbarter Netze (z.B. Wasserversorgung, Straßen, etc.) sowie der Vulnerabilität der Netzelemente beruht. Es wird für die verschiedenen Szenarien untersucht ob eine Anpassung an Einflüsse wie Klimawandel und Stadtentwicklung möglich und sinnvoll ist wenn man sie mit der notwendigen Sanierung kombiniert. Dieser ganzheitliche Ansatz soll helfen falsche Entscheidungen im Infrastrukturmanagement und in der Planung zu verhindern sowie dadurch auch die notwendigen Investitionen zu verringern bzw. die vorhandenen Mittel zielgerichteter einzusetzen.

La détérioration de notre réseau d'égouts en tant qu'opportunité d'adaptation

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RÉSUMÉ

Le vieillissement des réseaux d'infrastructures publiques ne doit pas être considéré uniquement comme une menace entraînant des coûts d'investissement importants. Il s'agit également d'une occasion d'adapter les systèmes à un environnement en pleine évolution. Cette étude montre l'impact des influences qui y sont liées (par ex. décroissance et croissance des villes) sur les réseaux de drainage urbain. Nous présentons différents scénarios de développement et présentons plusieurs possibilités d'adaptation pour chacun d'entre eux. De ce fait, la décision d'adaptation est prise en se concentrant sur les parties du réseau qui doivent de toute manière être réaménagées. Nous utilisons un « Modèle de priorité » pour identifier les zones où un réaménagement s'avère indispensable en regroupant des modèles de détérioration et l'historique des défaillances, avec d'autres facteurs de l'environnement qui exercent une influence, comme les habitants raccordés ou le nombre de raccordements domestiques, les besoins de réaménagement d'autres réseaux (rue, distribution d'eau) et la vulnérabilité des éléments du réseau. Pour les différents scénarios, nous testons si l'adaptation à un environnement changeant (à savoir le changement climatique et le développement urbain) est possible lorsque les mesures d'adaptation sont associées à un réaménagement ordinaire. Cette vision intégrée doit permettre d'éviter les mauvaises décisions dans la planification et la gestion de l'infrastructure ainsi qu'à réduire les coûts d'investissement requis ou tout au moins optimiser l'utilisation des fonds disponibles.

1. Introduction

In many parts of the world e.g. in central Europe, in the last decades the main challenge for operators of urban drainage systems has moved from connecting new areas to maintenance and rehabilitation of the existing infrastructure. For example in Austria more than 90% of the population are connected to sewer systems [1]. The deterioration of our sewers becomes a more and more emerging issue especially due to the fact that our actual rehabilitation rates are far too low (e.g. Austria 0.07% for the year 2012 [2]). Various deterioration and rehabilitation models exist ([3], [4], [5]) for the estimation of the expected lifetime of our sewers.

Additionally a changing environment can influence performance of drainage systems and require an adaptation of existing systems. Considering stormwater and wastewater collection systems, the most influencing factors are climate change and land use change caused by urban development ([6], [7]). These changes can put severe pressure on the existing infrastructure but also open a window of opportunities for implementing more sustainable management strategies. Also it has been shown that increased rainfall intensities can be compensated by the reduction of the impervious areas ([8], [9]) if the necessary adaptations can be implemented (e.g. infiltration systems).

The aim of this paper is to present the application of an integrated approach combining urban development, climate change impact, sewer deterioration models, and hydrodynamic simulations. The idea of this study is to test the drainage system's potential to combine rehabilitation and adaptation measures i.e. to investigate if it is possible to adapt the system for future conditions with only investing into infrastructure with pressing rehabilitation needs.

2. Methods

Case study and Scenarios

A case study of a medium sized alpine city with a sewer length of 228 km and a population of 125,431 inhabitants was used to develop and apply this method. In total 48 different scenarios for future development are examined differing in applied rehabilitation rate, the rehabilitation method and the impact of urban development and climate change. The performance of these scenarios, which are displayed and numbered for identification in Table 1, is assessed using the SWMM software tool [10]. The four baseline scenarios represent the current system status without rehabilitation. For this study the flooded volume of the total network was estimated for all scenarios as well as the costs of the different rehabilitation rates and methods. For the hydrodynamic calculation a design storm event “Euler Type II” with a duration of two hours and a return period of 5 years was used. This is a common assumption for the design of new and rehabilitated sewers in city centres according to Austrian guidelines [11].

Table 1: Examined scenarios and its identification numbers

Rehabilitation rate	Rehabilitation method	Climate change: Yes		Climate change: No	
		Urban development		Urban development	
		Yes	No	Yes	No
Max. 0.5%	Sliplining	1.1	2.1	1.4	2.4
	CIPP	1.2	2.2	1.5	2.5
	Open Cut	1.3	2.3	1.6	2.6
Max.1.0%	Sliplining	3.1	4.1	3.4	4.4
	CIPP	3.2	4.2	3.5	4.5
	Open Cut	3.3	4.3	3.6	4.6
Max. 1.5%	Sliplining	5.1	6.1	5.4	6.4
	CIPP	5.2	6.2	5.5	6.5
	Open Cut	5.3	6.3	5.6	6.6
Max. 2.0%	Sliplining	7.1	8.1	7.4	8.4
	CIPP	7.2	8.2	7.5	8.5
	Open Cut	7.3	8.3	7.6	8.6
Baseline scenario 9 = Current state		9.3	9.2	9.4	9.1

Rehabilitation scenarios

The maximum rehabilitation rates range from 0.5% of the total network length to 2.0%. In reality these rates highly depend on the budgetary situation and are therefore seldom reached (although a yearly rehabilitation rate of 1.0% would still require a lifetime of 100 years for our sewers). Because of the high impact of costs on the rehabilitation management this study examines three different methods for rehabilitation regulated by Austrian guidelines [12].

(a) In the sliplining method a new pipe (mainly PE-HD or PP) is pulled into the existing sewer by the means of a winch. The main disadvantage is the resulting reduction of the sewer cross-section area. For our scenarios we assumed that the diameter is reduced by 50mm until DN500 and above this threshold by 100mm. Sewers with a diameter of less than 200mm allow no reduction and therefore method (b) - Cured-In-Place Pipe (CIPP) is applied.

(b) For this method a hose saturated with resin is inserted into the sewer, pressed to the sewer walls with air or water pressure and cured in place by heat or UV radiation. The reduction of the cross section is therefore minimized and for our study we assumed it to be negligible for the hydrodynamic calculation. Further we assume that the roughness of the rehabilitated sewers for sliplining and CIPP decrease and a Manning roughness of 0.011 for smooth plastic pipes is applied [13].

(c) The third examined method is the classical open cut which allows the usage of pipes with a higher diameter. To estimate that pipes which would need a higher diameter under future conditions, we calculated the examined scenarios for the end of our observation horizon in the year 2030 including the used factors (climate change and urban development). We highlighted those sewers that reached their hydraulic capacity for more than 1 hour. For these conduits the diameter was expanded by 100mm in case of rehabilitation.

The costs of the different methods are estimated using the information of a Canadian Study [15] who recorded the diameter dependent costs of each method per m. These data were converted into Euro and multiplied with the construction cost index [16] to get a plausible cost function as shown in Figure 1. It can be observed that the open cut method is getting financially rewarding with higher pipe diameters.

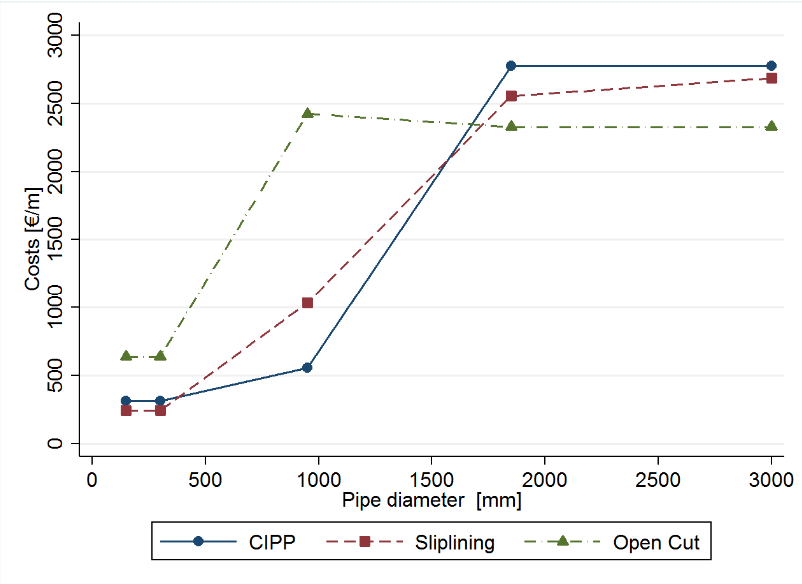

Figure 1: Costs of different rehabilitation methods from the data of a Canadian Study [15]

A priority model is used to select rehabilitated sewers for this case study consists of four parts: 1) the deterioration model (PDet), 2) the vulnerability analysis (PVul), 3) the importance of the affected street (PIS) and the 4) urban development model (PUD), which is not included in all scenarios (compare Table 1). These parts were weighted (W) and summed up to create a priority number for the individual pipe using the following formula:

$$P = |P_{Det}| \cdot W_{Det} + |P_{Vul}| \cdot W_{Vul} + |P_{IS}| \cdot W_{IS} + |P_{UD}| \cdot W_{UD}$$

The weights are depending on the objectives of the operating company. For this study it was assumed that the deterioration has the highest influence on the prioritization ($W_{Det} = 0.5$), while the other factors have a minor influence ($W_{Vul} = 0.25$ and $W_{IS} = W_{UD} = 0.125$).

Deterioration model.

For the deterioration model a binary logistic regression model (see [17] and [18] for detailed information) with a logit link is used. The estimation of the condition states is based on visual sewer inspection (in which 70% of the network was inspected) distinguishing 5 states from immediate action necessary (CS5) to no action necessary (CS1) following the ISYBAU coding [19]. The two condition states that require the highest attention (CS4 and CS5) are summed up into a group (not acceptable condition) and the rest of the condition states (CS1 to CS3) into another (acceptable condition) to form a binary variable. One of the main advantages of the logistic regression analysis is the fact that it does not make any assumption on the distributions of the explanatory variables [17]. The logistic regression model estimates for this binary response variable the conditional probability of observing the outcome “not acceptable condition” (for our model used as P_{Det}), given the regressors. Table 2 displays the significant regressors and the affiliated statistical properties – coefficients (are estimated using the maximum likelihood estimation), the standard errors, Wald statistics and significance levels. The significant regressors used are therefore pipe age, diameter, slope, length and a distinction if the pipe has a circular shape or not. Another study [17] found also the different materials to be significant but in our network this could not be verified due to the high amount of concrete pipes (73.68% of the total network) and no existing brick sewers. On the other hand in our study the pipe diameter has an influence. Pipes with higher diameters deteriorate more slowly. This was also observed by others ([20], [21] and [18]). In our study also pipes with a steeper slope deteriorate slower and circular shaped pipes faster, which was also observed in previous studies [3]. Figure 2 shows the receiver operating characteristic (ROC) curve of the model, where we can see that the fit of the model is reasonable. To reach a sensitivity and specificity of around 0.75 a cut-off value between the binary variables of 0.13 is estimated (Figure 3).

Table 2: Significant factor for the used deterioration model

Significant factors	Coefficients β	Standard Errors	Wald statistics	Significance levels
Pipe shape (circular)	0.574	0.234	6.017	0.014
Pipe age	0.023	0.002	132.250	0.000
Pipe diameter	-0.002	0.001	23.329	0.000
Pipe slope	-0.006	0.002	10.500	0.001
Pipe length	0.020	0.003	43.957	0.000

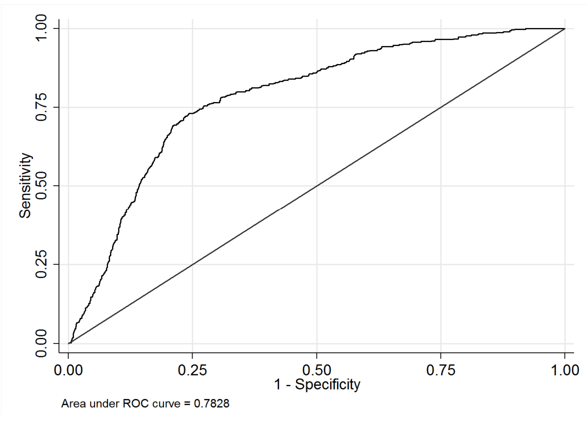

Figure 2: ROC-curve

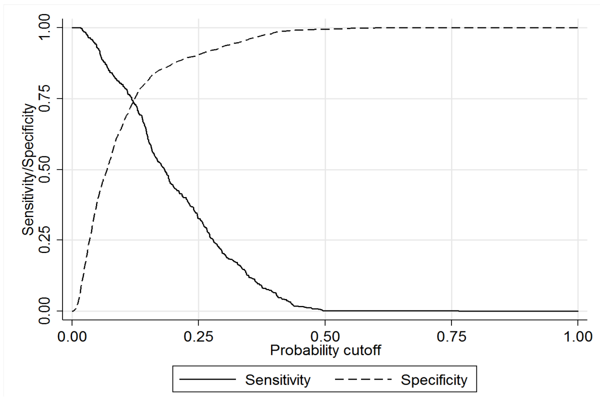

Figure 3: Estimation of probability cut-off

Vulnerability and importance of streets.
The vulnerability of the network is estimated by using the Achilles approach [22]. From this approach we derive the effect of the collapse of a pipe for flooding in the whole network (Figure 4). This value is normalized and used for the prioritization model (P_{Vul}). The importance of the affected streets (e.g. the streets where the sewers in need of rehabilitation are situated) is assessed by using the street types of Open street map and prioritizing them from motorway (P_{IS}=100) to path (P_{IS}=10).

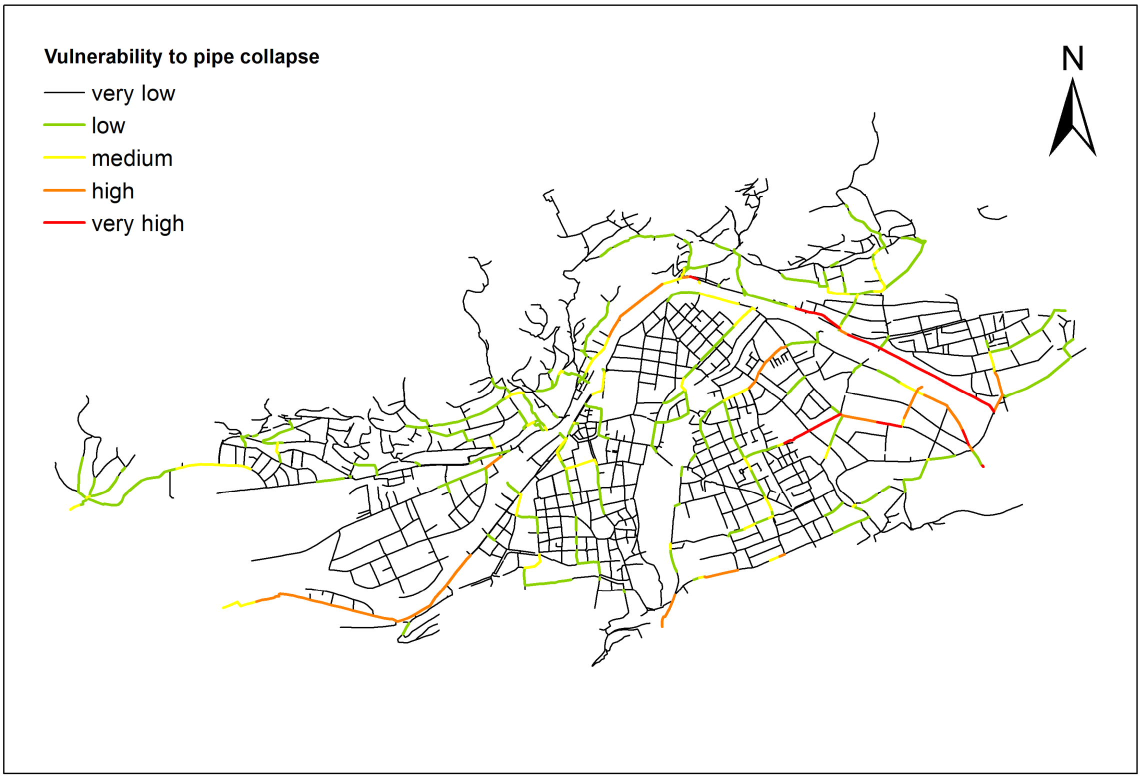

Figure 4: Vulnerability to pipe collapse of the case study

Urban development.
To simulate urban development the Simulation Framework DynaMind [23], a scientific workflow engine with focus on dynamics, is used to read the input data and simulate parcelling of areas. The simulation of urban development is done using a dynamic model described in [24]. Parcels are generated within given boundaries, buildings are placed onto the parcels and population is distributed based on population predictions on suitable areas which are determined by distance calculations. These steps are followed by the calculation of relevant parameters for urban water services like dry weather flow, peak runoff coefficient and water demand. These steps are repeated for a fixed amount of time where one cycle represents one 5 years in reality. At the end of each loop a polygon-shape file with attributes according to the simulation set-up is generated for further usage. Since the year 2000 governmental regulations enforce the application of infiltration methods on newly erected buildings. Nevertheless the effective impervious area increases simply due to the fact that there was no sealing at all before (e.g. undeveloped agricultural areas). Urban development and consequently changes in effective impervious area

happens from 2014 to 2020 when larger parts of the city get developed leading to more and more sealed areas. Until 2030 steady construction occurs although large-scale areas in the city are not available anymore. In overall the effective impervious area of the case study increases by 8% until 2030.

The influence on the priority model is given by the year of development of an area. For this year rehabilitation methods would be preferable carried through in this area due to already ongoing to construction works in this areas. So P_{UD} for the pipes surrounding the developed area for these years is set to 1 while for the previous and following 3 years it linearly decreases to 0.

Climate change scenarios

As assumed climate change scenario, an increase in rainfall intensities is considered. The assumed climate change factor of 1.3 for a 10 year return period [14] is used to estimate the rainfall intensity in 2030. For the period between the starting year (no climate change effect) and 2030 climate change factors are linear interpolated [9].

3. Results and Discussion

The result of the priority model for the different scenarios is used for the changes of qualities depending on the scenario in the hydrodynamic model. Additionally it delivers input for the cost estimation (pipe diameters and length). Figure 5 shows the exemplary result of the priority model for a maximum rehabilitation rate of 2.0% per year considering the effects of urban development. We see that the first rehabilitation measures have to be taken in the city center while the focus shifts more and more to the suburbs until the end of the observation period. The results for the scenarios of this rehabilitation rate (7.1 – 8.6 as seen in Table 1) are shown exemplarily in Table 3. Additionally the average yearly cost for rehabilitation measures at the given rehabilitation rate are displayed. We see that the open cut method (scenarios 7.3 and 8.6) is ca. 2.5 times more expensive than the other two methods, which differ only slightly in terms of costs.

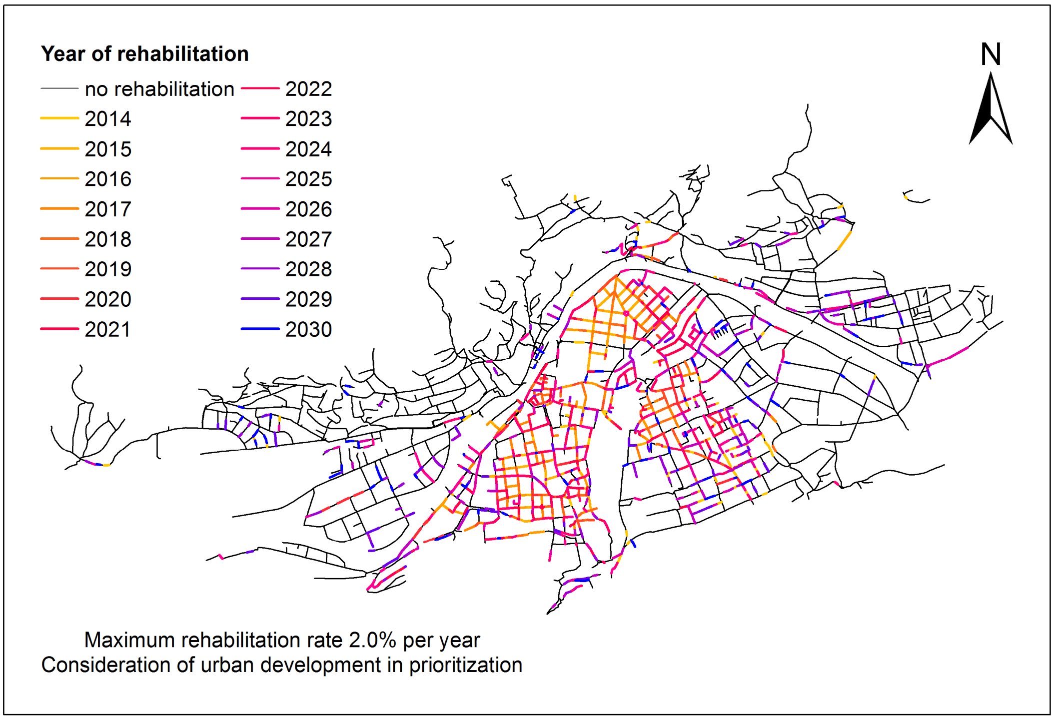

Figure 5: Result of the priority model for scenarios with a rehabilitation rate of 2.0% considering the influence of urban development

Table 3: Results for the exemplary scenarios in 2030

Scenario number	Flooding volume [m³]	Average yearly costs [€]
7.1	217.05	1,640,857
7.2	207.15	1,578,986
7.3	208.13	4,179,343
8.4	99.90	1,623,110
8.5	87.91	1,570,648
8.6	84.83	4,029,862
9.1	95.30	-
9.3	217.91	-

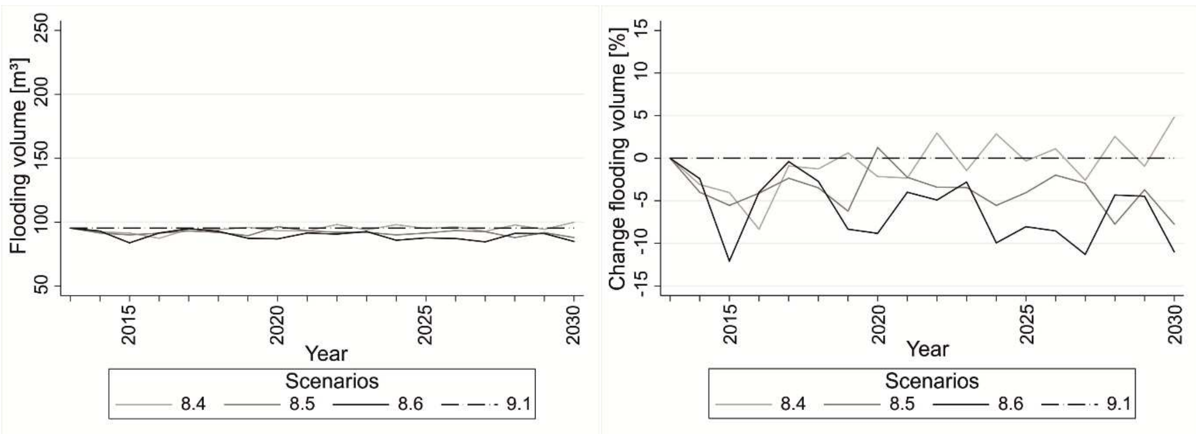

Figure 6: Increase and decrease of flooding volume for different scenarios in m³ and % referring to the baseline scenario 9.1

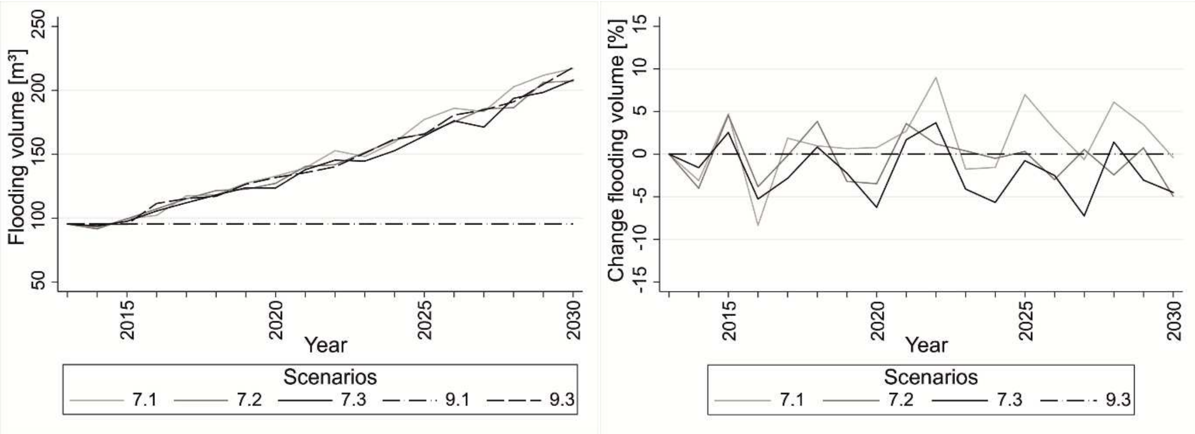

Figure 7: Increase and decrease of flooding volume for different scenarios in m³ and % referring to the baseline scenario 9.3

In Figure 6 we see the influence of the three rehabilitation techniques on a static system without including any influences from urban development or climate change (scenario 9.1). By using the open cut method (scenario 8.6) we can decrease the flooding volume on the static system by 11%, by using the CIPP method (scenario 8.5) still by 7.75%. With sliplining (scenario 8.4) the flooding would increase by 4.8%. If we consider the changes due to urban development and climate change (scenario 9.3) we see a slight change. The open cut method (scenario 7.3) and the CIPP method (scenario 7.2) cause the same decrease in flooding (5%) in comparison to the base scenario (scenario 9.3). The influence of the sliplining method has no influence at all. The fluctuations in flooding volume over the years in the scenarios is caused by the replacement of individual pipes, which could cause short-term effects (for example in Figure 7 in the year 2022). Also the baseline scenario 9.3 is not a linear increase as could be expected by the linear assumption of the climate change factor due to the system qualities and geometry of the observed network. The observed flooding volume can be regulated by combined sewer overflows in the system and in fact an increase in combined sewer overflow (CSO) emissions could be observed. This is however out of scope of this paper.

Another important parameter that is estimated is the costs of the different scenarios. In Figure 8 we see the total yearly construction costs for different rehabilitation methods at different rehabilitation rates. What we can see is that, using a fixed rehabilitation rate, can produce a wide range of costs due to the different prices for the rehabilitation of different diameters. The open cut method is by far the most expensive one with nearly double the costs of the other two. If we assume however a different life expectancy for the different methods (in our case 100 years for the open cut method and 50 for the other two) the picture changes (Figure 9) and in some years the open cut method is the most cost effective method.

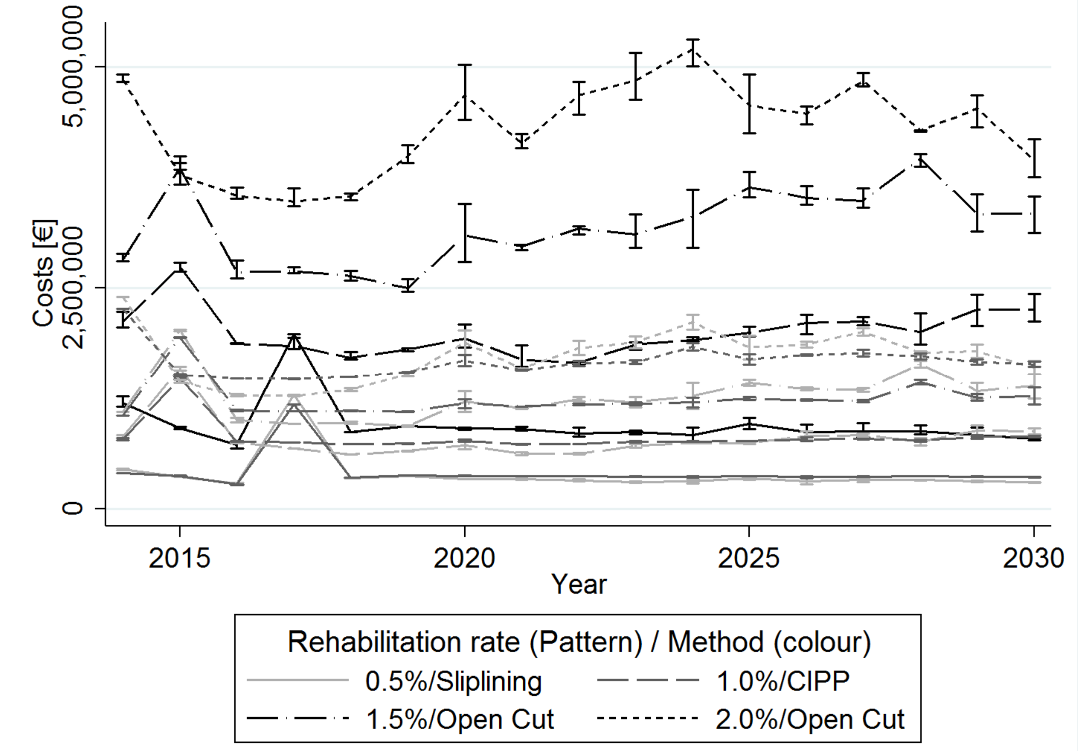

Figure 8: Yearly total costs of the different rehabilitation methods for different rehabilitation rates

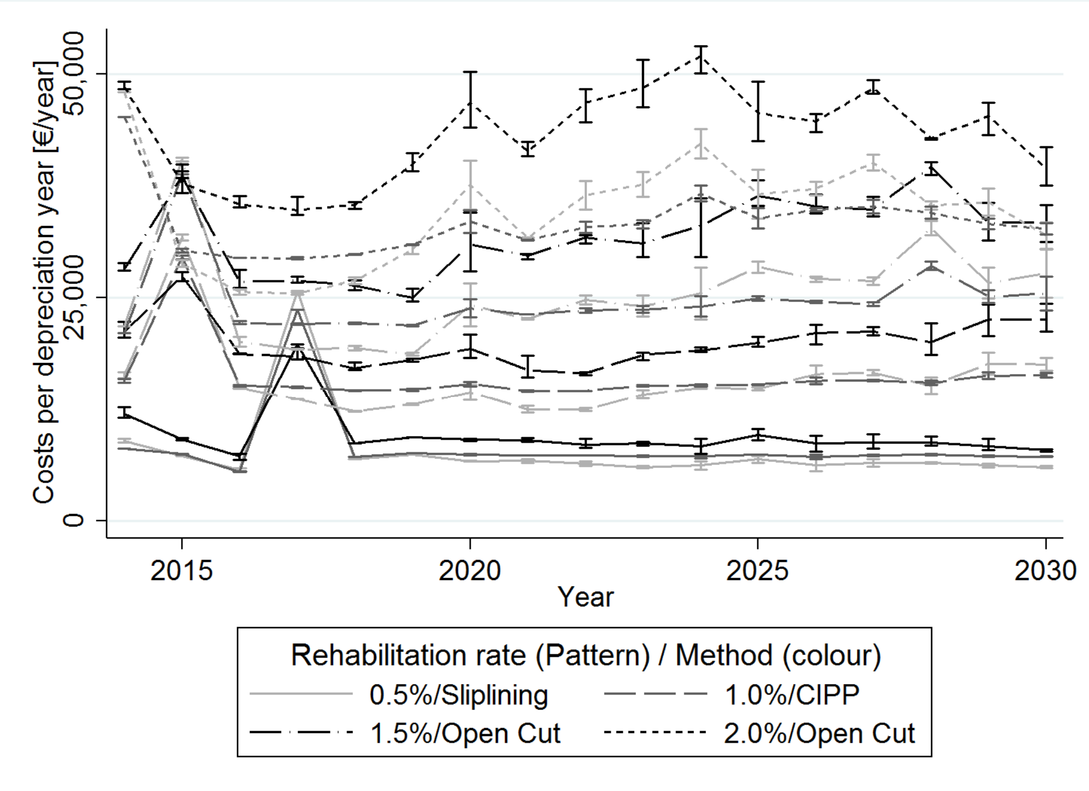

Figure 9: Costs of the different rehabilitation methods for different rehabilitation rates applied for different depreciation times

4. Conclusion

This paper shows that the necessary rehabilitation of the existing network can contribute to a certain amount to the adaptation to the changing environment. Still even this small amount should be exploited due to the fact that the rehabilitation has to be carried out anyway and a smaller amount of accompanying measures (e.g. infiltration) has to be constructed and budgeted.

The higher costs for open cut rehabilitation compared to trenchless method cannot be justified in terms of flooding. The performance of CIPP rehabilitation compared to open cut methods is nearly the same at 40% of the costs. Although in this case only an expansion of 100mm for the open cut was allowed and with higher diameters the performance could be enhanced the usage of open cut methods should be carefully planned and mainly used for higher diameters, customized profiles and easy accessible sewers. In times of restricted budgets a careful choice of methods by taking into account different scenarios and influencing factors gets even more important.

5. Acknowledgments

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