Integrated planning of rehabilitation strategies for sewers

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ABSTRACT

Building measures in sewer systems are increasingly driven by rehabilitation/retrofitting and adaptation needs. Aging infrastructure together with changing boundary conditions (due to climate change, land-use change, demographic change) and also changing design standards and legislation require a prospective design to preserve the functionality of urban drainage systems not only today, but also in a long-term perspective. To improve a prospective design of urban water infrastructure, the Austrian Research Promotion Agency funded the research project 'REHAB – Integrated planning of rehabilitation strategies of urban infrastructure systems'. Therein a novel strategic planning tool which considers these external drivers of rehabilitation strategies is developed. In this study the scope of the project is described and, as well as first results regarding sewer pipe conditions, future development and vulnerability assessment are also discussed.

Key words | adaptation, city development, climate change, deterioration, rehabilitation, urban drainage

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INTRODUCTION

Urban areas and their development strongly depend on the two key tasks of urban water management: supply of high quality potable water and disposal of wastewater and stormwater. These services are central for human well-being as well as for the economic development of urban settlements. Thus, urban water management depends on a reliable infrastructure of water supply networks, separate or combined sewer systems, wastewater treatment plants and stormwater treatment facilities.

In modern cities these assets have been constructed and maintained over decades by past generations. Therefore the water industry is one of the most cost-intensive sectors in the construction industry. For example Cashman & Ashley (2008) estimate that the required investment costs in the water sector infrastructure until 2030 will be 'considerably higher' than for the energy, telecommunications and transport infrastructure sectors. Hence, especially in times of limited national budgets, a cost-effective planning of water-related infrastructure is essential. For example a recent evaluation of Austrian sewer rehabilitation by the Federal Ministry of Agriculture, Forestry, Environment and Water Management showed that current investments in urban water infrastructure are far below a reasonable rehabilitation rate. In the year 2012 a refurbishment rate of only 0.07% (59 km out of 89,700 km) was reached in the (public operated) drainage systems. This means that sewer pipes would have to survive for approximately 1,500 years (Breindl 2013). As this will not happen, in the future either service levels will drop significantly or higher investments are required to maintain these assets. Hence, new solutions for sewer system rehabilitation and management are urgently required.

Building measures in sewer systems are increasingly driven by rehabilitation/retrofitting and adaptation needs. Aging infrastructure together with changing boundary conditions (due to climate change, land-use change, demographic change) and also changing design standards and legislation require a prospective design to preserve the functionality of urban drainage systems not only now, but also in a long-term perspective. For planning of rehabilitation measures, numerous decision-support tools exist (Vanier 2001; Ana & Bauwens 2007). Some tools integrate data management, prediction of failure of sewer pipes (due to aging) and hydraulic performance. Nevertheless changing future conditions as required by the European standard EN 752 (CEN 2008) are usually not considered and adaptation

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measures are often planned independently from rehabilitation strategies.

To improve a prospective design of urban water infrastructure the Austrian Research Promotion Agency (FFG) funds the research project 'REHAB – Integrated planning of rehabilitation strategies of urban infrastructure systems'. The project started in December 2011 and is going to last for 2 years. A project consortium – consisting of a consultancy, software developers and a university is developing a novel strategic planning tool for designing rehabilitation strategies. This project incorporates rehabilitation of water supply and drainage systems. Interaction of these systems and synergy effects in planning building measures for both systems are considered. Nevertheless this study focuses on prospective rehabilitation of combined drainage systems. Therefore sewer deterioration models are combined with performance assessment models (hydrodynamic simulation by means of the Storm Water Management Model software). Additionally vulnerability of individual system components (Möderl *et al.* 2009) is taken into account, as well as changing future conditions due to climate change (e.g. increase of rainfall intensities), land-use change (e.g. pavement of areas) or demographic change (e.g. population increase or decrease; increase of single-person households). As predicting future conditions contains substantial uncertainties, this approach is based on the stochastic generation of virtual future conditions and subsequent statistical evaluation (Sitzenfrei *et al.* 2010).

The method developed herein leads to a sophisticated planning of rehabilitation measures with an improved prioritisation of rehabilitation needs. For example highly vulnerable system elements can be identified to reduce the conditional probability of failure of those elements. Furthermore rehabilitation strategies can be combined with adaptation needs to reduce construction costs, for example by determining required pipe diameters for future conditions.

Consequently this paper analyses the driving impacts of sewer rehabilitation and shows first results when applying this methodology on a catchment of a combined sewer system in Austria.

METHODOLOGY

In this section the functional requirements of sewer systems and possible factors impacting sewer rehabilitation strategies are described: (1) sewer aging including sewer deterioration models which are trying to predict the aging behaviour, (2) city development (i.e. increasing or shrinking population) including demographic change (e.g. the trend from multiple-person households to single-person households), (3) climate change which is expected to lead to an increase in rainfall intensities of strong storm events, and finally (4) vulnerability and risk assessment of sewer collapse.

These factors are exemplified on a catchment of a city in the Alps. Here the city is drained by means of a combined sewer system and rainfall is characterised by strong storm events during the summer period.

Functional requirements for drainage and sewer systems

The European standard 'EN 752 Drain and sewer systems outside buildings' (CEN 2008) defines 13 functional requirements of drainage and sewer systems for the objectives of public health, occupational health, environmental protection and sustainable development. This includes, for example, protection from flooding, protection of receiving waters and groundwater, the structural integrity and design life of infrastructure parts (pipes, combined sewer overflows, etc.) or the prevention of odours and toxic gases. To achieve the functional main requirements the three streams of wastewater (liquid, solids, gas) have to be collected in the urban areas and subsequently transported to the wastewater treatment plant. Required service levels for the different functional requirements are not defined in this European standard but delegated to the national authorities. For flood protection a certain acceptable return period is defined for service failures (usually depending on the land-use representing affected people or critical infrastructure – in Austria this national regulation is ÖWAV RB 11 (2009). To protect receiving waters, discharges from combined sewer overflows are limited in terms of frequency, duration and/or volumes (in Austria this regulation is ÖWAV RB 19 (2007); an English description is available from Kleidorfer & Rauch (2011)).

Observations of sewer systems (e.g. by closed-circuit television) are required, to investigate the structural integrity of the system, to identify damages or blockages, to help to maintain the service levels (i.e. predict failure of system components), to develop rehabilitation plans and to predict required future investment. In this context EN 752 proposes an 'Integrated Sewer System Management' which is defined as 'the process of achieving an understanding of existing and proposed drain and sewer systems, and using this information to develop strategies to ensure that the hydraulic, environmental, structural and operational performance meets the specified performance requirements taking into account future conditions and economic efficiency'. This means that these different aspects of a sewer system have to be analysed and integrated into a common management plan. In this study a workflow is presented in which impact of aging infrastructure, changing environment (climate change, land-use change, population change) and risk considerations are combined in an integrated approach based on hydraulic modelling in order to improve prioritisation of rehabilitation needs.

Sewer aging

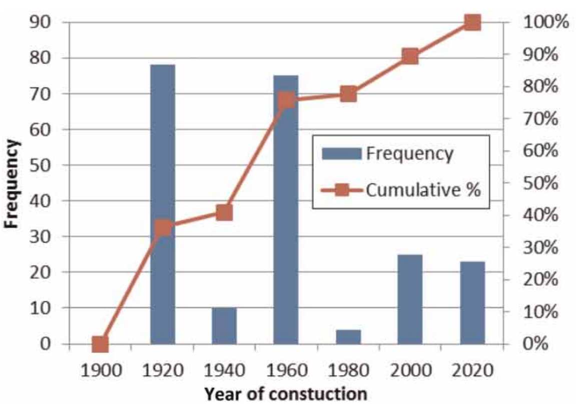
An important part of planning of rehabilitation strategies are sewer deterioration models trying to predict the deterioration behaviour from sewer inspection data (Wirahadikusumah *et al.* 2001; Saegrov 2006; Ana & Bauwens 2007; Tran 2007) as, for example, Markov models (Dirksen & Clemens 2008) or cohort survival models (Baur & Herz 2002).

In this case study sewer pipes are classified into five condition states (CS) ranging from 1 (best condition, full functionality) to 5 (worst condition, immediate action required). The long-term goal of the sewer system operator is to have all sewer pipes in a condition not worse than CS 3 (defects visible, need to take action over the medium term). This classification is based on a video-camera inspection according to CEN (2003). The building years in the test catchment range from 1904 until 2008 and the CS from 1 to 5. Histograms presenting the year of construction and the CS are shown in Figure 1. For CS three distributions are shown, one from on-site classification during the investigation, one from an automatic classification based on standardised classification protocols (ATV-M 149E 1999), and one after a manual correction of the sewer network operator. These different distributions of CS also show problems of planning rehabilitation strategies, as classification is always subjective and different classification can lead to different renewal strategies, e.g. in this case the on-site classification did not show an occurrence of CS 5. Figure 2 and Figure 3 show examples of visual inspection images leading to CS 3 and CS 4, respectively. Figure 4 shows the layout of the test catchment including CS classification. These classifications are inputs to a sewer deterioration model to predict future conditions of sewer pipes.

The sewer pipe conditions (either present or future state) are no direct input for the hydraulic model but they allow an estimation of effects of pipe failures. If, for example, a sewer pipe collapses, the impact on the hydraulic performance of the sewer system can be evaluated by 'closing' that pipe in the model. Partial blockages can be simulated as a change in the pipe diameter or by implementing orifice devices. Possible effects are, for example, an increased risk of flooding or pollutant discharges to the receiving water.

Changing environment

Performance and efficiency of a sewer system are heavily influenced by the environmental boundary conditions and the changes thereof. In terms of relevance for sewer systems the following two factors are recognised as the most pressing ones: climate change (more specifically, the increase in precipitation intensity) and land use change. Numerous studies have been published which show the impact of climate change on urban water systems (e.g. Grum *et al.* 2006; Butler *et al.* 2007; Kleidorfer *et al.* 2009), often outlined together with potential response strategies (e.g. Ashley *et al.* 2005; Semadeni-Davies *et al.* 2008; Arnbjerg-Nielsen & Fleischer 2009). Further impacts on rehabilitation strategies are, for example, the potential city development by



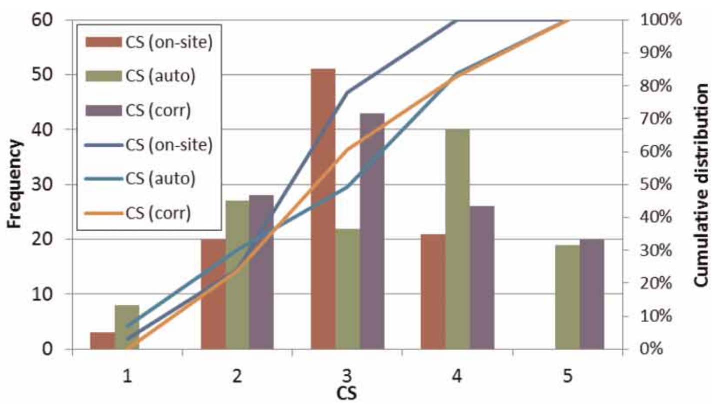


Figure 1 | Histograms of year of construction (left) and condition states (right).

Figure 2 | CS 3. Damage in concrete sewer pipe, circular shaped; construction year 1906.

Figure 3 | CS 4. Damage in stoneware sewer pipe, circular shaped; construction year 1906.

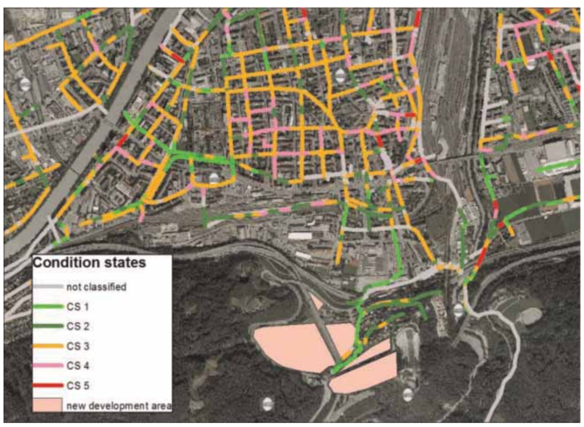


Figure 4 | CS classification in test catchment from CS 1 (best) to CS 5 (worst) including the potential for new developments (bottom); Orthophoto: www.geoimage.at ©.

means of population change (shrinking or increasing population), land-use change (increase of impervious area due to pavement of urban areas, or decrease due to implementation of in-site infiltration facilities). Kleidorfer *et al.* (2009) analysed these two impacts and concluded that both are of the same magnitude when investigating impact on urban flooding and combined sewer system emissions.

For a first, rough estimation of effects, detailed regional climate change projections (with the problem of temporal downscaling for urban rainfall runoff simulation) are not necessarily required. For example Arnbjerg-Nielsen (2008) calculated climate factors for consideration of climate change in design of urban drainage systems for Denmark based on three different approaches. He estimated the increase in design intensities to be 10–50% depending on duration, return period and anticipated technical lifetime of sewer systems.

Other potential impacts of climate change can be increased production of hydrogen sulphide (caused by longer dry weather periods and hotter days). This not only causes odour problems but also corrodes sewer pipes (i.e. decreases lifetime) (Zhang *et al.* 2008).

Urich *et al.* (2011) presented an approach in which the UrbanSim package (Waddell *et al.* 2008) was used to predict the population projections of the urban development together with infrastructure development in 1-year timesteps for investigating adaptation pathways of the urban water infrastructure. Although this approach is the final goal for predicting the urban development in the REHAB project, currently only defined city development scenarios are considered. For example Figure 4 shows potential development areas in the test catchment.

Not only (total) population changes might impact land-use change but also demographic changes or changes in the behaviour can cause an additional demand for homes. Figure 5 shows the expected increase of the population in the case study area starting with 2001 (=100%). According to national population projections (Hanika 2011) a population increase of 20% is expected until 2050. Additionally there is a trend from multiple-person households to single-person households anticipated, resulting in a decrease of the average household size from 2.4 to 2.15 until the year 2050. This trend leads to an additional demand for housing units and hence impacts land-use change (i.e. pavement of areas).

A changing environment is represented in a hydraulic sewer system model as changes in model input (e.g. rainfall or dry weather flow generation), model parameters (e.g. paved area) or as changes in the model layout (e.g. new

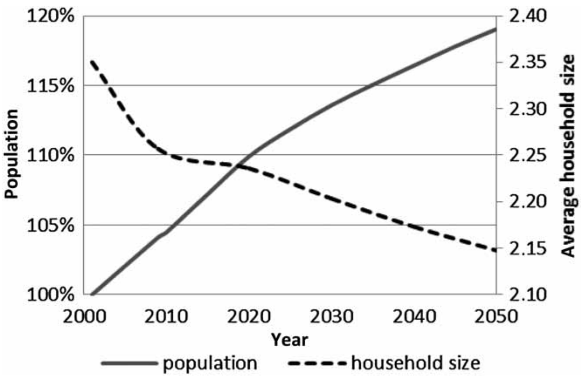


Figure 5 | Expected change in population and average household size (Data source: Hanika (2011)).

Figure 6 | Vulnerability assessment for sewer collapse.

connected development areas). To consider changes in input or parameters in a model is an easy task as it is often done in Monte Carlo-based procedures or scenario investigations. Changes in the model layout are harder to automate as these require severe manual procession steps or engineering decisions. However, recent studies show satisfactory results for an automatic network extension based on city development (Sitzenfrei *et al.* 2010).

Vulnerability and risk assessment

Finally, the different impacts on a drainage system can be described as risk. Risk is defined as the likelihood of a certain event (e.g. sewer collapse) multiplied by its consequence (e.g. people affected by flooding). Instead of the consequence, the vulnerability of a system can be used, representing the consequences of sewer pipe damages on the entire system performance (Möderl *et al.* 2009). In terms of modelling this is the same as the sensitivity of the model performance to a change in model input or model parameters (Mair *et al.* 2012). Hence rehabilitation strategies can benefit from the information about which pipe failures cause which related problems in the functionality of the system. For example Figure 6 shows a vulnerability assessment of the test catchment with respect to sewer collapse and flooding (no vulnerability, medium vulnerability, high vulnerability). This follows the methodology proposed by Möderl *et al.* (2009) and is described with more details by Fuchs-Hanusch *et al.* (2012). Therefore sewer collapse is modelled as a closed pipe in the hydraulic model, and the impact on the performance of the system to protect from flooding is evaluated.

Consequently it can be seen that, although the sewer pipe conditions are often CS 3 or CS 4 (see Figure 4), only a limited number of sewer pipes are crucial for maintaining the system functionality (with the aim to prevent flooding). When planning rehabilitation strategies this information can be used to optimally maximise out the anticipated lifespan of sewer pipes when system functionality is not at risk or to guarantee system functionality, for example by inspecting pipes more often than at regular intervals or by replacing them.

The shown vulnerability for flooding is only one example to be considered when planning rehabilitation strategies. Further external influencing factors can be, for example, groundwater contamination, emissions to receiving waters, and constraints of building measures (e.g. due to heavily used roads). Furthermore, cascading effects in the vulnerability of sewer pipes (e.g. sewer collapse leading to flooding, flooding leading to failure of pumping stations) can be considered (Sitzenfrei *et al.* 2011).

An integrated approach

A major challenge in this project is to combine the different aspects in a multi-criteria decision support system. These aspects also impact the decision towards reasonable measures (e.g. pipe inlining in case the structural stability is still provided and no future development is expected that demands an increase of the pipe diameter). Such integrated approaches have already been shown for urban drainage systems (Urich *et al.* 2010, 2011) and water supply systems (Sitzenfrei *et al.* 2010). The methodology of the REHAB project is based on these results and technologies. The workflow is shown in Figure 7 and starts with data collection (e.g. by means of visual inspection) and continues with evaluation of pipe damages and classification into

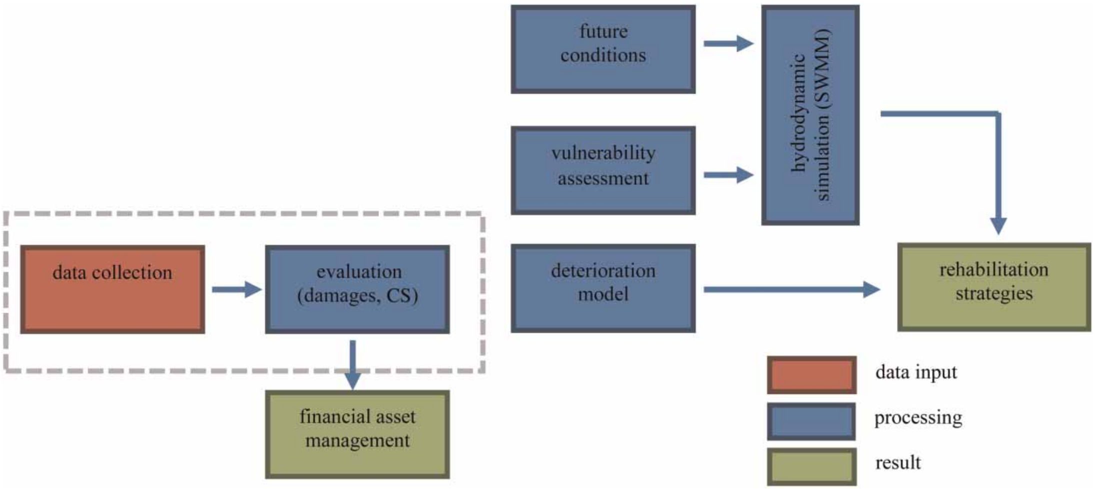


Figure 7 | Workflow for planning rehabilitation strategies in the REHAB project.

CS. Impact of future development (city development and climate change) is evaluated by means of hydrodynamic simulation to estimate if an increase or decrease of the pipe diameters is required. A vulnerability assessment (also by means of hydrodynamic simulation) enables the incorporation of information about consequences of failures (e.g. pipe collapse). Together with results from a deterioration model these boundaries will be considered, to evaluate an optimal anticipated lifespan of sewer pipes and to improve rehabilitation strategies.

Figure 8 shows some exemplary results of an integrated planning and management procedure. Two different scenarios of pipe collapse are compared to a development scenario (connection of new development area). As shown in Figure 6 the system's flooding performance is hardly vulnerable to a failure of pipe no. 1 (although it is in CS 5) and medium vulnerable to a failure of pipe no. 2. Figure 8 (left) summarises the impact on the flooding performance. Flooding volume increases by 26% in the case of pipe no. 1 collapsing, and increases by >100% in the case of pipe no. 2 collapsing. The connection of a new development area (4.14 ha of impervious area) increases the flooding volume by 43%. All these results are conditional on the rainfall input, here a design storm event with return period 5. Figure 8 (right) shows the effectiveness of a new drainage pipe to mitigate these effects. This new pipe is extremely effective at reducing flooding in the case of pipe no. 2 collapsing, and still has some potential to mitigate flooding in the other scenarios.

CONCLUSION AND OUTLOOK

In this paper the project 'REHAB – Integrated planning of rehabilitation strategies of urban infrastructure systems' is presented. Therein a project consortium (consultancy,

Figure 8 | Impact of pipe collapse scenarios and new development areas on flooding volume on original system (left) and extended system (right).

software developers, scientists) develops a novel strategic planning tool for designing rehabilitation strategies by incorporating climate change impacts, city development and sewer pipe deterioration. The prospected planning horizon is approximately 40 years, until 2050.

This method follows the approach of 'Integrated Sewer System Management' proposed by the European standard EN 752 (CEN 2008). Based on hydraulic modelling, different multiple functional requirements of a sewer system can be evaluated. The consideration of environmental changes (climate, land use, population) helps to reach the aim of sustainable development.

It is clear that such projections into the future contain substantial uncertainties of different types and that these uncertainties have to be mentioned in such a context. According to Walker *et al*. (2003) and Refsgaard *et al*. (2007) the different types of uncertainties are statistical uncertainties, scenario uncertainties, qualitative uncertainties, recognised ignorance and total ignorance. Planning engineers are usually only dealing with statistical uncertainties which are common in urban water management (e.g. Dotto *et al*. 2011, 2012; Deletic *et al*. 2012). Assuming future developments would be perfectly known, this would be only one additional point to be regarded in design of water infrastructure systems. Unfortunately future conditions are highly uncertain, both for climate change and for demographic change. Hence, more complex forms of uncertainties have to be considered or at least kept in mind. Thus, in the REHAB project, scenario uncertainties will be investigated by creating multiple realisations of future development.

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