Selective inspection planning with ageing forecast for sewer types

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Abstract Investments in sewer rehabilitation must be based on inspection and evaluation of sewer conditions with respect to the severity of sewer damage and to environmental risks. This paper deals with the problems of forecasting the condition of sewers in a network from a small sample of inspected sewers. Transition functions from one into the next poorer condition class, which were empirically derived from this sample, are used to forecast the condition of sewers. By the same procedure, transition functions were subsequently calibrated for sub-samples of different types of sewers. With these transition functions, the most probable date of entering a critical condition class can be forecast from sewer characteristics, such as material, period of construction, location, use for waste and/or storm water, profile, diameter and gradient. Results are shown for the estimates about the actual condition of the Dresden sewer network and its deterioration in case of doing nothing about it. A procedure is proposed for scheduling the inspection dates for sewers which have not yet been inspected and for those which have been inspected before.

Keywords Ageing; inspection planning; rehabilitation; sewer systems

Introduction
Sewers are deteriorating slower or faster under specific local circumstances. So their condition is not determined by age alone. There are variations in material, load, stress, wastewater and subsoil characteristics which have to be considered as factors influencing the process of sewer deterioration. In order to prevent sewers from collapse, choke, wastewater overflow or exfiltration and groundwater infiltration, the state of the sewers must be inspected, not necessarily at regular intervals but in due time before serious damage occurs.

In Germany, most States require the inspection of the total sewer network once in ten years. This means that, on the average, a sewer would have to be inspected eight to ten times in its lifetime. Apparently this is a very high and costly standard and it would be very inefficient to do it at constant regular intervals throughout the network. The efficiency of sewer inspection is greatly improved if failure prone sewers are inspected more frequently and others at larger intervals. In other words: the same risk level could be guaranteed with a smaller amount of inspection or, with the same inspection cost, the risk of failures could be reduced if local knowledge on specific sewer deterioration is used systematically for inspection planning.

Sewer inspection is producing enormous amounts of data which must be reduced by classification. Several classification schemes are in use for describing and evaluating the condition of sewers. In Germany, different classification models are in practice and under discussion right now (Hochstrate 2000). One major issue in this discussion is whether the data should be classified mainly with respect to the urgency of rehabilitation work, or whether the classification should indicate the extent of rehabilitation required within a sewer reach for a more realistic estimate of the investment needs. Whatever classification scheme for sewer condition is used, condition classes provide useful information for estimating and forecasting the state of individual reaches and to plan an efficient sewer inspection program.
In the following, a sewer deterioration model is presented which can be calibrated with local sewer inspection data and applied to forecast the condition of the sewer network in total as well as the condition of particular sewers. The case of Dresden sewers will show that these estimates are significantly improved by the inclusion of further sewer characteristics.

A deterioration model for sewers

The process of sewer deterioration can be described by a cohort survival model. In this model, cohorts are sewers of the same period of construction sharing some other features, such as material, diameter, bedding and subsoil characteristics, which are supposed to influence their service life. Within their life-span they pass through different categories of condition, from best to worst. With some probability, they survive a number of years within a category of condition. Actually these survival curves are transition curves into worse categories of condition. They can be determined from classified inspection data and used to forecast the number of years it takes until a specific type of sewer will enter a critical category of condition.

A cohort survival model for infrastructure deterioration was first formulated at Karlsruhe University by Herz and Hochstrate in 1987. From the mathematical model (Herz, 1995), two software packages emerged, one for drinking water networks (KANEW) and one for sewers (AQUA-WertMin). Both programs use a special distribution function, the so-called Herz distribution, which has some computational advantages and appears to be most appropriate to model the deterioration of long-lived infrastructure elements. After some time of resistance, the failure and transition rates start to increase exponentially up to the median age and then turn into a degressive curve approaching a finite maximum value. That is, at this stage, the most resistant infrastructure elements show no increase in their failure rate and, thus, get older but do not age any more. The failure and transition rate is mathematically linked with the probability density function of the service life and with survival and transition functions. From these functions, residual life expectancies and expected duration of stay in a specified category of minimum condition can be derived.

Without going into the details of the mathematics (Herz, 1995, 1996), the formula of the transition functions \( R(t) \) is given here as follows.

\[
R(t) = \frac{(A+1)}{(A+e^{B(t-C)})}
\]

with \( R(t) \) percentage of pipes that will not have changed into an inferior condition class at a particular age \( t \), indicating the ageing speed

\( A \) vector of ageing parameters (–), the larger, the smoother is the transition.

\( B \) vector of transition parameters (1/years), the larger, the faster is the transition; asymptotic transition rate at high age

\( C \) vector of resistance times (years) in condition class

Examples of such transition functions are shown in Figures 2, 3 and 5. The median age \( t_{50} \) is derived as \( t_{50} = C + B^{-1}\ln(A+2) \). At this age, 50% of sewers have entered the next worse condition class.

To forecast the lifetime of an individual sewer pipe, a minimum standard or critical condition class can be defined requiring major rehabilitation work. This critical condition class depends on local circumstances, for example whether the sewer is located in a water protection zone, and on the standards a Utility may want and can afford. In any case, at the end of a sewer’s service life, a decision has to be taken on the most appropriate rehabilitation technology. This is a matter of the type and severity of damage revealed, the remaining substance of the sewer and the external cost of public works in the street. In this decision,
economic aspects play a role as great as professional judgement of technical feasibility and future requirements. Therefore, the service life of a sewer is not determined just by technical wear, but also by unit costs of repair and rehabilitation work and by amended technical specifications and standards. Anyway, monitoring sewer condition will be necessary in order to take the right decision at the right time. There is no way of predicting the end of a sewer’s service life without reliable information on its actual condition.

The cohort survival model of sewer conditions implemented in the software package AQUA-WertMin® requires an inspected and classified inventory of sewers. It is not a sewer network database. Every national or local classification scheme with up to 6 condition classes can be used. The modules of this software allow exploration of strategies for asset management, particularly the calculation of financial requirements depending on sewer condition thresholds. Network rehabilitation investments and sewer condition can be simulated for different rehabilitation strategies in the long run (Herz and Krug, 2000). For selective inspection planning, the prediction of the residual service life of sewers with the formulae given in this paper is of special interest.

Case study: Dresden sewers

There are over 1,400 km of sewers in Dresden, the oldest dating from the early 1870s. About a quarter of the network was constructed before 1900, and about 85% of the sewers are older than 60 years. However, not always the oldest sewers cause the biggest trouble. More often it is the younger pipes that require rehabilitation, particularly those constructed during the socialist period with materials of poor quality and insufficient bedding conditions. At the time of the study, two thirds of the Dresden sewer network were TV-inspected, but only 15% of the data were formally classified and evaluated, a gap which is being gradually filled by the Dresden waste water company. The reason for this lag of inspection and evaluation is a shortage of funds in the first place. Available funds are spent to solve more urgent problems in the sewer network, which had been neglected over decades, particularly for reducing the pollution of the Elbe river through stormwater outlets and insufficient wastewater treatment. If the Dresden sewer network is to be inspected once within ten years, this would cost about 2 million €. So, like many other cities, Dresden has only partially fulfilled this requirement up to now, and an even smaller part of the sewer network has been formally classified so far (Baur and Herz, 1999).

In Dresden, the condition of inspected sewers is categorised with a specific classification model into 5 condition classes (cc), from condition class 5, very good, to condition class 1, the worst condition with highest priority for rehabilitation. The classification model considers both the importance of single faults and the substantial condition of the sewer reach. The subset of inspected and classified sewers which could be used for the model, was further reduced by the lack of information on the construction year or period of the inspected and classified reaches. Both items, condition class and year of construction were available only for 4.6% of the total network and, of course, this data set is not representative for the Dresden sewer network. However, a first analysis of this data showed, as expected, considerable variation of condition for sewers of the same age and type. Apparently under specific circumstances, the process of deterioration runs faster or slower.

The main interest of this study is in the ageing speed of different sewer types and its use for inspection planning. How many years will it take for a sewer, previously inspected or not, to enter a predefined critical condition class? Without data from a previous inspection, we have to assume average ageing behaviour of the sewer type. With data from a previous inspection, we can determine the ageing speed and may assume that the inspected reach will continue on its ageing path, which may be faster or slower than the average.

The average ageing of the Dresden sewer network was determined from a representative
sample of all sewers. Transition functions between the sewer condition classes were calibrated from this data set. They allow forecasting of the number of sewers that will be in each of the 5 condition classes in future years. Differences in ageing behaviour were subsequently identified and analysed for types of sewers with specific characteristics. Special attention is given here to the transition curves into condition class two, requiring rehabilitation measures, again after inspection.

Creating a representative data set
As mentioned before, 15% of Dresden sewers were classified after inspection and only 4.6% had complete information on condition class, year of construction and year of inspection. Because inspection and classification were primarily done for sewers that were suspected to have deteriorated, these data are not representative for the total Dresden network. Therefore, a sample was taken from these sewers by applying quotas corresponding to the percentages of materials and construction periods in the total network as shown in Figure 1. A random systematic draw from the above 4.6% resulted in a data set of 37.8 km representing 2.7% of the total Dresden network.

Calibrating transition functions
The parameters $A$, $B$ and $C$ of the Herz transition functions are determined by the weighted least squares method. The transition curve from condition class (cc) 4 (good) to 3 (not so good) shown in Figure 2 was calibrated from the Dresden data set (with $C = 0$). This was done with a special module of AQUA-WertMin©. In addition, the program calculates transition dates and residual lifetimes, ending with transition into cc1, as well as the ageing speed of inspected sewers.

For the representative sample of 37.8 km of Dresden sewers, the four transition functions shown in Figure 3 were calibrated. At an age of 60 years about 50% of the sewers are in condition class 4 and better (cc5). If inspection reveals that a sewer older than 60 years is still in condition class 4 or better, it has a lower ageing speed $R^*(t)$. Younger sewers in condition class 3 obviously have an ageing speed $R^*(t)$ over 50%, they are ageing faster than...
Simulating the state of the sewer network

With transition functions, the network condition can be determined for any year for the actual stock of sewers. Figure 4 shows the result of such a simulation for the Dresden sewer sample back to the year 1900 and into the future up to the year 2080, in the case of no rehabilitation measures being taken. This may serve as a reference for the calculation of net effects of alternative rehabilitation programs. As can be seen from Figure 4, the majority of these 38.7 km of sewers would be in the highest priority class cc1 in the year 2080.

Calculating ageing speed and residual service life of inspected sewers

Inspection reveals whether a sewer has deteriorated faster or slower than average. The individual ageing speed of a sewer allows generation of a better estimate of the next inspection date. The ageing speed $R^*(t)$ of an inspected sewer is determined by the middle of the condition class revealed by inspection at the particular age of the sewer (Figure 5).

Figure 5 may illustrate this procedure. A 60 year old sewer was found to be still in good condition cc4. So its ageing speed is halfway between the transition functions $cc5 \rightarrow cc4$ and $cc4 \rightarrow cc3$, in this case approximately at 30%. Without further information, the dates...
for entering subsequent condition classes are read on the 30% aging speed line: entering cc3 at age 80 and cc2 at age 130. So the residual service life is about 70 years, if a condition as bad as cc2 is not tolerated. This condition class could be defined as the intervention class. It takes another 40 years before the sewer enters cc1, the ultimate condition requiring rehabilitation. During such long periods, of course, further inspections are needed to check the underlying assumption of a constant ageing speed. This should be done before entering cc2, at the latest. Table 1 gives an example of the AQUA-WertMin© output for three sewers from the Dresden sample.

Scheduling inspection dates
Transition functions calibrated for the local network of sewers help to schedule inspection dates. For the first inspection, average ageing behaviour is assumed and a condition threshold set at a relatively good condition, for example before entering cc3, as a matter of precaution. For the second inspection, the individual ageing speed of the sewer is used in combination with a somewhat lower threshold, for example before entering cc2. Subsequent inspection dates can be scheduled according to the updated ageing speed of the sewer, based on the result from the most recent inspection. There are good reasons to assume that further information on the characteristics of the sewer reach will lead to better estimates of the individual ageing speed. Therefore, subsets of the Dresden sewer sample were used to calibrate transition functions for specific types of sewers.

Deterioration of sewer types
The following variables were used to establish types of sewers with presumably different ageing behaviour:

- construction period: \(< 1900, 1900–1939, >1940\)
- material: concrete, stoneware, PVC, others
- function: wastewater, stormwater, combined
- type of pipe: feeder channel, main channel
- shape of profile: circular, egg-shaped, others
- size of profile: \(< 300 \text{ mm}, 300–1,000 \text{ mm}, > 1,000 \text{ mm}\)
- gradient: \(< 1\%, 1–5\%, > 5\%\)
- street category: main street, side street, others

Due to the sample size, a cross classification was not feasible. Thus a uni-variate analysis was performed for sewers by each category of the above variables, adding up to a total of 21 sewer types. The ageing parameters of each sewer type were calibrated. The median age \(a_{i,\text{type}}\) of entering class \(i\) according to the Dresden sewer condition classification model was chosen as a complex ageing indicator for each sewer type. This indicator was standardised in relation to the median age \(a_{i,\text{total}}\) for the total Dresden sewer sample. Because the median age of entering a particular condition class is not independent from the one of the preceding class, the geometric (instead of arithmetic) mean was calculated from the standardised factors \(f_{a_{i}}\) as follows:

![Table 1 Example of aging speed \(R^{*}(t)\) and transition years for sewers](http://iwaponline.com/wst/article-pdf/46/6-7/389/42610/389.pdf)
Sewer types with \( f_{a,\text{type}} < 1.0 \) are ageing faster than the average Dresden sewer. The results from this calculation are presented in Table 2 together with the age of transition into the condition classes cc. Sewer types are ranked according to their relative overall ageing speed. For example, for the average Dresden sewer the median age of entering \( \text{cc2} \) is 104 years. A median age factor \( f_{a,3 \rightarrow 2} = 0.80 \) (circular profile) means that \( \text{cc2} \) will be reached earlier. In this case, at an age of 83 years, 50% of all circular profiles will be in \( \text{cc2} \) (or worse) which is 0.8 times the network mean. Egg-shaped sewers, by comparison, have a median age of 145 years which is 1.4 times the network value. So on average, in the present sample, it takes 62 years longer for egg-shaped sewers to reach \( \text{cc2} \) than for sewers with a circular shape. Note that these are results from a uni-variate analysis with all other variables being not controlled.

### Implications for scheduling first inspections

The results from this analysis show that specific attributes of sewer types should be considered for the estimation of inspection dates and residual service lives. Special attention should be given to sewers with attributes that show small median age factors \( (f_{a,\text{type}}) \) or small factors for the transition into specific condition classes \( (f_{a,3 \rightarrow 2,\text{type}}) \). Due to the limitations of a uni-variate analysis, the results of this study cannot be directly applied to multi-attribute sewers. In this situation, for the first inspection, a “safe” estimate would be to take the earliest date from all the sewer types of Table 2 with characteristics known for that particular sewer. An example is presented in Table 3 which shows, once again, the importance of including the individual attributes of sewers into the estimation procedure. A multi-variate analysis combining two or more characteristics of individual sewers would lead to more reliable inspection dates. They would be less “on the safe side” and the first inspection date would certainly be later than 2009 for the sewer presented in Table 3.

### Table 2  Median age factors and transition ages for Dresden sewer types

<table>
<thead>
<tr>
<th>Sewer type</th>
<th>( f_{a,\text{type}} )</th>
<th>( f_{a,3 \rightarrow 2,\text{type}} )</th>
<th>( \text{cc5-c4} )</th>
<th>( \text{cc4-c3} )</th>
<th>( \text{cc3-c2} )</th>
<th>( \text{cc2-c1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC</td>
<td>0.24</td>
<td>0.35</td>
<td>7</td>
<td>11</td>
<td>36</td>
<td>57</td>
</tr>
<tr>
<td>1940–to date</td>
<td>0.30</td>
<td>0.33</td>
<td>8</td>
<td>13</td>
<td>34</td>
<td>52</td>
</tr>
<tr>
<td>Circular</td>
<td>0.76</td>
<td>0.80</td>
<td>21</td>
<td>47</td>
<td>83</td>
<td>100</td>
</tr>
<tr>
<td>Gradient &gt; 5%</td>
<td>0.78</td>
<td>1.05</td>
<td>28</td>
<td>64</td>
<td>140</td>
<td>511</td>
</tr>
<tr>
<td>Waste water</td>
<td>0.85</td>
<td>0.84</td>
<td>26</td>
<td>53</td>
<td>87</td>
<td>108</td>
</tr>
<tr>
<td>(&lt;300 \text{ mm})</td>
<td>0.86</td>
<td>0.88</td>
<td>24</td>
<td>49</td>
<td>91</td>
<td>124</td>
</tr>
<tr>
<td>Storm water</td>
<td>0.89</td>
<td>0.94</td>
<td>21</td>
<td>56</td>
<td>98</td>
<td>133</td>
</tr>
<tr>
<td>Gradient &lt; 1%</td>
<td>0.90</td>
<td>1.35</td>
<td>23</td>
<td>44</td>
<td>109</td>
<td>681</td>
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<tr>
<td>In side streets</td>
<td>0.92</td>
<td>0.93</td>
<td>26</td>
<td>56</td>
<td>97</td>
<td>126</td>
</tr>
<tr>
<td>Minor channel</td>
<td>0.95</td>
<td>1.00</td>
<td>24</td>
<td>56</td>
<td>104</td>
<td>142</td>
</tr>
<tr>
<td>In main streets</td>
<td>1.05</td>
<td>1.04</td>
<td>31</td>
<td>62</td>
<td>108</td>
<td>141</td>
</tr>
<tr>
<td>Combined</td>
<td>1.06</td>
<td>1.01</td>
<td>33</td>
<td>62</td>
<td>108</td>
<td>142</td>
</tr>
<tr>
<td>Main channel</td>
<td>1.06</td>
<td>1.01</td>
<td>29</td>
<td>78</td>
<td>105</td>
<td>129</td>
</tr>
<tr>
<td>(&gt;1,000 \text{ mm})</td>
<td>1.08</td>
<td>0.92</td>
<td>43</td>
<td>81</td>
<td>96</td>
<td>99</td>
</tr>
<tr>
<td>1900–1940</td>
<td>1.11</td>
<td>1.00</td>
<td>42</td>
<td>65</td>
<td>104</td>
<td>131</td>
</tr>
<tr>
<td>300 mm &lt; (\phi) &lt; 1,000 mm</td>
<td>1.18</td>
<td>1.16</td>
<td>33</td>
<td>67</td>
<td>121</td>
<td>178</td>
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<tr>
<td>Stoneware</td>
<td>1.19</td>
<td>1.52</td>
<td>32</td>
<td>60</td>
<td>158</td>
<td>354</td>
</tr>
<tr>
<td>Gradient &lt; 5%</td>
<td>1.20</td>
<td>1.52</td>
<td>36</td>
<td>74</td>
<td>158</td>
<td>993</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.25</td>
<td>1.38</td>
<td>33</td>
<td>74</td>
<td>143</td>
<td>485</td>
</tr>
<tr>
<td>Egg-shaped</td>
<td>1.43</td>
<td>1.39</td>
<td>44</td>
<td>77</td>
<td>145</td>
<td>208</td>
</tr>
<tr>
<td>Before 1900</td>
<td>1.66</td>
<td>1.49</td>
<td>48</td>
<td>81</td>
<td>155</td>
<td>309</td>
</tr>
<tr>
<td>Average</td>
<td>1.00</td>
<td>1.00</td>
<td>29</td>
<td>60</td>
<td>104</td>
<td>135</td>
</tr>
</tbody>
</table>
This procedure was applied to sewers in a district of the Dresden network which was inspected recently. The condition class calculated “on the safe side” was compared with the classified TV-inspection data. The majority of sewers were within the calculated condition class, some were still in a better one. No sewer was in a condition class worse than calculated.

Summary and conclusions
In this pilot study, a cohort survival model was applied to a representative sample of the Dresden sewer network. The process of sewer deterioration is described by transition functions into successively worse condition classes, calibrated from TV-inspection data. Significant differences were found in the ageing behaviour of sewer types. Sewers with specific attributes seem to deteriorate much faster than others, so they should be inspected at shorter intervals. Inspection intervals should be chosen according to the expected date for entering a critical condition class. The Wastewater Company should define such an intervention class. For the first inspection, it is recommended to use the median age of transition into this condition class. Estimates of transition dates are improved by referring to transition functions of particular types of sewers. For successive inspections, the condition class revealed by the preceding inspection allows determination of the ageing speed of that particular sewer. This information is particularly useful in the absence of further attributes of the sewer because it gives a more reliable estimate of future transition dates. With this procedure of modified inspection intervals, selective inspection will increase efficiency and provide lower risk at the same cost.

References
AQUA-WertMin: www.aqua-ingenieure.de
KANEW: www.tu-dresden.de/biwiss/stadtbau/KANEW.html

Table 3  Example of first inspection date estimate

<table>
<thead>
<tr>
<th>Sewer characteristics</th>
<th>Median age of transition into cc3</th>
<th>Median age of transition into cc2 for intervention class cc2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction year</td>
<td>1975</td>
<td>13</td>
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<tr>
<td>Material</td>
<td>PVC</td>
<td>11</td>
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<tr>
<td>Function</td>
<td>Minor</td>
<td>53</td>
</tr>
<tr>
<td>Type</td>
<td>Wastewater</td>
<td>56</td>
</tr>
<tr>
<td>Average Dresden sewer</td>
<td>60</td>
<td>104</td>
</tr>
</tbody>
</table>