Selective inspection planning with aging forecast for sewer types

Rolf Baur* and Raimund Herz*

* Technische Universität Dresden, Fakultät Bauingenieurwesen
Lehrstuhl Stadtbauwesen, Nürnberger Straße 31A, 01187 Dresden
e-mail: *raimund.herz@mailbox.tu-dresden.de*

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, implemented in a software package, 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 on the estimates about the actual condition of the Dresden sewer network and its deterioration in case of doing nothing against it. A procedure is proposed for scheduling the inspection dates for sewers which have not yet been inspected and for those who have been inspected before.

Keywords
Sewer systems, aging, rehabilitation, inspection planning

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 were 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's 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 & 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 anymore. 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 $\boldsymbol{R}(t)$ is given here as follows.

$$\boldsymbol{R}(t) = (\boldsymbol{A}+1)/(\boldsymbol{A}+e^{\boldsymbol{B}(t-C)})$$

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

$\boldsymbol{A}$ vector of aging parameters (-), the larger, the smother is the transition.

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

$\boldsymbol{C}$ 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 $t_{50} = \boldsymbol{C} + \boldsymbol{B}^{-1}\ln(\boldsymbol{A}+2)$. 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 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 data base. Every national or local classification scheme with up to 6 condition classes can be used. The modules of this software allow to explore 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 on the long run (Herz and Krug 2000). For selective inspection planning, the prediction of the residual service life of sewers with the formulas 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 seventies of the 19th century. 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 damages 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 aging 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 previous inspection, we have to assume average aging behaviour of the sewer type. With data from previous inspection, we can determine the aging speed and may assume that the inspected reach will continue on its aging path, which may be faster or slower than the average.
The average aging 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 to forecast the number of sewers that will be in each of the 5 condition classes in future years. Differences in aging 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 was primarily done for sewers that where suspected to be deteriorated, this data is 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.

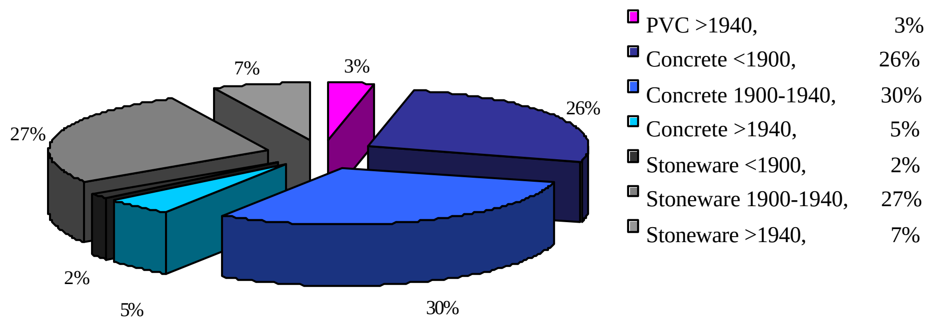

Figure 1: Materials and construction periods of Dresden sewers investigated

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 programme calculates transition dates and residual lifetimes, ending with transition into cc1, as well as the aging speed of inspected sewers.

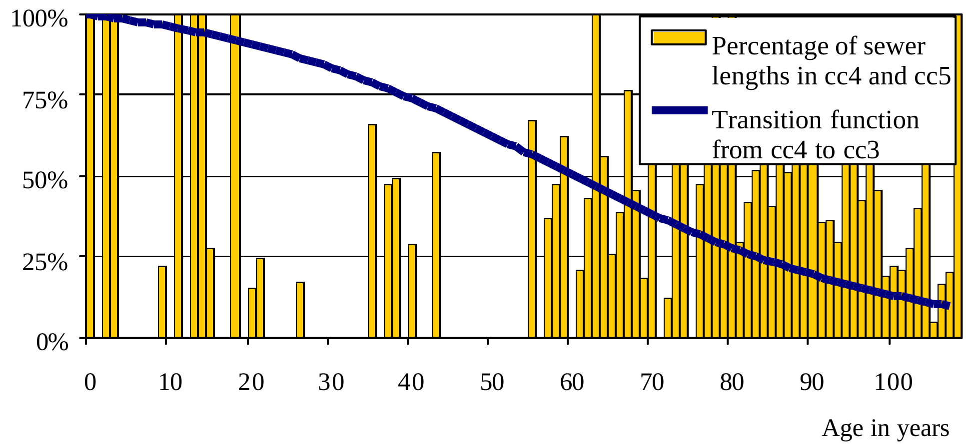

Figure 2: Calibrated transition function from cc4 to cc3, good to not so good

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 still is in condition class 4 or better, it has a lower aging speed R*(t). Younger sewers in condition class 3 obviously have an aging speed R*(t) over 50 %, they are aging faster than average.

Simulating the state of the sewer network

With transition functions, the network condition can be determined at 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 case of no rehabilitation measures 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.

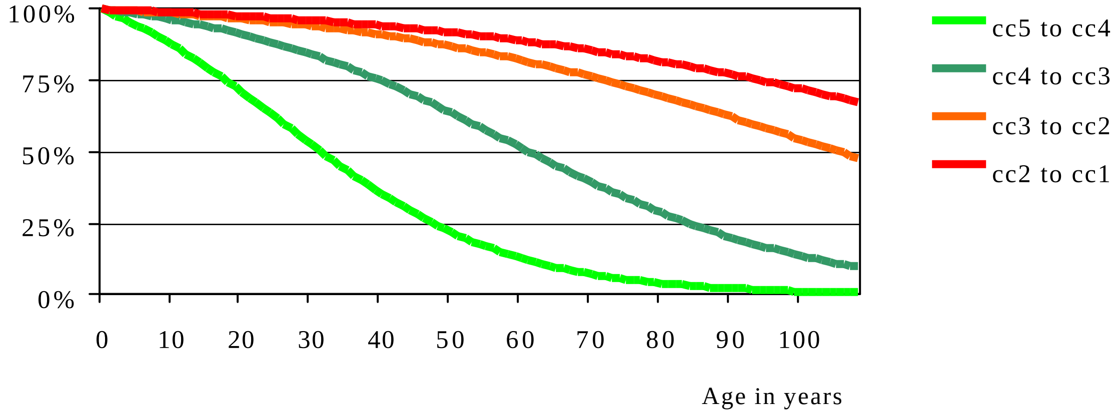

Figure 3: Transition functions for the Dresden sewer sample

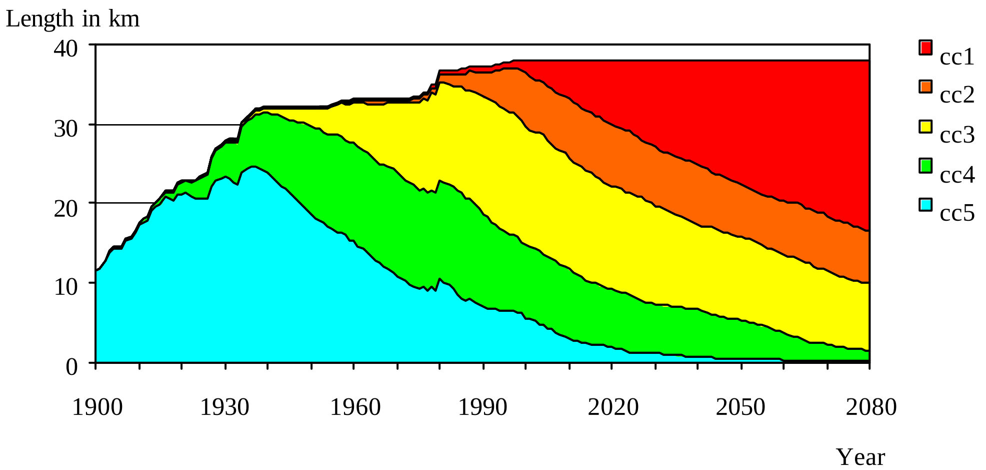

Figure 4: Condition forecast for the Dresden sewer sample

Calculating aging speed and residual service life of inspected sewers

Inspection reveals whether a sewer has deteriorated faster or slower than average. The individual aging speed of a sewer allows to generate a better estimate of the next inspection date. The aging 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).

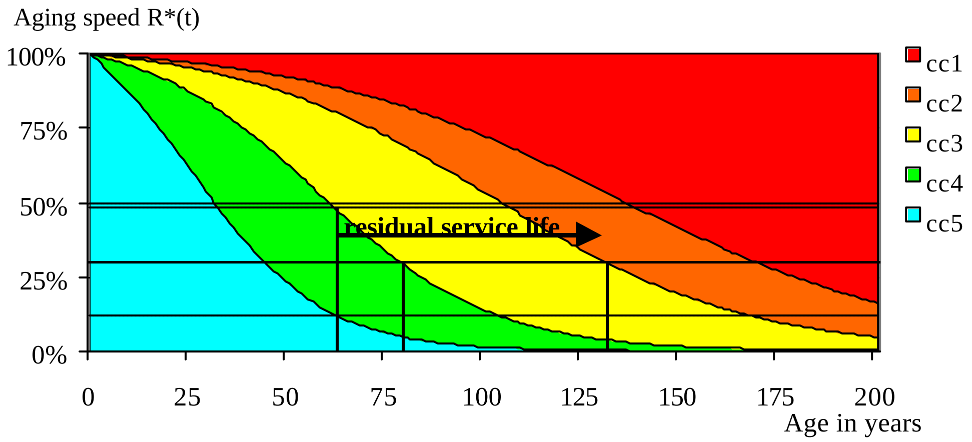

Figure 5: Aging speed and residual service life estimate

Figure 5 may illustrate this procedure. A 60 years old sewer was found to be still in good condition cc4. So its aging speed is half between the transition functions cc5 → cc4 and cc4 → 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 aging 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.

Table 1. Example of aging speed R*(t) and transition years for sewers

sewer no.	Inspection year	condition class cc	R*(t) %	construction year	year of transition between classes				lifetime estimate	residual life-time in years (in 2000)
					5-4	4-3	3-2	2-1		
01A14	1997	3	35	1899	1940	1973	2023	2059	160	58
01R84	1994	3	40	1903	1950	1985	2038	2077	174	76
05O10	1995	5	23	1960	2011	2048	2104	2145	185	145

Scheduling inspection dates

Transition functions calibrated for the local network of sewers help to schedule inspection dates. For the first inspection, average aging 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 aging 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 aging 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 aging 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 aging 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 mm, 300-1000 mm, > 1000 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 aging parameters of each sewer type were calibrated. The median age $a_{i,type}$ of entering class i according to the Dresden sewer condition classification model was chosen as a complex aging indicator for each sewer type. This indicator was standardised in relation to the median age $a_{i,total}$ 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:

$$f_{a,type} = \sqrt[4]{\prod_{i=2}^{n=5} f_{a,i\rightarrow i-1}} \qquad \text{with} \qquad f_{a,i\rightarrow i-1} = \frac{a_{i\rightarrow i-1,type}}{a_{i\rightarrow i-1,total}}$$

Sewer types with $f_{a,type} < 1.0$ are aging 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 aging speed.

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

			Median transition age in years			
Sewer type	$f_{a,type}$	$f_{a,3\rightarrow2,type}$	cc5 – cc4	cc4 – cc3	cc3 – cc2	cc2 – cc1
PVC	0.24	**0.35**	7	11	**36**	57
1940 – to date	0.30	**0.33**	8	13	**34**	52
circular	0.76	***0.80***	21	47	***83***	100
gradient > 5 %	0.78	**1.05**	28	64	**140**	511
waste water	0.85	**0.84**	26	53	**87**	108
∅ < 300mm	0.86	**0.88**	24	49	**91**	124
storm water	0.89	**0.94**	21	56	**98**	133
gradient < 1 %	0.90	**1.35**	23	44	**109**	681
in side streets	0.92	**0.93**	26	56	**97**	126
minor channel	0.95	**1.00**	24	56	**104**	142
in main streets	1.05	**1.04**	31	62	**108**	141
combined	1.06	**1.04**	33	62	**108**	142
main channel	1.06	**1.01**	29	78	**105**	129
∅ > 1000mm	1.08	**0.92**	43	81	**96**	99
1900 – 1940	1.11	**1.00**	42	65	**104**	131
300 mm < ∅ < 1000mm	1.18	**1.16**	33	67	**121**	178
stoneware	1.19	**1.52**	32	60	**158**	354
gradient < 5 %	1.20	**1.52**	36	74	**158**	993
concrete	1.25	**1.38**	33	74	**143**	485
egg-shaped	1.43	***1.39***	44	77	***145***	208
before 1900	1.66	**1.49**	48	81	**155**	309
average	1.00	**1.00**	29	60	**104**	135

Exemplification: For the average Dresden sewer. the median age of entering cc2 is 104 years. A median age factor $f_{a.3\rightarrow2} = 0.80$ (circular profile) means. that cc2 will be reached earlier. In this case. at an age of 83 years. 50% of all circular profiles will be in 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 the average. in the present sample. it takes 62 years longer for egg-shaped sewers to reach cc2 than for sewers with 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 ($f_{a.type}$) or small factors for the transition into specific condition classes ($f_{a.3\rightarrow2.type}$). 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 3: Example of first inspection date estimate

Sewer characteristics		Median age of transition into cc3	into cc2	First inspection date for intervention class cc2
Construction year	**1975**	13	**34**	→ **2009**
Material	PVC	11	36	2011
Function	Minor	53	104	2079
Type	Wastewater	56	87	2062
Average Dresden sewer		60	104	2081

This procedure was applied to sewers of 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 aging 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 to determine the aging 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 modified inspection intervals. selective inspection will increase efficiency and provide lower risk at the same cost.

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