Modelling sewer deterioration for selective inspection planning – case study Dresden

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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. However, sewer inspection and evaluation is costly. In Dresden, unit cost for inspection is about 1.4 € per meter. If the total Dresden sewer network of 1,400 km is to be inspected, as required by German regulations once within ten years, this would sum up to 1.9 million €. No wonder that Dresden, like many other German cities, up to now, has only partially fulfilled this requirement, and that an even smaller part of inspected sewers has been formally evaluated so far. 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. Furthermore, it doesn’t make sense to inspect sewers which can be expected to be still in relative good condition. So sewer inspection should be a matter of cost-efficiency, and not just formal fulfilment of general regulations.

This paper deals with the problems of forecasting the condition of sewers in a network from a small sample of inspected sewers. The technique of selecting a representative sample of sewers is presented first. Transition functions from one into the next poorer condition class were empirically derived from this sample. By the same procedure, implemented in the AQUA-WertMin software, 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. Furthermore, a procedure is proposed how to schedule the date of inspection for sewers which have not yet been inspected and for those who have been inspected before.

Keywords

Sewer systems, ageing, rehabilitation, inspection planing

1 The state of Dresden sewers

The total length of the Dresden sewer network is 1,402 km, where the oldest ones are from the early seventies of the last century. Almost 85% of the whole network are older than 60 years and 25% were constructed before 1900. But not only the old sewers make so much trouble, even younger sewers constructed during the socialist period with poor quality materials require rehabilitation. Considering their age, they are even in a worse condition, so age cannot be taken as criterion for rehabilitation, sewers are ageing faster or slower under specific circumstances.

In Germany, classification models are not standardised, different methods are under discussion right now. They are not the object of this study. So, the Dresden condition classification was used. In Dresden, the actual condition of 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.

Creating a representative data set

Two thirds of the network are video inspected, but only 15% of the data are evaluated. The subset applicable for the study, sewers with known condition from previous inspection and known construction year, resulted in 4.6% of the total network. However, for obvious reasons, these sewers were not representative for the total Dresden network. Applying quotas corresponding to the percentages of materials and construction periods in the total network (column 4 in tab.1) to these 4.6%, only 2.7% or 35.7 km of sewers remained as a data set representative of the total network. The selection process is shown in Tab.1.

type	share total	in network	length required	length available	ratio	proportion factor	proportional length
	%	%	m	m	(4)/(5)		m
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
PVC; >1940	3.00	3.16	2,048	4,694	2.29	0.24	1,126
concrete <1900	23.73	24.98	16,205	9,773	0.60	0.91	8,912
1900 - 1940	28.35	29.84	19,352	29,506	1.52	0.36	10,643
>1940	4.92	5.18	3,359	3,689	1.10	0,50	1,847
stoneware <1900	1.44	1.52	983	1,711	1.74	0.32	540
1900 – 1940	27.33	28.76	18,656	10,220	0.55	1.00	10,220
>1940	6.23	6.56	4,256	3,844	0.90	0.61	2,341
sum	95.00	100.00	64,861	63,439			35,674

Tab.1: Reduction of data set for representative sample of sewer types

A random systematic draw from the available data set (5) resulted in a data set of 37.8 km of Dresden sewers, shown in Tab.2, which were subsequently used for empirical analyses.

type of sewer	length	percentage
	m	%
PVC; >1940	1,257	3.3
concrete <1900	9,773	25.9
1900 - 1940	11,306	29.9
>1940	1,965	5.2
stoneware <1900	592	1.6
1900 – 1940	10,220	27.0
>1940	2,687	7.1
sum	37,803	100.0

Tab.2: Total set of sewers investigated

2 Objectives of this study

Obviously, TV-inspection reveal, for different types of sewers in the same age, different conditions. So the process of deterioration runs faster or slower. Taking the classified condition as granted, the main interest of this study lies in the different ageing speed of sewers, characterised by the years between the transition into worse condition classes. It was assumed that sewers, according to their characteristics, could be identified that show significant differences with respect to their ageing speed. To verify (or falsify) this assumption, the prognostic modules of the AQUA-WertMin software were applied to the sample of Dresden sewers. After the analysis of the total set of 37.8km, different sub-sets of sewer types were created and investigated with respect to their typical ageing behaviour and subsequently compared with the average network ageing.

3 Methodology

The software used in this study is AQUA-WertMin. It is based on a cohort survival model for infrastructure networks that has been developed at Karlsruhe University (Herz/Hochstrate, 1987). Special ageing functions were introduced by Herz (1995) which can be calibrated from TV inspection data in order to describe the transition of sewers into lower condition classes over time.

The ageing model

There are several probability distributions for lifetimes of infrastructure elements (Trujillo, 1995). The mathematics implemented in AQUA-WertMin are the ageing functions of the Herz distribution, which has developed specifically for the ageing of pipelines. A particular feature of this distribution is that the transition rate increases with age, then slows down and finally approaches asymptotically a boundary value (Herz, 1995).

In this model, the time a sewer stays in a specific condition, before moving into the next worse one, is considered as a random variable. Sewers of a particular type have a mean age when they stay in a particular condition. The age distribution of specific condition classes, the transition function into the next worse condition, and the rate of transition are mathematically interrelated. These ageing functions are calibrated from condition classes revealed by inspection. For calibration of reliable ageing functions, Hochstrate (1996) recommends to use a sample of at least 20% of the total sewer network to be inspected.

The transition functions $\boldsymbol{R}(t)$ give the percentage of pipes that will not have changed into an inferior class of condition at a particular age t. There are only two parameter vectors in the formula $\boldsymbol{R}(t) = (\boldsymbol{A}+1)/(\boldsymbol{A}+e^{\boldsymbol{B}t})$, the ageing parameters $\boldsymbol{A}$ and the transition parameters $\boldsymbol{B}$. From this formula, the half-life-value or median age t_{50} is derived as $t_{50} = \boldsymbol{B}^{-1}\ln(\boldsymbol{A}+2)$. At this age, 50 % of the sewer cohort, characterised by the same installation year, have changed into the next condition class. Apparently, and for different reasons, the rate of deterioration is slower for some sewers than for others. Thus, different parameter vectors would have to be used in order to describe the ageing process of different types of sewers.

Since the introduction of TV-inspection, the prediction of rehabilitation needs resulting from sewer deterioration has received considerable attention. Rehabilitation needs now arise from revealed sewer damages, which get worse as time goes by. To forecast the lifetime of a sewer pipe it becomes necessary to define a critical condition which will require mayor rehabilitation work, such as sewer replacement or relining. It is up to the community to define a minimum standard for sewer condition, and the percentage of sewers that would be tolerated in the lowest condition class.

At the end of a sewer service life, a decision has to be taken on the most appropriate rehabilitation technology, depending on the severity of damage and other circumstances. 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, and there is no way of predicting the end of a sewer service life without reliable information on its condition.

Ageing simulation with AQUA-WertMin

The cohort survival model of sewer conditions implemented in the MS Access based software AQUA-WertMin (AQUA-Ingenieure,1998). There is no sewer network databank included, however, AQUA-WertMin requires an inspected and classified inventory of sewers. Every national or local classification scheme can be used, with up to 6 condition classes. The program supports strategies for maintaining the value of the assets and for calculating financial requirements depending on critical sewer conditions, and for predicting the residual lifetime of sewers, which is of particular interest for selective inspection planning.

AQUA-WertMin is structured in modules. The base module carries out the calibration of the transition functions and the calculation of condition class statistics such as half-time-values, particularly the dates for transition into the intervention class, the residual lifetime of the pipe. Future network conditions are calculated from the ageing speed of every sewer, and so is the average age and the residual lifetime of the sewer network. Other modules provide the scheduling of TV-inspection dates and the calculation of replacement and relining costs. Network rehabilitation investments and sewer condition can be simulated for different rehabilitation strategies on the long run.

4 Transition functions of Dresden sewers

Calibrating transition functions

For every network the transition functions have to be calibrated to take into account local specifications and inspection results. By statistical analysis of condition classes over age, the program calculates transition dates and residual lifetimes for each sewer. Hereby, AQUA-WertMin is using transition curves describing the average percentage of sewers remaining within a given condition class limit, by minimising weighted squared deviations. An example from the Dresden sewer network sample is given in Fig.1. showing the transition from condition class (cc) 5 to 4, from very good to good condition.

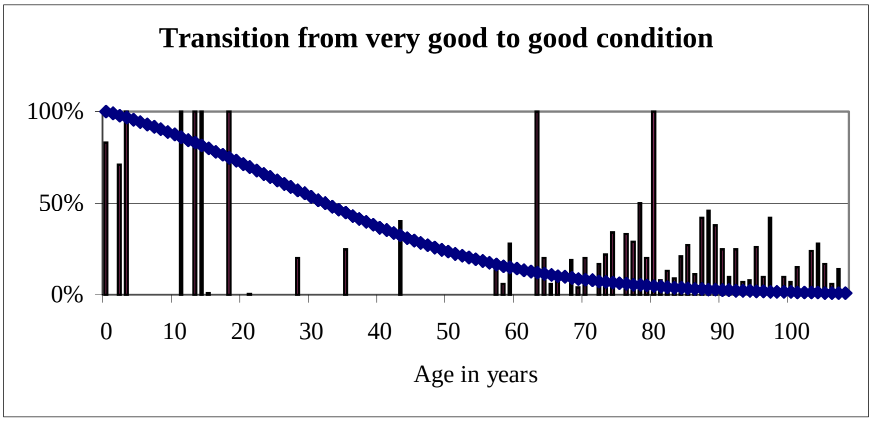

Fig.1: Calibrated transition function from cc5 to cc4, very good to good

Average sewer network deterioration

The analysis of the total sample of 37.8 km of Dresden sewers by AQUA-WertMin resulted in transition functions without parameter vectors shown in Tab.3. At an age of 104 years, 50% of the sewers are expected to be in condition class 3 or better (Tab.3).

sewer condition	class	***A*** -	***B*** % p.a.	**50% value** age in years
very good - good	5-4	4.7	5.95	29
not so good - bad	4-3	13.9	4.52	60
bad – very bad	3-2	23.8	3.10	104
very bad - useless	2-1	29.4	2.52	135

Tab.3: Parameter vectors ***A***, ***B*** and 50% value for sample of Dresden sewers

A sewer older than 104 years but still in condition class 3 or better, has a lower ageing speed. For sewers younger than 104 years which are already in condition class 2, apparently R(t) must be larger than 50%. So, they are ageing faster. The ageing speed is calculated in the middle of the known condition class at the given age of the sewer, thus allowing a better estimate of the residual lifetime of a sewer after its condition being revealed by inspection. Tab.4 shows an example of the output from the calculation of AQUA-WertMin for three sewers from the Dresden sample.

sewer no.	inspection year	condition class cc	R*(t)	construction year	year of transition between classes				lifetime estimate	residual life-time in years (1998)
			%		5-4	4-3	3-2	2-1		
01A14	1997	3	35	1899	1940	1973	2023	2059	160	60
01R84	1994	3	40	1903	1950	1985	2038	2077	174	78
05O10	1995	5	23	1960	2011	2048	2104	2145	146	185

Tab.4: Ageing speed R*(t) and transition years for sewers

The transition curves for the Dresden network sample are shown in Fig.2. Once again, It should be mentioned that their shapes and distances depend very much on local conditions and the classification of sewer conditions, so transition functions must be calibrated for each network and local characteristics again.

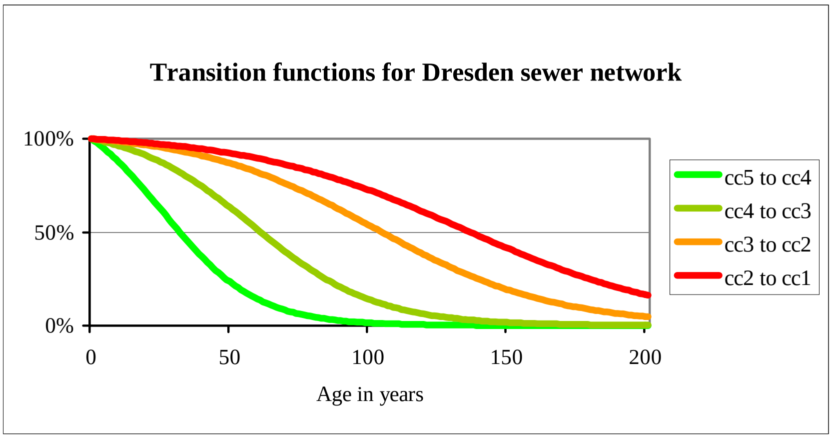

Fig.2: Transition functions for the Dresden sewer sample

Deterioration of sewer types

To get more reliable transition functions, 8 characteristic features of sewers were chosen in order to identify different sewer types. The characteristics were construction period, material, pipe function, type of pipe, shape of profile, size of profile, gradient and street category.

Within these 8 groups, 21 different sewer types were specified (Tab.5). For the different types of sewers, specific factors $f_{HWZ,type}$ were calculated characterising their ageing behaviour in relation to average network ageing behaviour. This factor is the geometric mean of the ratios $f_{HWZ,i}$ between the half-time values HWZ of the particular sewer type and the average Dresden sewer, and is called the “half-life-factor” or 50%-factor. The geometric mean was taken because of the interdependence of the transition into the various condition classes. The formula for the “half-life-factor” is

$$f_{HWZ,\,type} = \sqrt[n]{\prod_{i=1}^{n} f_{HWZ,\,i}} \qquad \text{with} \qquad f_{HWZ\,,i} = \frac{HWZ_{\;i \to i+1}}{HWZ_{\;total}}$$

The output of “half-life-values” $f_{HWZ,3\to2}$ and “half-life-factors” f_{HWZ} for all sewer types that have been investigated in this study are presented in Tab.5 below, together with transition ages between the condition classes (cc). In the last row of the table, the average values for the total Dresden sewer network sample are given.

			age at 50% transition in years			
sewer type	f_{HWZ}	$f_{HWZ,3\to2}$	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
slope > 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
slope < 1 %	0,90	1,35	23	44	109	681
in riparian road	0,92	0,93	26	56	97	126
tributary	0,95	1,00	24	56	104	142
in main road	1,05	1,04	31	62	108	141
combined	1,06	1,04	33	62	108	142
main	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
∅ < 1000mm	1,18	1,16	33	67	121	178
stoneware	1,19	1,52	32	60	158	354
slope < 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

Tab.5: Half-life-factors and transition ages for Dresden sewer types

Example: A half-life-value $f_{HWZ,3\rightarrow 2}$ = 0,80 (circular) means, that the condition class 2 by circular sewers will be reached earlier than by the average network sewer. In this case, at an age of 83 years, 50% of all circular sewer sections are already in condition class 2 (or worse) which is 0.8 times the the network mean, compared with egg-shaped sections which have a half-life-value of 145 years that is 1.4 times the network value (Fig.4). So egg-shaped sewers deteriorate, other things being equal, at a slower rate than sewers with circular shape. On an average, the half-live-value from condition class 3 to 2 is 104 years.

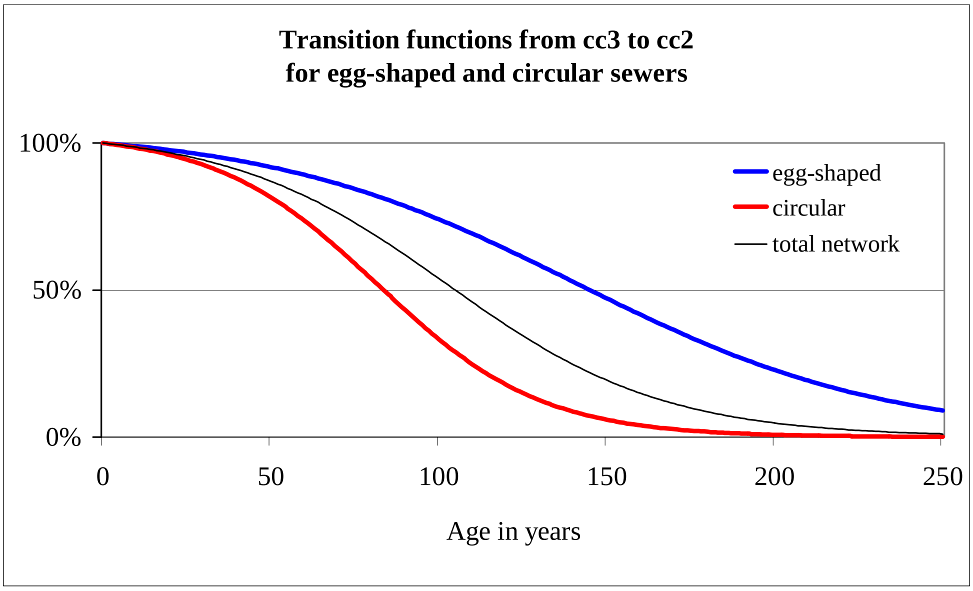

Fig.4: Transition functions into intervention class 2 for circular and egg-shaped sewers

This uni-variate analysis of sewer types may seem to be an oversimplification, however, the estimation of the first sewer inspection date will certainly be improved by considering specific attributes of sewers instead of assuming average ageing behaviour. Large differences between the mean half-life-factor (f_{HWZ}) and the factor for transition into specific condition classes ($f_{HWZ,3\rightarrow 2}$) are a strong indication of deviant ageing behaviour and lead to the conclusion that this factor of influence should be considered. Others, such as the gradient of the sewer seem to be of minor importance (Tab.5).

5 Selective sewer inspection planning

Inspection planning depends on the definition of a sewer condition that wouldn't be acceptable any more. This condition class is called the intervention class and can be defined individually and depends, among others, on the importance of the particular sewer in the network and the environmental risk a damage may cause. In this study, condition class 2, very bad, is assumed to be the condition requiring rehabilitation. So, some time before condition class 2 would be reached, the sewer should be inspected in order to check the condition forecast, to evaluate its actual condition and, in case, decide on appropriate measures of rehabilitation.

First inspection dates

For a sewer found to be in a particular condition class, AQUA-WertMin calculates the probable residual lifetime and the transition date into the condition class defined to be the intervention class. Inspection planning would start some time before this date, so the program allows to choose a head time for preparation, e.g.5 years.

The question is, how the ageing behaviour of particular types of sewers, revealed from the statistical analysis of the Dresden sample, could improve the forecast of the first inspection date. As shown in Fig.3 for circular and egg-shaped sewers, there are significant differences in transition functions from condition class 3 to the intervention class 2, both between these two types of sewers and in relation to the average sewer of the Dresden sample, which can be measured by their “half-life-factors”.

There are three possibilities of using these half-time-factors, derived from a uni-variate categories of sewers, for improving the forecast of the first inspection date for a particular sewer with known characteristics.

(a) As different pipe types have different half-life-values for the transition into the intervention class, a “safe” estimate would be to take the smallest value for calculating the inspection date:

$$\min\ f_{HWZ\ ,3\to 2} = \frac{HWZ_{\ 3\to 2}}{HWZ_{\ total}}$$

(b) In order to include more than one characteristic of the particular sewer, the geometric mean of the half-life-values could be used instead of the minimum value.

(c) For sewers with specific combinations of characteristics, sub-samples with these characteristics could be created from the sample as long as there is a sufficient number of sewers for calibration of the transition function. In this case, the first inspection date could be calculated without referring to the average residual lifetime.

Two examples for results of these three approaches are given in Tab.6.

sewer characteristics	sewer 1	sewer 2
construction year	1975	1930
material	PVC	-
function	-	minor
type	wastewater	-
intervention class	2	2
inspection year (a)	2009	**2021**
(b)	2016	2023
(c)	**1997**	2024

Tab.6: Example for the estimation of first inspection dates

Approach (c) was found not to be reliable enough due to insufficient sample size. With the geometric mean of the half-life-values (approach b) the overall ageing speed of this sewer is considered. However, to stay on the safe side, the result of approach (a) is recommended for the first inspection date in this case.

From the data set of Dresden sewers of which construction year and condition class were known, condition classes were calculated according to their transition functions with a 50% ageing speed.

The result was that the majority of sewers were assigned to the observed condition class, some were one class better, but no sewer worse than calculated.

Dates for subsequent inspections

Transition functions are calibrated to describe average ageing behaviour. Inspection reveals the real condition of the particular sewer, which may have deteriorated slower or faster than average. From the observed condition, the ageing speed is calculated as shown in Fig.5. For a given sewer age, it is assumed that the sewer is in the middle of the range of the observed condition class. Thus the residual lifetime up to the transition into the intervention class is calculated along the horizontal line of the observed ageing speed, assuming this speed to continue.

An example may illustrate this procedure (Fig.5). A sewer with 50 years of age was found to be in condition class 3. So his ageing speed is over average. In the middle of condition class 3 the ageing speed is 72,25%. From there it takes 22 years to enter the intervention class 2 and 45 years to the ultimate class 1.

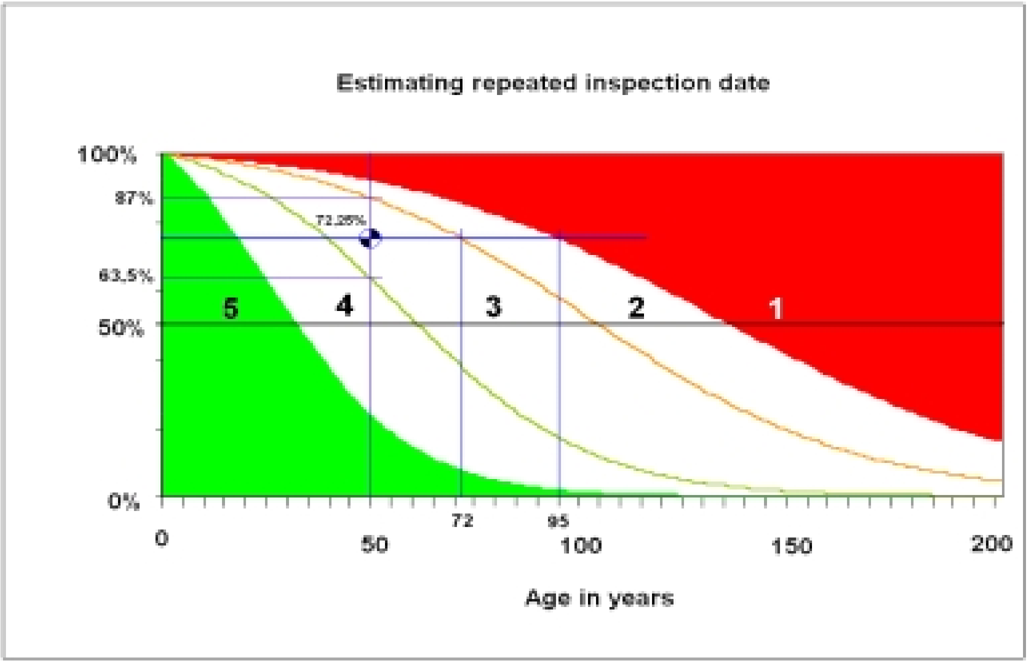

Fig.5: Estimating subsequent inspection dates

Forecasts of the deterioration of sewers that have been inspected already, can be based on average transition functions because the particular ageing speed of the sewers is taken into account. Forecasts with specific transition functions according to type of sewer did not yield results with significant differences.

6 Discussion and outlook

In this pilot study, the prognostic tools of AQUA-WertMin were applied to a small sample from the Dresden sewer network. Other tools of economic evaluation, asset maintenance and strategic network rehabilitation planning were not applied. A larger sample size would be required for the exploration of rehabilitation strategies preventing the state of the Dresden sewer network to fall below a defined minimum standard.

The results gained from a small sample of Dresden sewers showed that there are significant differences in the ageing behaviour of different types of sewers, which were defined with available data thought to exert some influence on the deterioration process. This information could be used to improve the efficiency of sewer inspection, particularly for scheduling the first inspections. Subsequent inspection dates will be more reliable because deterioration rates of the past can be taken into account for individual sewers.

With an increasing portion of sewer networks being inspected and evaluated, the deterioration process of sewers can be modelled more realistically, so rehabilitation measures and strategies can be selected in a more rational and effective way.

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