APUSS

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REPORT

Approaches for sewer leakage modelling

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Mandy Rutsch, Torsten Franz, Christian Karpf and Peter Krebs
Dresden University of Technology, Institute for Urban Water Management, 01062 Dresden
Mail: pkrebs@rcs.urz.tu-dresden.de

EAWAG
Swiss Federal Institute for Environmental Science and Technology

TECHNISCHE UNIVERSITÄT DRESDEN

Czech Technical University in Prague
Faculty of Civil Engineering

Content

1 Introduction

Work area 3 comprises the identification and development of conceptual models for infiltration and exfiltration at different scales. The investigations revealed that a joint approach modelling ex- and infiltration is not feasible with the available data and measuring methods. This was due to several reasons:

- Exfiltration is quantified by measurements at the small scale (pipes, reaches), infiltration by catchment scale investigations.
- Large variations in measuring exfiltration suggested that a huge number of experiments is required to set up a model with a reasonable correlation. Yet, the number of measurements performed within project was insufficient, as the methods were not perfected within the first 2 years.

Therefore, different approaches modelling ex- and infiltration were investigated, as well as a joint analysis of sewerage and catchment characteristics to gain as much information on sewer leakage. The report is thus structured as follows:

The first part aims at formulating a conceptual model describing sewer exfiltration on the basis of information available from exfiltration measurements and data bases and damage classes. It is focused on an identification of variables affecting sewer deterioration and sewer leakage and a correlation analysis of the identified variables (chapter 2):

To model the infiltration process, a leakage approach (Karpf and Krebs, 2004) was selected although the approach can only be applied on catchment or sub-catchment scale. Long term groundwater data and flow measurements at the catchment outlet are required to calibrate the model. The results of the leakage approach applied in the city of Dresden fit very well with the observations in the sewer network (chapter 3).

The similarity approach (Franz and Krebs, 2005) looks for and works with “similarities” within a sewer system. The approach is based on the classification and generalisation of homogeneous areas and homogeneous groups of reaches performing a joint analysis of sewer and catchment data (chapter 4).

2 From structural sewer data to leakage rates

To formulate a conceptual model describing sewer exfiltration on the basis of information available from measurements and data bases, the following focal points deserve special attention:

- Identification of variables affecting sewer deterioration and sewer leakage
- Correlation analysis of the identified variables

2.1 Identification of variables affecting sewer deterioration

To identify variables affecting *sewer deterioration* CCTV derived damage or condition classes of 21% of all pipes (approx. 467 km) of the Dresden sewerage system were evaluated by means of rank variance analysis. Construction material, year of construction, pipe dimension, distance to the river, and inspector are used as predictor variables. These were selected after a thorough analysis of the literature (e.g. Davies et al., 2001b; Davies et al., 2001c; O'Reilly, 1989, Fenner and Sweeting, 1999) and according to their availability for our purpose. To evaluate damage classes rank variance analysis (Mann-Whitney u-test, analysing 2 independent samples) was applied, comparing two samples concerning their mean value for some variable of interest, which is in this case damage class or magnitude of damage (dependent variable). The differences in the magnitude of damage are shown with help of cumulative lines (Müller, 2002). The bisecting line represents the cumulative line of the significance levels for the random distribution. The farther on the down right the cumulative lines are, the more significant are the differences; the farther top left the less significant are the differences.

Small and medium pipes behave similarly concerning their magnitude of damage, contrary to this, pipes with large diameters show significantly differing damages (Figure 1). As a consequence, pipes with diameters smaller than 900 mm can be merged into one group. This suggests, that small and medium pipes need not to be considered as single treatment of the variable dimension in any statistical analysis.

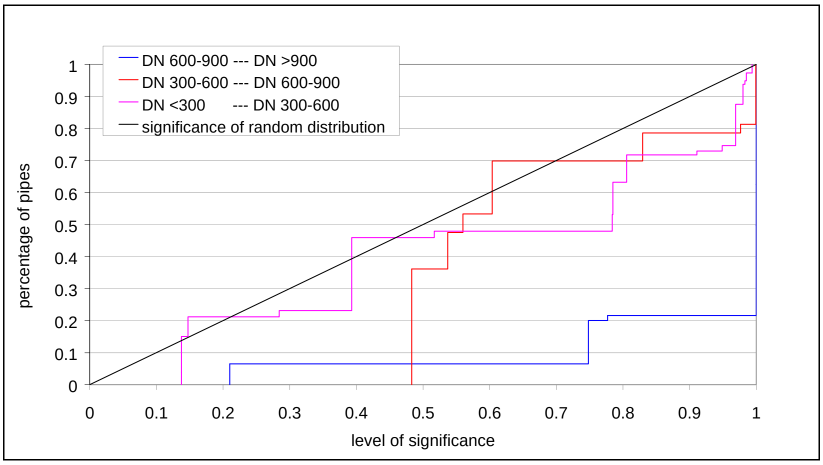

Figure 1: Comparison of condition classes of different dimension groups

Most frequent materials in Dresden are concrete and clay with dimensions of 300-600 mm. Significant differences in damage classes suggests material being a relevant variable in analysing the deterioration of sewer pipes. Figure 2 exhibits the results of the analysis of differences in damage classes according to year of construction. Damage classes are similar in pipes constructed before 1900 and 1900-1916. The difference in the periods 1929-1945 and 1946-1989 is not very distinct. All other graphs are located in the very down right-hand corner of the diagram and indicate large differences in damage magnitude for the single construction period. Due to poor data availability in the years 1946-1989 this group comprises a very large period. The period can be paraphrased as “sewer construction in GDR”, even under the condition that within this period construction quality might have changed.

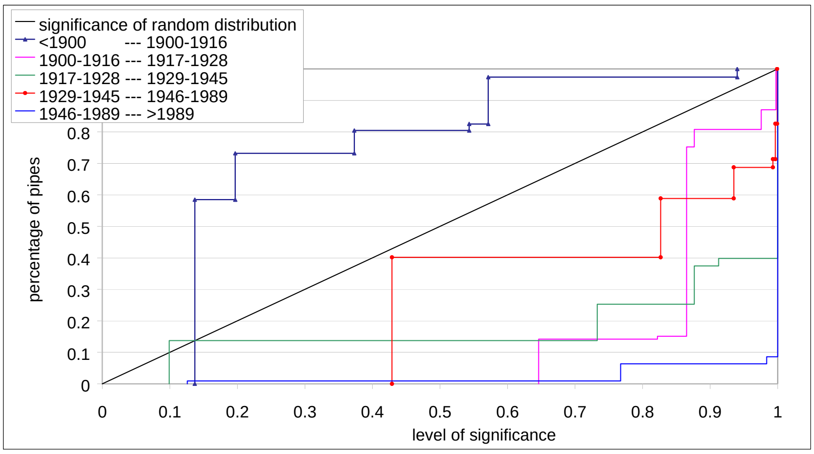

Figure 2: Comparison of condition classes in different construction periods

Interesting results were obtained investigating the relevance of the executive company. No significant differences in damage classes were revealed by comparing damage classes provided by different inspectors, with curves arbitrarily distributed over the plot (Figure 3). The results do not support the common opinion that CCTV protocols do largely depend on the executing inspector.

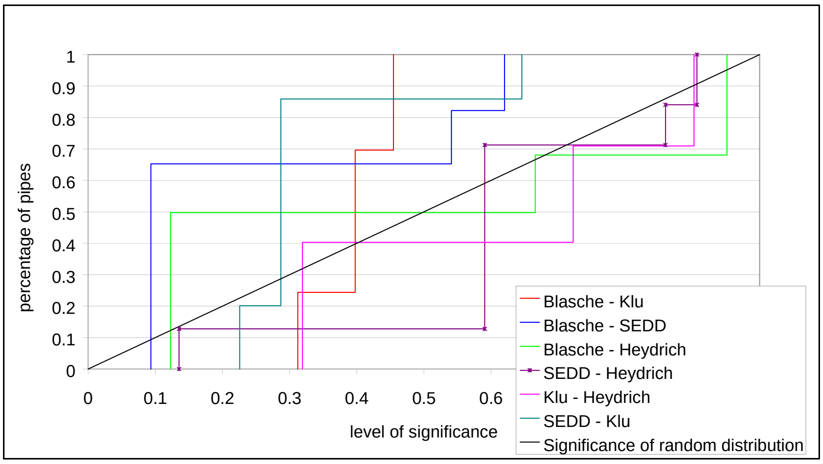

Figure 3: Comparison of condition classes recorded by different inspectors

Groundwater in the City of Dresden is partly influenced by the river Elbe. With decreasing distance to the river the number of sewers influenced by the river stage controlled water table increases. It is also known that groundwater infiltration or varying groundwater aggravate sewer deterioration. The results indicate significant difference in damage class of sewers for different distances to the river. The result suggests that river and probably its river-induced groundwater have a considerable influence on the condition of sewers.

Table 1 summarizes the outcomes of the analysis of damage classes and estimates the level of relevance of the variables on the condition of sewers.

Table 1: Results of rank variance analysis

Variable	Observations	Significant difference in magnitude of damage	Relevance of variable for condition of sewer
Year of construction	< 1900 and 1900-1916 1900-1916 and 1917-1928 1917-1928 and 1929-1945 1929-1945 and 1946-1989 1946-1989 and > 1989	No Yes Yes Yes Yes	High
Material	Concrete and clay	Yes	High
Distance to the river Elbe	300 and 600 m 600 and 1000 m 1000 and more than 1000 m	Yes	High
Dimension	< 300 and 300-600 mm 300-600 and 600-900 mm 600-900 and > 900 mm	No No Yes	High for large dimensions
Inspectors	Blasche Klu SEDD Heydrich	No	Small

2.2 Identification of variables affecting sewer leakage

To identify variables affecting *sewer leakage* exfiltration rates observed in %dwf, sewer and catchment characteristics were used. Sewer characteristics being input to a model have been pre-selected by (i) the literature review and (ii) data availability, namely material, quality of construction expressed by year of construction, dimension, and catchment (traffic, surface load). Data were grouped to limit additional variance:

- Material groups: concrete, clay, and mixed material
- Year of construction: 1900-1930, 1960-1980
- Dimension: smaller 300 mm, 300-600 mm
- Catchment: Berlin-MAL, Berlin-LR, Dresden-HEL, Dresden – DD1, Dresden – DD2

Table 2 comprises sewer and catchment characteristics in more detail.

Table 2: Sewer and catchment characteristics

	DD1	DD 2	DD_HEL	MAL	LR
Area	suburban area	suburban area	row houses	multistorey buildings	housing estate
Geology	slopes of the river valley	river valley sediments	river valley plateau, confined and floating groundwater	Barnim plateau, confined and floa-ting groundwater	Teltow plateau, confined and floating groundwater
Soil	inhomo-geneous	landfill, sand		landfill, sand	landfill, loamy sand
Ground-water	below invert	river induced, but not detected	unknown	4-20 m below invert	10-20 m below invert
Pipe dimen-sion	200-600	300-750	250	200-600	200-450
Year of con-struction	1900-1936	1908-1925	1910	1980	1930/1965
CCTV records	no	partly	no	yes	yes
No. samples	5	2	5	7	8

The number of experiments is rather small and does not meet the requirements of the normality assumption. Thus, nonparametric statistics were applied. To evaluate differences in exfiltration rates the Kruskal Wallis analysis of ranks was used. It expresses to what extend the group rank differs from the average rank of all groups. Due to the small sample and to confirm the results obtained with Kruskal Wallis analysis bootstrapping was used building a picture of the sampling distribution of the parameter by frequent resampling. The results of the Kruskal Wallis analysis and Bootstrap sampling with the predictor variables catchment, year of construction, and pipe dimension are shown in Table 3.

Table 3: Results of Kruskal Wallis test with sewer characteristics

grouping variable	predictor	significance	probability (bootstrap samples)
year	catchment		
1900-1930	HEL, DD1, LR	**0.006**	**0.063**
1960-1980	LR, MAL	0.909	0.477
year	dimension [mm]		
1900-1930	< 300 300-600	**0.058**	**0.058**
1960-1980	< 300 300-600	0.862	0.384
dimension [mm]	year		
< 300	1900-1930 1960-1980	0.13	**0.028**
300-600	1900-1930 1960-1980	0.825	0.258

Exfiltration rates from sewers in different catchments which had been constructed from 1960-1980 are not significantly different, this is contrary to exfiltration rates from sewer constructed in the years 1900 to 1930. The probability derived from bootstrapping confirms the findings, but also reveals that the catchment as such has a much larger affect on the exfiltration rate than the year of construction.

The comparison of exfiltration rates grouped by dimension and year yields insignificant differences in rates comparing small and medium diameters constructed 1960-1980. Differences are significant on the 10% confidence level for small and medium pipes constructed 1900-1930. These results indicate that quality of construction at the beginning of the 20th century is depending on workmanship. Insignificant variations in sewer leakage in the two construction periods for small and medium diameter pipes were found by Kruskal Wallis analysis. Bootstrapping confirms the findings for medium sized pipes, but claims significant differences in exfiltration rates for small diameter pipes within the two construction periods. Yet, this contradiction might be caused by the small number of small diameter pipes constructed 1960-1980. The findings concerning pipe diameter confirm the outcomes of the previous analysis of damage classes.

2.3 Correlation analysis of the identified variables

A correlation analysis of *damage classes* and the predictor variables construction period, pipe dimension, depth of pipe, and material indicates only a weak relationship between the observed and the model-predicted values of damage classes (Table 4), weak especially for the large dataset of 10200 reaches being used in the correlation analysis.

Table 4: Correlation coefficients damage classes and predictor variables

	Year of construction	Dimension	Material	Depth of pipe	Damage class
Year of construction	1	-0.497**	-0.249**	-0.304**	0.389**
Dimension	-0.497**	1	0.288**	0.415**	-0.263**
Material	-0.249**	0.288**	1	0.132**	-0.019
Depth of pipe	-0.304**	0.415**	0.132**	1	-0.131**

* Correlation is significant at the 0.01 level (2-tailed).

** Correlation is significant at the 0.05 level (2-tailed).

The correlation analysis investigating *exfiltration rate* [%dwf] and the predictor variables catchment, dimension, material, and year of construction reveals low correlation coefficients (Table 5).

Table 5: Correlation coefficients exfiltration rates [%dwf] and predictor variables

	Catchment	Dimension	Material	Year	Exfiltration [%dwf]
Catchment	1	0.054	0.233	0.290	0.537*
Dimension	0.054	1	0.518*	0.306	0.024
Material	0.233	0.518*	1	0.638*	0.104
Year	0.290	0.306	0.638*	1	0.147

* Correlation is significant at the 0.01 level (2-tailed).

** Correlation is significant at the 0.05 level (2-tailed).

2.4 Summary

If a relationship between variables in question is weak in the population, the relation can only be identified when the research sample is correspondingly large. Analogously, if a relation in question is very strong in the population, it can be found to be highly significant even in a study based on a very small sample. According to the literature, a weak relation must be assumed, as only weak relation between pipe characteristics and deterioration records was found (Fenner and Sweeting, 1999, Kettler and Goulter, 1985).

The analysis of sewer characteristics and damage classes in the City of Dresden exhibited that only pipes with diameters more than 900 mm have a higher percentage of pipe length in poor categories. New pipes show best performance. Various materials are present in all damage classes. Results of the rank variance analysis performed with CCTV data and sewer characteristics of 21% of the Dresden sewer system show significant differences between large diameter pipes and 600-900 mm pipes indicating that large diameter pipes differ in their damage development. The findings confirm results of Karpf and Krebs (2004), who identified large diameter pipes as having the highest potential for sewer leakage. According to the rank variance analysis, damage classes of adjacent construction periods (after 1900), different materials, and increasing distance to the river Elbe are significantly different. The overall sample size was large, but creation of strata resulted in a low strata resolution for in particular construction period.

The regression model for damage classes yields a rather low R^2. It can be assumed, that the variables construction period, dimension, and material (which are in most cases the only available variables) do not properly predict damage classes.

Investigating the relationship of leakage rates of 26 experiments and corresponding asset data did not result in convincing findings. A larger number of measurements and CCTV data for all test sites would possibly yield different findings.

The model resulting from this study only reveals weak correlation between sewer deterioration and asset data, making it difficult to highlight sewer sections which are heavily exfiltrating by means of the model alone. Nevertheless indicators were found, allowing for a focus on potentially risky combinations of asset data, thus serving as a basis for the planning of more detailed and focused investigations in large sewer systems.

3 Leakage Approach

3.1 Background

The leakage approach to infiltration can be traced back to the Darcy equation. It is widely used for modelling hydrological interactions between aquifer and surface water and is related to the wetted area of the river bed, the difference between groundwater and surface water level, and a specific leakage factor representing the permeability of the reach for groundwater infiltration. As an integrative parameter, the leakage factor describes various attributes of the soil layer of the river bed and thereby the potential exchange between the ground- and surface water compartments.

According to Gustafsson (2000) and Karpf and Krebs (2004) the leakage approach can be modified for the simulation of groundwater infiltration into sewer systems:

$$Q_{Infiltration} = k_L \cdot A_S \cdot (h_G - h_S) \qquad \text{condition: } h_G > h_S$$

where:

$Q_{Infiltration}$	infiltration of groundwater (m^3/s)
A_S	groundwater-influenced pipe surface (m^2)
h_S	water level in sewer pipes (m)
h_G	groundwater level (m)
k_L	leakage factor (s^{-1})

An extended model, which takes into consideration regional differences and house connections, was proposed in APUSS (2003b) for further development and implementation:

$$Q_{\inf} = (h_{GWL} - h_w) \cdot P_{w1} \cdot L \cdot K_l \cdot K_r + q_{0\inf} + \overline{q_{\inf HC}} \cdot N_{HC} \qquad \text{condition: } h_{GWL} > h_w$$

where:

Q_{inf}	infiltration flow (m^3/d)
h_w	water level in the pipe (m)
h_{GWL}	groundwater level around the pipe (m)
P_{W1}	external wet perimeter (m)
L	length of the pipe (m)
K_l	local coefficient (d^{-1})
K_r	regional coefficient (-)
$q_{0\ inf}$	infiltration flow from other infiltration sources (m^3/d)
$q_{inf\ HC}$	mean infiltration flow for a single house connection (m^3/d)
N_{HC}	number of house connections to the pipe

The achievable spatio-temporal resolution of the approach is relatively high but depends on the data situation. It is (theoretically) possible to estimate infiltration at single pipe level and at daily scale. However only little information about processes can be expected and the quality of modelling and predicting infiltration rates is higher for larger catchments (Karpf and Krebs, 2004).

3.2 Application

3.2.1 Data needs

The data needs for the application are listed in Table 6.

Table 6: Data needs

Type	Data	Source
structural data	L	The structural data are contained in the sewer data base. Profile shape, diameter and slope are necessary to calculate P_{W1}.
	N_{HC}	
	profile shape	
	diameter	
	slope	
water levels	h_w	The water level in the sewer pipe can be modelled. However, it is also feasible to estimate it by measurements of water levels in the system at known conditions.
	h_{GWL}	The estimation of groundwater level at each pipe is based on the interpolation of groundwater measurements.
coefficients	K_l	The coefficients have to be calibrated (see chapter 3.2.2).
	K_r	
specific infiltration rates	$q_{0\ inf}$	The constants must be determined by independent investigations (e.g. by balancing). At least $q_{inf\ HC}$ does not seem to be essential for a successful application.
	$q_{inf\ HC}$	

For the calibration of the coefficients, time series of groundwater levels and infiltration rates Q_{inf} at the end of the catchment and the WWTP, respectively, must be available. To cover various groundwater conditions, a long time period and a high temporal resolution of data is necessary with monthly values over a period of several years being recommended.

The infiltration rates can be balanced by calculating the difference of wastewater flow and the average consumption of drinking water. Due to uncertainties associated to balanced drainage rates (Karpf and Krebs, 2003), the variation of infiltration rates may be smoothened.

3.2.2 Calibration

The regional coefficient K_r is determined for a group of pipes according to field measurements. Unless external inputs from measurements are available it should be set to a default value equal to 1.

The calibration of the local coefficient K_l is based on the following equation.

$$K_{l,T} = \frac{Q_{\inf,T}}{\sum_{i=1}^{n}\left[\left(h_{GWL,i,T} - h_{w,i,T}\right)\cdot A_{i,T}\right]}$$ condition: for all reaches with $h_{GWL,i,T} > h_{w,i,T}$

where:

$K_{l,T}$	integral leakage factor at time *T*
$Q_{inf,T}$	balanced infiltration in the catchment at time *T*, without Q_{infHC} and Q_{0inf}
$h_{w,i,T}$	water level in the sewer pipe *i* at time *T*
$h_{GWL,i,T}$	groundwater level at the sewer pipe *i* at time *T*
$A_{i,T}$	groundwater-influenced pipe surface of pipe *i* at time *T*

The calculated leakage factor represents an integral parameter for all groundwater-influenced pipes at a certain time *T*. In order to refer individual leakage factors to pipes, the calculation has to be carried out for a number of time spots. Thereby, the leakage factor of each groundwater-influenced pipe can be estimated by a weighted average of all calibration cases:

$$K_{l,i} = \frac{\sum_{T_i} K_{l,T}}{n_i}$$ condition: equidistant time steps

where:

$K_{l,i}$	calibrated leakage factor for pipe *i*
$K_{l,T}$	integral leakage factor at time *T*
T_i	time spot when $h_{GWL,i,T} > h_{w,i,T}$
n_i	number of time spots when $h_{GWL,i,T} > h_{w,i,T}$

A simplified example for the calibration procedure is shown in Figure 4. For every time T (march and october), one leakage factor was calculated. The weighting for every pipe is done by averaging these $K_{l,T}$-values. Thus, the calibrated leakage factor of pipe 1, which is not groundwater-influenced in march, is equal to $K_{l,October}$; the factor of pipe 2 is equal to the average of $K_{l,october}$ and $K_{l,march}$. etc..

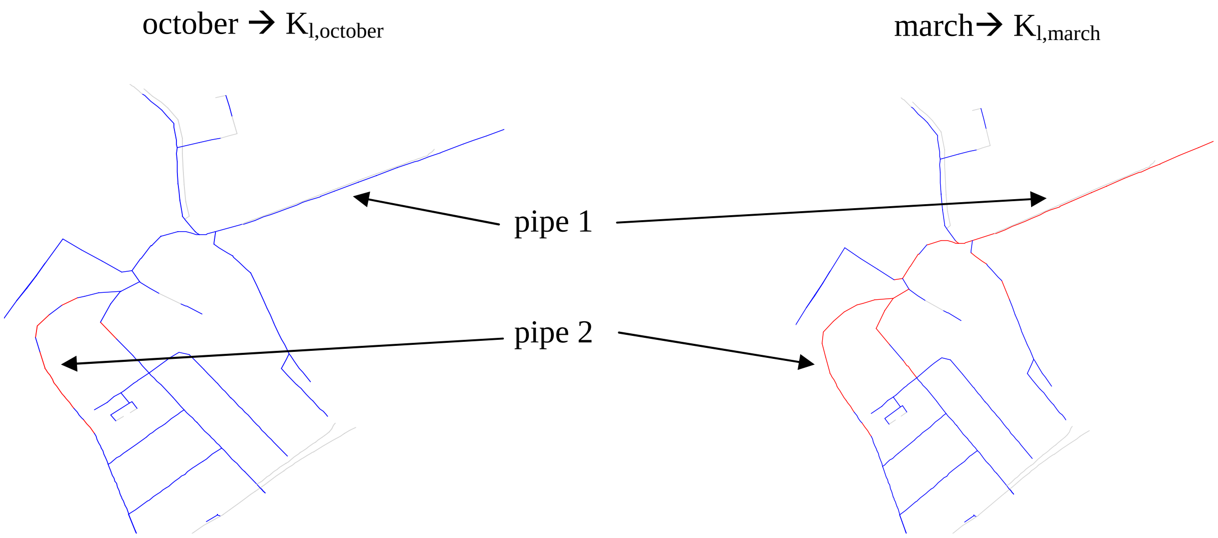

Figure 4: example for calibration

3.2.3 Extrapolation of K_l

Where the calibration of K_l is not possible for all reaches, the coefficient for the remaining reaches can be determined by using a neural network (Franz, 2004).

With a data set of the Dresden catchment containing the metric parameters of network coverage, date of construction, distance to buildings, distance to streets, distance to surface water, population density, reach surface (length and circumference were combined for simplification purposes) and street type it was possible to model the coefficient with an average error of 9 %.

4 Similarity approach

4.1 Motivation

At the present time, tests and validations of I/E models at pipe scale are not possible, as due to the developed measuring methods, infiltration can only be measured at subcatchment scale and exfiltration at branch scale, i.e. including a relatively high number of reaches. Therefore, an analysis of the situation was made under the following premises:

What do we want to know? The objective is the determination of the infiltration and exfiltration (I/E) situation in an urban catchment with a sufficient resolution in space and time, at low cost and completed in a relatively short time.

What do we know? I/E rates are defined by the water head between the inside and outside of the pipe and the leakage of the pipe (including backfilling). In addition to the structural state of pipes, biological chemical processes are also relevant as indicated by the growth of slimes and biofilms. Whereas the groundwater table can be determined relatively detailed by measurements and geostatistical methods (Isaaks and Srivastava, 1989, Dagan, 1986), only general relationships between pipe characteristics, the pipe environment and structural state are known (Rutsch and de Benedittis, 2004). Complementary information on loss rates related to leakage area, flow/pressure rates and defect types are available (Blackwood *et al.*, 2005, Vollertsen and Hvitved-Jacobsen, 2003). Based on this knowledge several I/E models were developed. For an overview see Rutsch and de Benedittis (2004).

What do we not know? The knowledge about cause-effect relationships between pipe characteristics, pipe environment and I/E rates is fairly limited. There is a significant lack of data due to an enormous number of relevant processes and influencing factors (Davies *et al.*, 2001b) as well as due to the general data situation of large sewer systems (Franz *et al.*, 2004). Thus, both deterministic (e.g. Dupasquier, 1999) as well as empirical models (e.g. Gustafsson *et al.*, 1991) are difficult to apply and depend strongly on extensive I/E measurements or CCTV inspections. Due to the high personnel and financial requirements (APUSS, 2004b) as well as due to the methods limitations, measurements with a high spatial resolution are not possible.

The analysis lead to the conclusion, that the potential model development is limited and that new approaches are necessary (q.v. Franz and Krebs, 2003).

4.2 Basic assumption

With the assumption that “similar pipe conditions lead to similar infiltration or exfiltration rates” it is possible to look for and work with “similarities” within a sewer system. With a procedure based on classification and generalisation of homogeneous areas and homogeneous groups of reaches, respectively, these groups should be comparable and information should therefore be transferable.

Models and procedures based on this approach do not have typical input/output functions as they compare and classify states. Therefore, the results are to be considered within the boundary conditions of the data set and they will always have a significant uncertainty. A definite parameter set is advantageously not necessary and the models can be adapted to nearly every data situation.

4.3 Verification of the basic assumption

By means of typical data sets and methods of classical statistics and exploratory data analysis, similarities and dissimilarities of sub-catchments having different infiltration rates were studied.

The following data sets were available:

- 22 sub-catchments of Dresden catchment without groundwater information
- 5 sub-catchments of Dresden catchment with groundwater information
- 5 sub-catchments of Emscher catchment with groundwater information.

The parameters considered are listed in Table 7. For every sub-catchment the infiltration rate was known by measurements.

Table 7: Independent Parameters

abbreviation	parameter
both catchments	
DATE_CONSTR	date of construction
FUNCTION	function (regional, main, tributary)
MATERIAL	material
SEW_SYSTEM	sewer system (foul, combined)
PROF_TYP	profile type (egg, circle, other)
PROF_CIRC	profile circumference
LENGTH	reach length
POP_DENS	population density
POP_LENGTH	population-spec. length
DIST_WATER	distance to surface water
DIST_BUILD	distance to buildings
STREET_TYP	street type (main, residential, …)
DIST_STREET	distance to streets
SLOPE	slope
COVERAGE	coverage[1]
Dresden catchment only	
DIST_ELBE	distance to river Elbe
DIST_STORM	distance to storm sewers
DIST_DRAIN	distance to drainage
THICK_COHSV	thickness of cohesive layers
GW_LEVEL	distance to groundwater[2]
Emscher catchment only	
K	soil permeability
A_IAREA	reduced area ratio
NO_JOINTS	number of joints

[1] incl. wall thickness
[2] based on only one measurement campaign

First, the characteristics of the sub-catchments were compared. An “all-in-one” test was not available, because the considered parameters belong to different statistical scales (these are: metric (numbers like *SLOPE*), ordinal (ranks like *STREET_TYP*), nominal (names like *MATERIAL*), e.g. Walford, 1995). Therefore, every parameter was analysed individually using one-way ANOVA (metric scale), Kruskal-Wallis-ANOVA (ordinal scale), and contingency tables (nominal scale), respectively (Müller, 1991). With these analysis-of-variance methods (ANOVA) it can be investigated as to whether several grouped samples belong to one basic population. For that purpose the methods analyse variances to verify significant inter-group difference of mean values. The observed variances are separated into a component based on the coincidental error (i.e. sum of the squares within the groups) and into components based on different mean values. The latter are tested on the basis of their statistical significance.

For every parameter it could be shown that the reach populations of the sub-catchments differ significantly from each other in terms of their defining characteristics. Due to the wide range of observed infiltration rates (minimum:maximum = 1:16) it seemed to be probable that the dissimilarities between the reach populations are linked in some way with the infiltration rates.

Second, the relationship between the independent parameters and the infiltration rates was analysed by multidimensional scaling (MDS). This method efficiently transforms a high-dimensional arrangement of objects, such that a low-dimensional and interpretable configuration with the optimum approximation of the observed pattern is reached. The distances between the objects are a measure for dissimilarity. The sub-catchments can be seen as objects in an n-dimensional space with n as the number of parameters. Compared with other multivariate methods, the MDS has the advantage that parameters of all scales can be handled together (Borg and Groenen, 1997; Fahrmeir *et al.*, 1996).

The MDS result for the Dresden data set without groundwater is shown in Figure 5. Due to the relatively high number of objects the parameter set was reduced to two dimensions. A relation between these dimensions and the infiltration rate could not be found. However a relation between the parameter set and the urban quarter type (e.g. inner centre, broader centre, suburb) could be found and furthermore, the parameter set was reduced to one dimension. Significant correlations between this dimension and metric parameters are shown in Table 8. It can be concluded, that the parameters of the sewer system – esp. *DATE_CONSTR*, *PROF_CIRC*, *POP_DENS*, *POP_LENGTH* and *DIST_STORM* – can be used as an indicator for the degree of urbanisation and urban development, respectively.

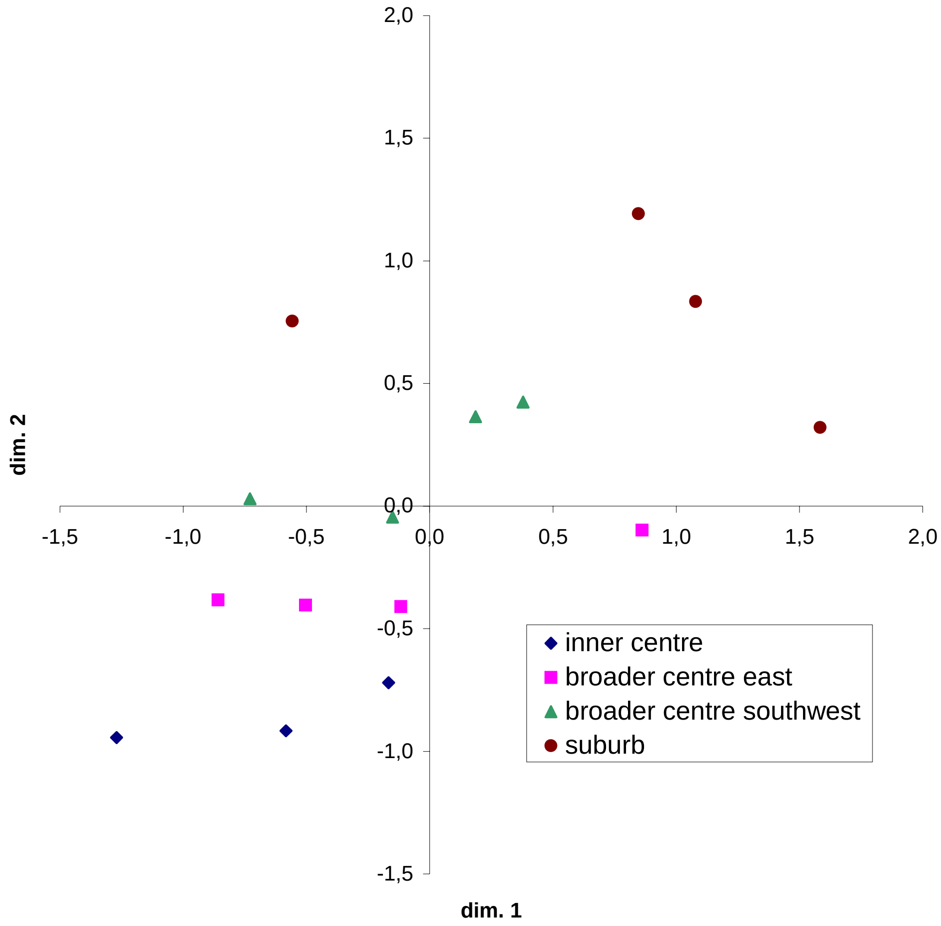

Figure 5: MDS result of Dresden data set without groundwater information

Table 8: Significant correlations between MDS results and parameters

parameter	correlation r
DATE_CONSTR	0.74
PROF_CIRC	-0.92
POP_DENS	-0,88
POP_LENGTH	0,73
DIST_WATER	-0,67
DIST_STORM	-0,83
THICK_COHSV	0,56
SLOPE	0,65
COVERAGE	0,71

dim. 1(centre) < dim. 1(suburb)

The MDS result of the Dresden data set with groundwater information is shown in Figure 6. Only reaches influenced by groundwater were considered and the parameter set was reduced to one dimension. A good correlation between reach-surface-specific infiltration rate q_f and the parameter dimension was found. A comparison with the time-weighted head shows that this correlation, i.e. the specific infiltration rate, is not dominated by the groundwater head (Figure 6).

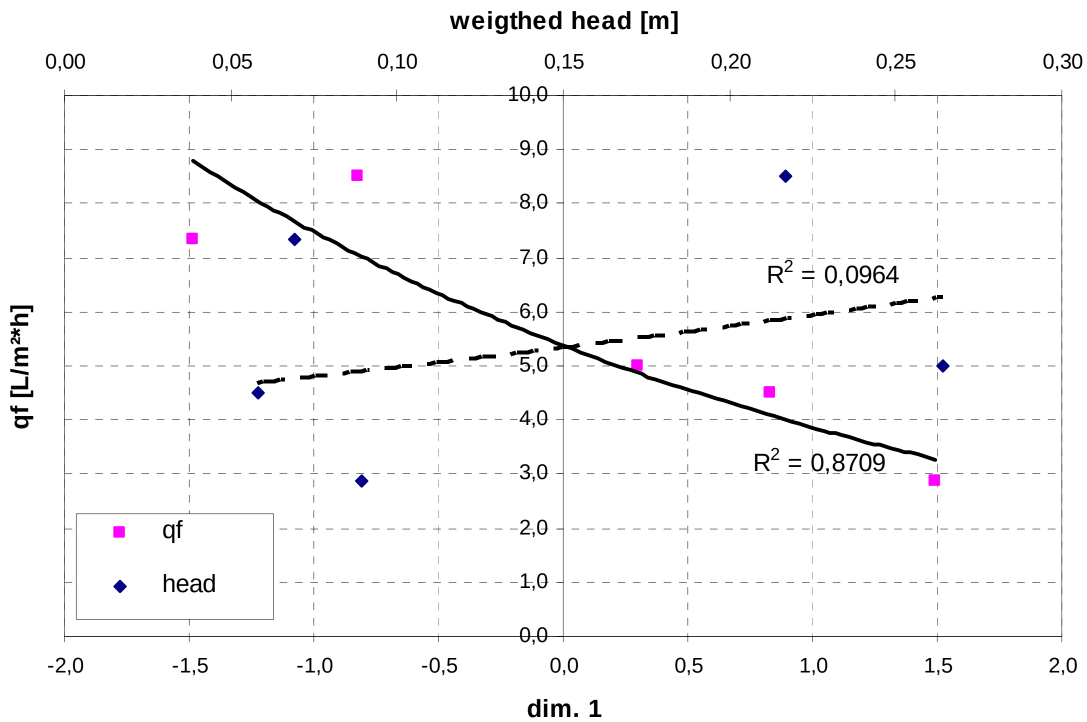

Figure 6: MDS result of Dresden data set with groundwater information vs. infiltration rate

4.4 Conclusion

Because of the reasonable correlation demonstrated between the dimension 1 standing for the independent parameters, and the infiltration rate (Figure 6), it can be concluded that (i) there is a recognisable relationship between the independent parameters and the infiltration rate and (ii) that the parameters - or a part of them - are sufficient to describe infiltration. Thus, the basic assumption of the similarity approach "similar pipe conditions lead to similar infiltration/exfiltration rates" can be accepted as a fundamental concept for further research.

4.5 Applications

The following applications of the similarity approach were developed:

Looking for optimal measurement points: For a given data set a "similarity figure" is calculated for every potential subcatchment. In order to find the optimal number and distribution of gauges, an optimisation algorithm by means of this figure is run (APUSS, 2004c).

Transfer of measurement results: Reaches with unknown I/E rates are assigned to reaches with known I/E rates. Thus, the information about the I/E situation in a city can be significantly improved and aggregated on catchment scale (APUSS, 2004d).

Consequently, these applications are commensurate to classification methods for sub-catchments and reaches with consideration of their flow-related relationship, respectively. Therefore, the similarity approach has a great potential for further development and application possibilities for other problems.

5 References

APUSS (2003a): Minutes of the APUSS management committee meeting, Paris, France, 19-20 February 2003.

APUSS (2004b). Del. 11.3: Summary of economic valuation. APUSS report

APUSS (2004c). Del. 5.1: Classification method to identify sub-catchments for an efficient measurement procedure and transfer of measuring results. APUSS report

APUSS (2004d). Del. 5.2: Integrated model to assign and merge infiltration rates of sub-catchments. APUSS report

Blackwood, D J., Ellis, J B., Revitt, D M and Gilmour, D J. (2005): Factors Influencing Exfiltration Processes in Sewers. *Water Sci. Technol* **51**(2), 48 – 56.

Borg I. and Groenen P. (1997): Modern Multidimensional Scaling. Springer-Verlag New York Inc.

Dagan G. (1986). Statistical theory of groundwater flow and transport: Pore to laboratory, laboratory to formation and formation to regional scale. *Water Resources Research*; **22** (9), 120-134.

Davies, J P., Clarke, B A., Whiter, J T and Cunningham, R J. (2001). Factors influencing the structural deterioration and collapse of rigid sewer pipes. *Urban Water*, **3**, 73 – 89.

Davies, J.P., Clarke, B.A., Whiter, J.T., Cunningham, R.J., and Leidi, A. (2001c) The structural condition of rigid sewer pipes: a statistical investigation. *Urban water* **3**, 145-154.

Dohmann M., Decker J. and Menzenbach B. (1999): Untersuchungen zur quantitativen und qualitativen Belastung von Untergrund, Grund- und Oberflächenwasser durch undichte Kanäle. In: Dohmann M. (Edt.): Wassergefährdung durch undichte Kanäle. Springer Verlag.

Dupasquier B. (1999). Modélisation hydrologique et hydraulique des infiltrations d'eaux parasites dans les réseaux séparatifs d'eaux usées (Hydrological and hydraulic modelling of infiltration in separated sewers). PhD thesis, ENGREF Centre de Paris, 1999.

Fahrmeir L., Hamerle A. and Tutz G. (eds.) (1996): Multivariate statistische Verfahren. (Multivariate statistical methods.) Walter de Gruyter: Berlin, New York. ISBN 3-11-013806-9.

Fenner, R.A. and Sweeting, L. (1999) A decision support model for the rehabilitation of non-critical sewers. *water sci. technol.* **39(9)**.

Franz T. (2004): Reduction of Parameter Number. Internal report for the APUSS project.

Franz T. and Krebs P. (2003): Modifications of Work Package 5. Internal report for the APUSS project.

Franz T., Rutsch M. and Krebs P. (2004). Field Data to Estimate Infiltration into Sewer Systems. Proc. 19th European Junior Scientist Workshop on "Process Data and Integrated Urban Water Modelling", Lyon, France

Franz, T. and Krebs, P. (2005) Statistical methods towards more efficient infiltration measurements. Proc. 10th International conference of urban drainage Copenhagen.

Gustafsson L.G., Lindenberg S., Olsson R. (1991). Modelling of the indirect runoff components in urban areas. Proc. Int. Conf. on Urban Drainage and New Technologies, Dubrovnik, 1991, 127-133.

Gustafsson L.-G. (2000). Alternative drainage schemes for reduction of inflow/infiltration – prediction and follow-up of effects with the aid of an integrated sewer/aquifer model. Proceedings 1st International Conference on Urban Drainage via Internet.

Isaaks E.H. and Srivastava R.M. (1989). An introduction to applied geostatistics. Oxford University Press: New York. ISBN 0-19-505012-6.

Karpf C. and Krebs P. (2003). Definition und Bilanzierung von Fremdwasser. (Definition and Balancing of Parasiting Water.) Umweltpraxis (10/2003), 35-38, ISSN 1616-5829.

Karpf C. and Krebs P. (2004). Sewers as drainage systems – quantification of groundwater infiltration. *Proceedings Novatech 2004, Lyon*.

Kettler, A.J. and Goulter, I.C. (1985) An analysis of pipe breakage in urban water distribution networks. *Canadian journal of civil engineering* **12**, 286-293.

Müller, K. (2002). Entwicklung eines allgemein anwendbaren Verfahrens zur selektiven Erstinspektion von Abwasserkanälen und Anschlussleitungen. http://www.isa.rwth-aachen.de/index.php?option=content&task=view&id=102

Müller P. H. (ed.) (1991): Wahrscheinlichkeitsrechnung und mathematische Statistik. (Probability calculation and mathematical statistics.) Akademieverlag: Berlin. ISBN 3-05-500608-9.

O'Reilly, M.P. (1989). Analysis of defects in 180 km of pipe sewers in Southern Water Authority, Rep. No. 172. TRRL.

Rauch W. and Stegner Th. (1994): The colmation of leaks in sewer systems during dry weather flow. *Water, Science &Technology*, **30**(1), 205-210, 1994.

Rieckermann J., Borsuk M., Reichert P. and Gujer W. (2004): A novel tracer method for quantifying sewer exfiltration. *Water Resources Research* **41**(5).

Rutsch M. and de-Benedittis, J. (2004): Literature review on ex- and infiltration models. APUSS report

Vollertsen J. and Hvitved-Jacobsen T. (2003): Exfiltration from gravity sewers: a pilot scale study. *Water Sci. Technol.* **47**(4), 69-76.

Walford N. (1995): Geographical Data Analysis. John Wiley & Sons Ltd: Chichester. ISBN 0-471-94162-X.