APUSS

Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems

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Conceptual model for the ex- and infiltration of sewers

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1.1. Hydrological models

1.1.1. Overview

Various hydrological models based on reservoir analogy, which simulate inflow/infiltration, are descibed. These models are derived from conceptual runoff models. The models work with pluviometer and evapotranspiration data and inflow/infiltration obtained from measurements of the total flow at the outlet of the catchment. De-Benedittis [2001] focused on the models RORB, NAM, BREIL-Model and SEPI1.

1.1.2. RORB model

The RORB model was developed by Laurenson and Mein (1992) to simulate inflow/infiltration of separate sewers. RORB is a rain-flow model used in Australia. It consists of several tanks in cascade with special outlet functions. They distinguish various flow components supposing that dry-weather flow corresponds with wastewater and permanent contributions of infiltration due to groundwater drainage. During rain events inflow and fast drainage are added. In order to take into account the response time of the water storage in the ground, rain is introduced into the tank with a 10 hours delay.

This model was tested in a 67 km² residential area. Simulations of various contributions were carried out in 20 subcatchments, the flow in the subcatchments was calculated. Rather good results were obtained for single rain events, but the inflow/infiltration varies for different rain events. The model does not take into account the variability of ground moisture surrounding the pipes and permanent groundwater drainage, respectively. It is a very simple approach with a small parameter set.

1.1.3. MouseNAM

NAM [Gustaffson, 1991] is a hydrological runoff model. This model simulates rain-flow transformation via four inter-connected tanks. Gustafson included inflow (Fast Response Component FRC) and infiltration (Slow Response Component SRC) into sewers.

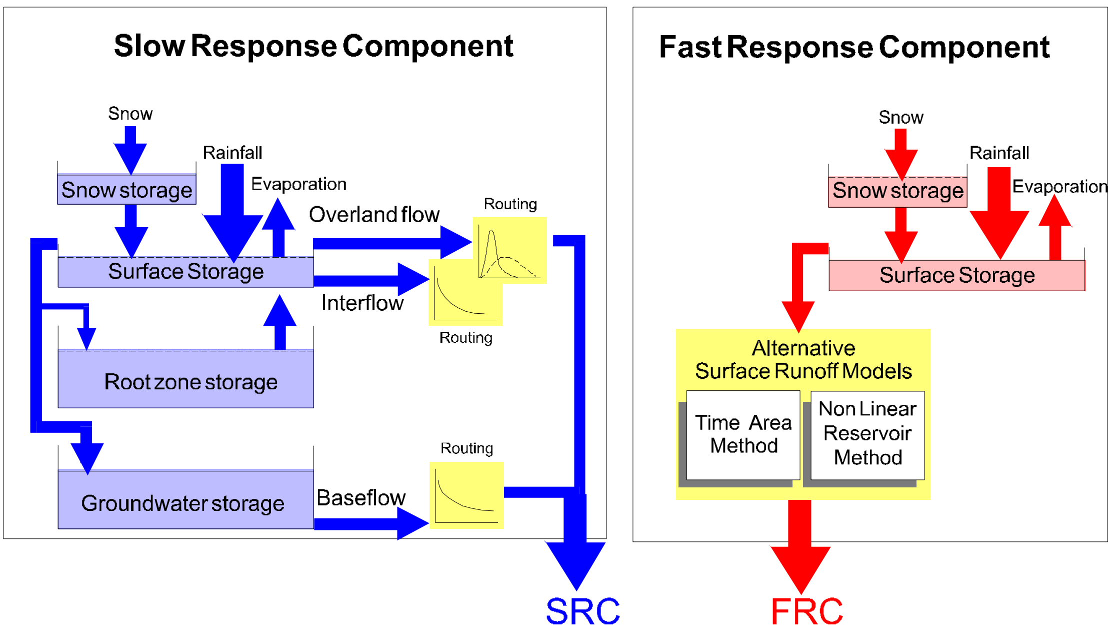

Figure 1: MouseNam model structure by Gustafson et al (1991)

The model delivers very good results. Yet, MouseNam has a rather complex structure and a high number of parameters. The numerical freezing of these parameters is critical as discontinuities in model operation and the existence of a second optimum was found.

1.1.4. The Breil-Model

The model proposed by Breil [1990] is a global model with two tanks (slow drainage – groundwater infiltration, fast drainage – inflow) and 12 parameters. It was first developed by "Laboratoire Central des Ponts et Chaussées (LCPC)" to simulate infiltration into sewers. Breil was also inspired by the GR2 rain-flow model. The model reproduces correctly flows observed during dry and wet season. Yet, the high parameter number causes problems of fixation and identification of optimum parameters. Moreover, the fixation requires tensiometric measurements.

1.1.5. SEPI model

The SEPI-model [Belhadj, 1994] is based on Breil and GR2 models. From a 16-month record of hourly rain and flow measurements a model with three tanks and six parameters was developed. The first tank (production) is associated with a function of rain output. It gathers various hydrological phenomena like interception, evapotranspiration or surface retention. The second transfer tank connects the estimated rain depth with the catchment's diurnal flow. In this state, the model with only two tanks does not include the variability of inflow/infiltration, it underestimates peak flows and overestimates recession velocity. A calibration was proposed with the contributively active surface. The two components of inflow/infiltration (groundwater and rain) are thus calculated starting from water stocks in their respective tanks. The calibration requires a small dataset, although interdependences of parameters need to be excluded.

1.2. Statistical models

These models focus on the damage/leakage of sewers and water mains. They do not refer to infiltration or exfiltration rates in particular. Factors influencing the damage of pipes are identified and data requirements are revealed.

Müller [2002] calculated the relevance of factors in evaluating the damage recorded within a reach. A very comprehensive database was provided with 4 sewer systems and their complete databases including closed-circuit-television (CCTV) inspections and structural data. Initially, all available factors were included in statistical tests used (u-test, h-test) and a ranking was set up, resulting in the following table.

Table 1: Factors influencing the condition of sewers [Müller, 2002]

Factor	Relevance	Comments
Date of construction (Age, standards of pipes, sealing and workmanship)	Very high	Investigated since 1940
Dimension	High	No statement for bigger diameters
Sewerage system (combined, storm, foul)		
Depth of cover		Depending on compaction and backfilling, cover depth less than 2m
Soil		
Sewer material		
Traffic load, bedding arrangement	Low	Dependent on compaction and backfilling
Profile	No statement possible	
Groundwater level		
Catchment		

The transferability of the results to the basic population of the whole sewer system is guaranteed with a sufficient accurate forecast having a sample of approximately 500 reaches. The ranking is also usable for house connection pipes.

DAVIES [2001] investigated sewer pipe deterioration and collapse. As a large number of factors may contribute to the collapse and complex interactions exist between these factors a so-called interactions matrix (IM) was set up. 28 factors were used to construct the IM, the vast majority of the factors having previously been identified by a literature review. The 28 factors are:

Table 2: Factors influencing the structural deterioration of sewers [Davies, 2001]

Construction features	**Local external features**	**Other factors**
Construction method	Surface use	Presence of rodents
Standard of workmanship	Surface loading	Sewage characteristics
Sewer diameter	Surface type	Inappropriate maintenance
Depth of cover	Ground movement	Investment history
Bedding arrangement	Other utility maintenance	Age of sewer
Sewer material	Ground water regime	Sediment level
Pipe section length	Infiltration/exfiltration	Surcharge
Line and level	Native soil properties	
Connections	Root interference	
Joint type	Water main burst/leakage	
Fill quality		

In considering the views of expert sewerage practitioners the following factors were thought of as having the largest effect on the system of sewer deterioration and collapse.

- Surface use
- age
- investment history
- depth of cover
- native soil
- sewer diameter
- standard of workmanship
- connections

These investigations do rely on expert views and are thus largely subjective. The factors were identified in a more objective manner by means of a statistical investigation. A logistic regression model was applied to investigate the association of 18 independent (explanatory) variables with sewer structural condition (dependent variable). The CCTV data formed the reference point to which all other data sources such as soil data, traffic data, property age data and so on were matched. 10 factors were found to be significant on the 5 %level in multivariate logistic regression. These 10 terms were as follows:

- Debris
- Sewer pipe section length
- Sewer size
- Sewer use/purpose
- Soil fracture potential
- Soil corrosity
- Sewer location
- Groundwater regime
- Sewer material
- Bus flow

Both investigations of Davies [2001] returned similar results in the sense that a wide range of factors was identified as important in determining the likelihood of an existing rigid sewer pipe collapsing. The methods were not able to pinpoint one parameter or a small group of factors as being of overriding importance. Comparing the two methods the factors connections/sewer pipe length, sewer diameter/sewer size, sewer location/surface use (both describing the use of the ground immediately above the sewer) and soil were found to have an above average influence in the IM and significant in statistical analysis. A number of discrepancies were also identified.

The distribution of defects examined with structural conditions (defects found during CCTV survey inspection of sewers in southern England) was analysed by O'Reilly et al. [1989]. The defects were observed in some 180 km sewer, which represents only 0.1 % of public sewers in the UK. It was compared with other studies carried out in the UK and a fair consistency in the percentage of structural defects was recorded. The main statements with regard to the deterioration of the sewer are:

- With decreasing age the number of structural defects also decrease.
- The distribution of faulty connections and junctions do very slightly decrease with increasing age.
- The highest defect rate was associated with vitrified clay pipes (7,5%).
- The average fault rate increases with increasing pipe diameter.
- The number of structural defects decreases the smaller the road above the sewer. A very high incidence of defects in gardens was recorded.
- A slight decrease of the average structural defect rate with increasing depth of sewer invert was found.
- An association of the distribution of structural defects with sewer use showed that storm water sewers have a higher potential of structural deterioration. As the main part of the samples is foul sewers, this figure can be somewhat misleading.
- Concerning the soil type only stability criteria were analysed.
- A connections frequency with pipe diameter was recorded. With a rising number of connections per km an increase of the number of structural defects was recorded.
- As a conclusion concerning the connections: the banning of connections and their substitution by junctions would eliminate a major source of defects from sewers.
- As a conclusion concerning the age: As a result of technological improvement, pipe sewers constructed since 1945 show a much lower rate of structural defects than older sewers. Pre-1850 built sewers differ only marginally from those constructed in the 1876-1917 period.

According to EPA [1977] leakage in sewer systems is directly related to the material characteristics, soil and groundwater conditions, and to the quality of workmanship.

Fenner and Sweeting [1999] developed a decision support model for the rehabilitation of non-critical sewers. Within these investigations a prediction relating to probability of sewer failure were to be derived from historical performance and asset data. A criticality number was formulated, which was based on overall frequency of the pipe length, the age of the sewer, factors to allow for pipe characteristics (such as number of connections, pipe material), normal system deterioration, changes in environmental conditions (such as fluctuating groundwater levels), and a term reflecting the extent of customer complaints concerning garden flooding, traffic disruption, etc. It was intended to use this number to target those sewers most at risk. After an investigation of availability of existing data it became obvious that only pipe material, sewer type, pipe size, and event history were consistently available. Other information could be abstracted from elsewhere but is not stored in standard databases. The initial concept was therefore rejected in favour of a simpler method of analysis. A first approach was a grid square analysis using GIS. Each square was queried for event history and pipe characteristics available. It was assumed that each grid cell contains assets of similar type and age and has consistent environmental factors. The resolution of the grid may be defined to suit the type of catchment being considered. It was stated that the use of those physical asset information available did not produce high rank correlations.

A second approach was an individual pipe ranking based on a Bayesian model. The probability of failure on a given pipe length can be obtained by adjusting the catchment wide probability of failure based on the relevant characteristics of the pipe. The pipe characteristics, which might be expected to influence failure, are sewer type, depth, size, shape, material, gradient, traffic flow, age, construction type, joint type, and soil type. As only a few of these characteristics are commonly stored, the analysis could be refined by the remaining characteristics in the future. As the aim of this investigation to predict sewer failure due to lack of maintenance differs to our approach the results can only be named but cannot influence the decision which characteristics are most likely to influence the leakage of sewers. Besides, no statement concerning the ranking of the characteristics was given. Fenner and Sweeting corroborate the theory that large amount of characteristics are expected to influence the condition of sewers but the data availability constrains the analysis considerably.

Wanaars et al. [1999] investigated the hydrologic behaviour of storm water infiltration and concluded in obviously different function of two trenches due to their different soil characteristics (field saturated hydraulic conductivity and storage capacity).

In setting up a probability model Cooper et al. [2000] established and analysed quantifiable relationships between factors, which influence mains failure. By measuring or estimating these factors, relationships are applied which predict failure under specified sets of conditions. It was stated that this method requires a large amount of detailed data or estimates to produce accurate results. The factors included within the modelling process were:

- soil corrosivity class and soil fracture potential
- no. of buses, cars/light goods vehicles, and goods vehicles per hour
- trunk main peak pressure at 3 am (modelled)
- maximum pressure difference (modelled)
- ground elevation
- pipe density function (proximity to other pipes)
- pipe diameter
- urban development year (as a surrogate for pipe age)

5 factors were claimed explaining the distribution of mains failure assuming that they may provide surrogate measurements for a wider range of factors. These were:

- no. of buses per hour which indicates the impact of heavy traffic loads
- pipe diameter also as a surrogate for wall thickness
- soil corrosivity class merged with soil fracture potential, representing the effect of corrosions and soil movements on trunk mains
- pipe density function including disturbance from local excavation or operational procedures
- pipe age and material were claimed to be important as well, however this information was not available in this survey

With this approach the distribution of failures can be explained in a robust manner with the aim to collect additional data to increase confidence in key decisions.

An approach to sewer maintenance [Hasegawada et al. 1999] claims to predict a time when the sewer pipe should be repaired based on the knowledge of diameter, length, materials and other sewer characteristics, and is based on the accumulated knowledge and experience of those professional engineers involved with sewer maintenance and management. CCTV is used to classify pipe defects. Since the condition of the sewers due to the kind of maintenance is investigated a detailed description is not given.

Galeziewski et al. [1995] describes a prioritisation procedure based on a photographic inspection and CCTV survey for the rehabilitation of large diameter unlined concrete sewers, which were prone to hydrogen sulphide corrosion damage. This uses an algorithm, which combines the corrosion and structural condition of each pipe with other observed defects and an impact factor to produce an overall score which is used to rank pipes in order of deteriorating condition, allowing pipes to be grouped into five condition categories.

Stalnaker [1992] describes a sewer rehabilitation methodology used in Texas, which uses data from recent CCTV inspections and flow surveys and a number of pre-set rules to formulate maintenance decisions.

Rostum et al. [1999] use the results of CCTV inspections to group sewers into condition classes. The transition between these condition classes is then used to describe the deterioration process of sewers. An advantage for these investigations is the available information of the structural data, long records of failure data and CCTV inspections.

Fenner [2000] summarized, that sewers, which have not yet collapsed but are in a poor condition, would not be identified simply from sewer failure records, as only breaks are recorded that lead to complete collapse. Thus, CCTV inspections will be more suitable for modelling the technical state of sewer pipes.

A comprehensive review of statistical models applied for the analysis of the structural deterioration of water mains are given by Kleiner and Rajani [2001]. The statistical methods for predicting water main breaks are based on available historical data on past failures to identify pipe break patterns. These patterns are then assumed to continue into the future in order to predict the future breakage rate of a water main or its probability of breakage. The deterministic models predict breakage rates using two or three parameters that are based on pipe age and breakage history. Many factors, operational, environmental and pipe type dependent, jointly affect the breakage of a water main. The population of water mains has to be partitioned into groups that are uniform and homogeneous with respect to these factors. These groups have to be small enough to be uniform but to be large enough to provide significant results. Some correlations were postulated in applying these approaches [quoted in: Kleiner and Rajani, 2001] but mostly with only a moderate correlation and not validated by applying it to a holdout sample.

- Strong negative linear correlation between pipe diameter and breakage rate (larger pipes break less frequently than smaller pipes) [Kettler and Goulter, 1985]
- Moderate correlation between annual breakage rate and pipe age for asbestos cement and cast iron pipes [Kettler and Goulter, 1985]

Le Gat and Eisenbeis [2000] illustrate the use of the survival theory approach using a Weibull Proportional Hazard Model and discuss its validity in the case where only short maintenance records are available. Two water networks were investigated: one with good data availability and one with rather poor data availability. It was assumed that a pipe is a segment of network serving the same road and is homogenous in material, diameter, age, and environmental covariates. The most important factors were claimed to be the number of observed previous failures. The data were split into strata according to the material as interactions between pipe material and other explanatory variables (e.g. corrosion due to soil different for different materials) are to be justified. It was pointed out that the factors act differently according to material and the number of previous failures of the pipe. Each water network has specific features affecting pipe failures and an universal model seems unlikely to exist. The results of the water network with long records show that with a small number of factors i.e., only factors specific to the pipe it is possible to detect pipes with the highest risk of failure. Taking into account environmental factors should improve the precision of the prediction. Another crucial consequence is that the result obtained in a given water company cannot be directly transferred to another one.

Lei and Saegrov [1998] postulated from their investigations in water mains that the age of a pipe does not play a significant role for the remaining lifetime of the pipe. They introduced two different approaches for describing failures and lifetimes of water mains. With counting models one can see the deteriorating (or improving) trend in time of a group of “identical” pipes and their rates of failure occurrence. Groups of pipes were identified according to installation year, dimension and material, respectively. With the information on failures observed during the last years eleven classes were defined where each class corresponds to a group of identical pipes with a linear graph predicting the number of failures per year. With lifetime models, one can estimate the probability, which a pipe will fail within a time horizon. Therefore a survivor function is estimated, which may depend upon a given set of explanatory variables. It was found that pipe material was a stratification criterion rather than an explanatory variable, implying that the underlying ageing processes are different for various pipe types.

The time-dependent Poisson model represents the pipe breakage as a power function of pipe age. The scale parameter is modified by environmental an operational covariates, while the power parameter is said to be unique to the type of failure [Kleiner and Rajani, 2001].

On one hand, the probabilistic multi-variate models show moderately low correlations, when applied to different water networks. On the other hand most of the reports did not provide any indication as to the quality of predictions or no attempt to fit the model into a holdout data set was reported. It was an overall agreement that an obvious lack of data limits the potential benefits of these models. The probabilistic single-variate group-processing models include models that use probabilistic processes on grouped data to derive probabilities of pipe lifetime expectancy [Herz, 1996, Kulkarni, 1986], probability of breakage and probabilistic analysis of break clustering phenomenon.

Herz [1996] proposed with the cohort survival model a lifetime probability distribution based on the principles that had originally been applied to population age classes. Transition functions from one into the next poorer condition class are used to forecast the condition of sewer. With these transition functions, the most probable date of entering a critical condition class can be forecasted from sewer characteristics such as material, period of construction, location, purpose (foul, storm water), profile diameter and gradient. The model is to be applied to groups of pipes that are homogeneous with respect to their material type and environmental/operational stress class.

Kulkarni et al. [1986] developed the cast iron maintenance optimisation system for the gas research institute to identify failure-prone segments of gas pipes and to determine the optimal time for their replacement. The model is based on the Bayes theorem. Two groups of pipe characteristics were identified: static (e.g., diameter, length, soil type, etc.) and dynamic (e.g., cumulative number of breaks, age, etc.). The mains are to be partitioned into homogeneous groups (condition states) and the failure ratio (probability of a failure with a specified condition state) in these groups are compared and evaluated. The model cannot predict the number of breaks of time; rather it indicates the probability of failure in the next period.

Other probabilistic single variate group-processing models were mentioned by Kleiner and Rajani [2001], such as the modelling of the breakage history of water mains as a semi-Markov process, but found this model inadequate for predicting future breaks. Goulter et al. [1993] proposed a significant temporal and spatial clustering of water main failures in Winnipeg. They found strong evidence that an occurrence of a repair event is very likely to trigger a subsequent breakage in close proximity soon thereafter. They attributed this phenomenon to

- deteriorated bedding conditions around the failure location due to the leakage of water
- repairs of water mains in the winter
- the actual repair process.

Since there is no publication indicating whether this model has been applied elsewhere, it is not clear whether it describes a global clustering phenomenon or a situation that is unique to Winnipeg.

The approaches described are more or less limited by the existing knowledge and available data. The sewers are partitioned into homogeneous groups (treatments) with respect to their condition classes. Mostly pipe lifetime expectancy models were developed, which can be useful to predict and plan for the future needs of utilities for renewal of water mains. However a relation of structural condition and breakage rate could only be established with a moderate correlation figure.

Physical/mechanical models attempt to predict pipe failure by analysing the loads to which the pipe is subject as well as the capacity of the pipe to resist the loads. The residual structural capacity of pipes exposed to material deterioration and subjected to internal and external loads requires the consideration of numerous components such as frost loads, influence of corrosion rates, and materials properties such as strength and fracture toughness, etc. With their review of these models Rajani and Kleiner [2001] support the understanding of the structural performance of water mains. An overview of factors that accelerate/influence the structural deterioration of water mains (mainly metallic pipes) is given, as well as an explanation of pipe breakage types. The breakage and therefore the design of the models is mainly attributed to /traced back to the fact of corrosion. As this is only a small part of structural deterioration of sewer systems and corrosion processes are different in sewer systems due to the different materials used, this is of minor importance.

Summarizing, it was not possible to pinpoint one parameter or a small group of factors as being of overriding importance. To establish a model with the connection of influencing sewer characteristics and leakage of sewer a large amount of characteristics need to be considered. Factors frequently named and thus expected to affect the leakage of sewers are:

- Material
- Connections (number and type)
- Soil and groundwater conditions
- Quality of construction
- Size
- Location (traffic, surface load)

Differences in the structural condition of neighbouring treatments were proved, e.g. a comparison of large and medium pipe diameters showed a different extent of damage.

1.3. Design of experiments

1.3.1. General

With the statistical approaches the importance/influence of the structural data on the condition of sewers or furthermore on the leakage of sewers was investigated. The focus of experimental design is on the planning of experiments. As infiltration is estimated in a relative large subcatchment, exfiltration measurements are conducted over a certain sewer section. The number of samples and the categorization of their treatments will be answered with experimental design. The main question is, how many samples are required to interpret the following effects:

- Main effects of the independent variables on the dependent variable
- Interdependencies of the independent variables
- Effects due to different combinations of dependent and independent variables

Different techniques have been tested as evaluation of our measurements with regard to the number of samples and significance (described in sections below):

1.3.2. Logistic regression [Urban, 1994, Bahrenberg et al., 1992]:

A small number of variables, categories, and samples is required to test the main effects and the quality of the model adaptation, respectively. An increase of the independent variables, the number of samples, or the categories improves the quality of the model until it complies with the observed values. The logistic regression results in likelihood that a sewer with the independent variables material, date of construction, and diameter shows a certain leakage/condition. The result can be underlined by a figure of merit, which estimates whether the estimated values correspond to the observed values. Yet, the logistic regression needs a high number of samples, as far as all specifications will be combined with each other.

1.3.3. Variance and covariance analysis [Bortz, 1993]

Table 3: Description of Variance and Covariance analysis

	Variance analysis	**Covariance analysis**
Definition	Systematic variation of the input variables to measure the effect due to disturbing variables → reduction of error variance	Correlation of covariate with dependent and independent variables → reduction of the error variance without decrease of sampling number
Input	Normal distribution of samples Minimum number of samples: 270 samples	Normal distribution of samples Minimum number of samples: 90 samples
Result	- Influence due to disturbing variables - Significant or arbitrary differences between the categories - Main effects - Interdependencies 1.order - Interdependencies 2. order	- Test, whether error variance can be attributed to the covariate - Significance of main effects - Significance of interdependencies
Evaluation	Highest number of samples: Best possible result	Smallest number of samples Main effects and interdependency of independent variables

1.3.4. Incomplete experimental design

Only selected or hypothesized effects are observed under a reduction of the number of samples. 3 designs have been analysed:

- Partly hierarchical design with 180 samples (3 independent variables) to obtain main effects and interdependencies,
- Hierarchical design with 120 samples (3 independent variables) to obtain main effects
- Latin squares with 90 samples (3 independent variables, large categories) to obtain main effects

1.3.5. Rank order statistics or relevance test of certain variables

The rank order statistics are non-parametric tests, which means that no or only a few assumptions regarding its distribution function are required [Storm, 1995]. The relevance test is performed with the Mann-Whitney Test or the Wilcoxon Test (also known as the u-test) [Sachs, 1997]. Two samples from different populations are given. The u-test is a statistical test to see if the null hypothesis (H_0) that the two populations are identical can be rejected with a certain level of significance. That means to detect differences between the two populations in the basis of random samples from those populations. The equivalent situation is that one random sample is obtained, which is randomly subdivided into two samples. One sample receives one action and other sample receives a different action.

This test is based on assigning ranks to the sample values. Hence, the null hypothesis can be rejected if the ranks associated with one sample tend to be larger than those of the other sample. Ranks may be considered preferable to the actual data for the following reasons:

- The numbers assigned to the observations contain no more information than the ranks.
- Even if the numbers have meanings the probability theory of ranks does not depend on the distribution in many cases.

The asymptotic relative efficiency (A.R.E.) of the test is good when compared to the t-test. The u-test is a safer test to use. The hypotheses for a two-tailed test (with F(x) and G(x) as the two random samples) are:

$H_0 : F(x) = G(x)$ for all x

$H_1 : F(X) \neq G(x)$ for some x

1.3.6. Summary

Hierarchical designs require categories with a rather fine resolution. The number of samples required is higher than for the covariance analysis with similar results expected. The best information about significances of the single variables regarding to the condition of sewers is delivered by the variance analysis. The smallest number of samples and still sufficient information are received from the covariance analysis. Latin squares give only a first idea about the significance of the main effects. Its results can be used, if any interdependency can be excluded. The number of experiments and thus obtained results and the available data are the limiting factors applying the proposed statistical analyses. The above-mentioned methods always require a certain number of samples and the assumption of a normal distribution of the data. The rank variance analysis requires least assumptions, however the result is only a comparison of different behaviour regarding to their dependent variable. Still, it was the only possible test to be applied.

1.4. Theoretical investigation regarding the process of ex- and infiltration

1.4.1. Year of construction and its influence on the condition of sewers

The year of construction was assumed more substantial than only the consideration of the sewer age. Quality of workmanship, quality of material and sealing, as well as state of bedding is comprised in the year of construction. The historical background can also be deduced. Figure 2 shows a compilation of released standards in Germany and the historical development of sealing construction quality.

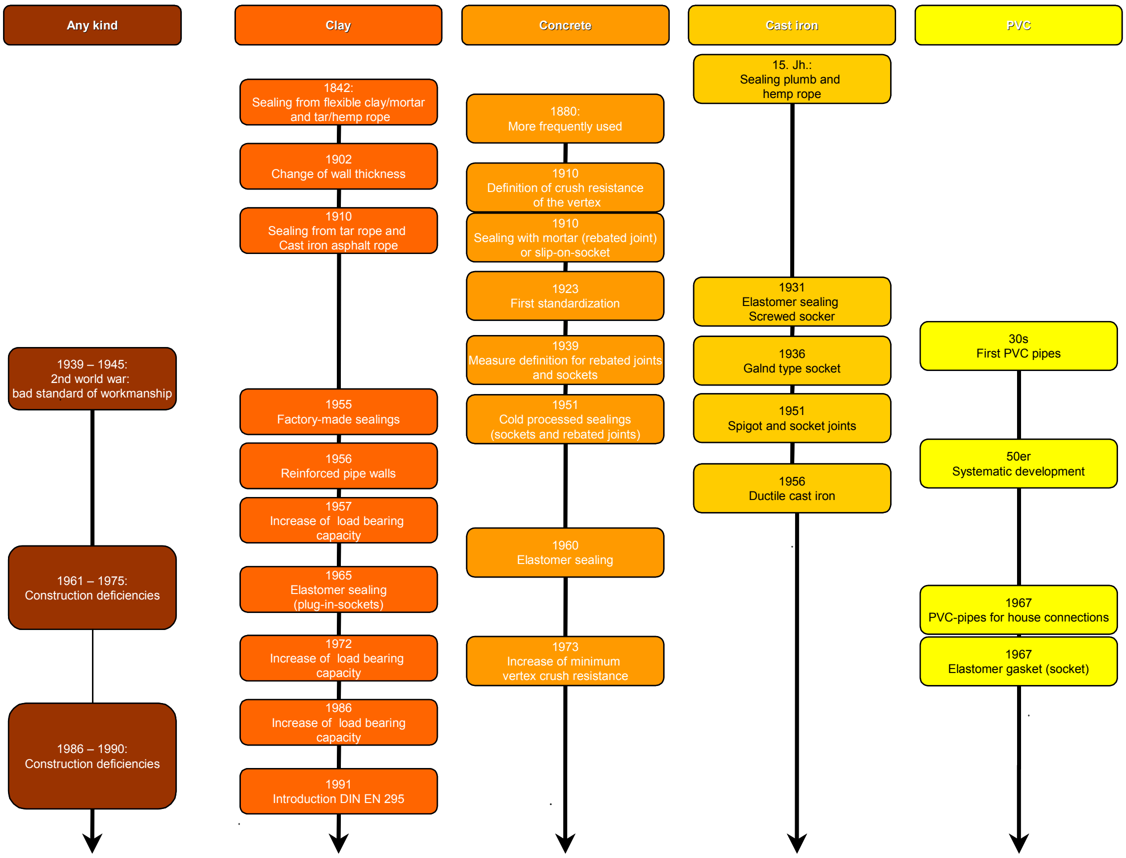

Figure 2: Development of the sewer construction [derived from Stein and Niederehe, 1992]

The clear change of the construction standard lead to the assumption that for particular times a certain condition of sewer and hence a certain leakage of sewer might be expected. For example, until 1965 the sealing was produced with tar or hemp ropes, which were not even stable against the wastewater composition. Only in 1965 the elastomer sealing was standardized. Still, the quality of workmanship is difficult to reproduce, as the performing company was not recorded.

1.4.2. Soil and soil clogging

Infiltration is defined as entry of water into soil. At the beginning high infiltration rates due to large pores and a low water potential of the dry soil is expected. The infiltration velocity is decreasing with increasing water potential. Eventually, the infiltration rate reaches a stable value (percolation rate). The percolation rate is equivalent to the permeability coefficient in saturated soil conditions. The mechanisms of soil clogging are described by e.g. Grotehusmann [1995].

Filtration: In the unsaturated zone seepage water flows through the soil grain in thin layers developing a turbulent current touching the grain. In the saturated zone the seepage water flows mostly laminar. The matter transport is slower and the filtration potential smaller. Only undissolved matters are filtered. The filtration process changes over the time due to colmation.

Physical clogging occurs, if suspended solids block the pores. When the soil pore size is larger than the diameter of the suspended solids, some particles may penetrate to greater depths. Suspended solids are deposited, building up a restricting layer. The hydraulic properties of the layer are best expressed in terms of the hydraulic resistance or impedance, which is defined as the thickness of the layer divided by its hydraulic conductivity. This impedance can be calculated as the head loss through the layer divided by the infiltration rate [Bouwer, 1972]. The impedance will increase the more suspended solids are deposited.

Sorption describes the reactions of dissolved matter with the surface of the solid phase. Solution contents are adsorbed by the solid phase and solids are desorbed by a solution. A stable equilibrium between matter concentration of solution and solid phase in the soil is established.

Precipitation is only considered at occurrence of heavy metals.

Biological and chemical degradation: Chemical degradation is hydrolysis and oxidation. Chemical clogging is caused largely by chemical interaction between dissolved slats in the water and the soil, resulting in a decreased pore diameter and lower permeability. Chemical clogging seldom occurs unless the sodium content of the water is high. Biological clogging occurs if bacterial growth or its by-products reduce the pore diameter. Biological substances are degraded metabolically and co-metabolically.

De Vries [1972] hypothesized that the filter failure is a result of the deposition of a layer. It happens when sludge in the soil surface seals off the surface pores. Tests were conducted to determine the site of pore clogging associated with filter failure as effluent treatment after the primary treatment. After 240 days there was no evidence of filter failure due to the deterioration of the soils physical properties (measurements of pore size distribution). Moreover, the surface layer exhibited more favourable pore size distributions than the original material (sand). As hypothesized, a deposit of sludge on the filter surface caused the detected small values of the hydraulic conductivity.

Orth and Ebers [1988] consider the impact of filtration as the limiting factor. The filter pores clog up in terms of a high amount of suspended solids. After infiltration experiments with untreated waste water a fast colmation of the infiltration field was observed. In contrast the hydraulic conductivity did not change that much when treated wastewater (tertiary waste water effluent) was infiltrated.

Within the reuse of wastewater in Arizona [Bouwer et al., 1974] the effect of the flooding schedule on the infiltration rate was investigated. The infiltration decreased during flooding about linearly. But the soil drying (5-10 days recovery) effectively restored the infiltration rate to original values. It was also postulated that the suspended solids content should not exceed 10 mg/l for sustained high infiltration rates.

The mentioned filter recovery was also detected by de Vries [1972]. After a period of approximately 8 days the O_2 and CO_2 concentration in the filters, which failed reached higher values than initially observed. This was attributed to an accumulation of organic matter within the filters. The organic matter was oxidized during the recovery under O_2 consumption and CO_2 production. Moreover, a decrease in organic matter is followed by an increase of pore volume, accompanied by an increase of the hydraulic conductivity. Still, it is to be questioned if wetting and drying or only the establishment of an aerobic system is supposed to be a requirement for a partial recovery of the infiltration capacity. The production of activated sludge in the soil in aerobic conditions was not discussed.

Rice [1974] studied soil clogging in soil columns (loamy sand and coarse sand) looking at the relationship between total solids load and the hydraulic properties of the restricting layer. According to Rice clogging occurred mostly at the surface, as indicated by increasingly high gradients in the top 1 cm of soil. The hydraulic conductivity of the rest of the column remained constant for a given infiltration period. The main difference in clogging of the two different sands was the extent of the layer. In coarse sand the solids moved farther into the pores at higher gradients because of higher seepage forces. This distributed the solids over a larger volume of soil, resulting in a thicker clogged layer. In contrast, low gradients of the loamy sand yielded in a looser layer of solids in the surface because of the lower infiltration rates. Rice showed that adequate infiltration rates could be obtained by keeping the suspended solids concentration below 10 mg/l. In a long-term investigation of the 10 to 30 cm depth of the columns the hydraulic conductivity was observed over the time. After 3 years of intermittent infiltration the hydraulic conductivity was reduced 50 to 60 percent, which was attributed to entrapped gases.

Hill [1983] observed a decrease of the hydraulic pore volume down to the lower limit of 20 %, remaining stable after 45 days of filtration until the 110th day. But an increase of pressure loss was recorded from 5 cm on the 45th day up to 12 cm on the 110th day.

Siegrist et al. [1987] observed the infiltration of grey water and wastewater from a septic tank. The soil clogging developed more rapidly in those cells loaded with wastewater. Soil clogging eventually led to intermittent and then to persistent ponding, above all in the wastewater cells and in cells with 4 times higher grey water load. The increase was an expression of continuous soil clogging. The increasing hydraulic head compensated for an increasing resistance to infiltration. After all, the soil cell continued to transmit the daily loading. A recovery of the filter due to intermittent operation was detected and a better hydraulic conductivity in case of a reduction of TSS loading rates.

2. Modelling approaches

2.1. Rank variance analysis

2.1.1. Requirements by the test

Approximately 7.2 % of the Dresden sewer system is surveyed via CCTV and can be attributed to their structural data/pipe characteristics. This sample is used to identify a possible relevance of these structural data on the condition class calculated from the CCTV records. The independent variables are material, construction period and dimension. Data about the leakage of sewers (ex- or infiltration rates) were not available; the dependent variable is the condition of sewers expressed in a condition class from CCTV records. The rank variance analysis does also not concentrate on ex- or infiltration, but on the leakage of sewers. The influences of structural data on the leakage are to be tested.

Still, the u-test has 4 requirements discussed in the following:

1. Both samples are random samples, or in our case one random sample is randomly subdivided into two samples.
2. In addition to the independence within each sample, there is mutual independence between the two samples.

As the CCTV records of Dresden are randomly distributed, the first two assumptions are fulfilled. Besides the dataset of the population, i.e. all reaches of the Dresden sewerage system is compared to the dataset of the sample. Figure 3 illustrates the material distribution whereby concrete and clay represent very well the distribution of the population. The other materials do not comply with the requirements concerning a proper amount of reaches for a statistical analysis or do not represent their population.

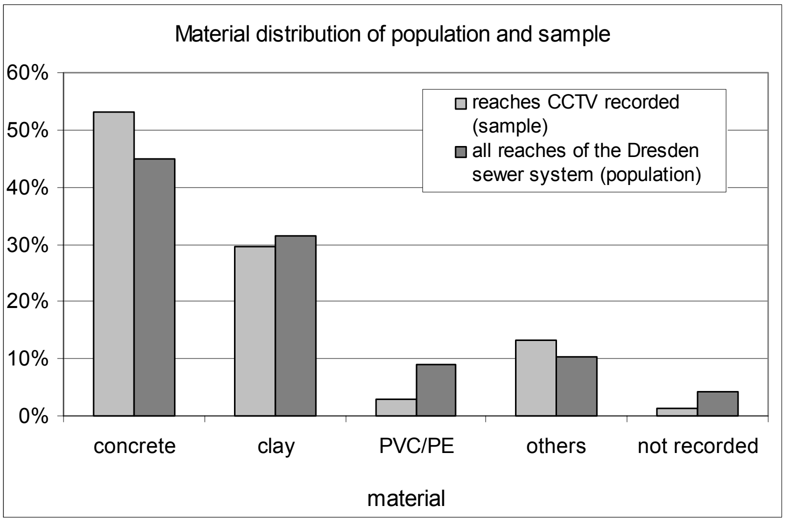

Figure 3: Comparison of the dataset of the whole sewer system and the sample (Material distribution)

Figure 4 shows the comparison of the diameter distribution. An observation of every single diameter is not applicable due to a lack of data for some diameters. The following groups were formed according to the available data with regard to the diameter distribution of the whole sewer system and the random sample.

- DN ≤ 300 mm
- DN 301 – 600 mm
- DN 601 – 900 mm
- DN > 900 mm

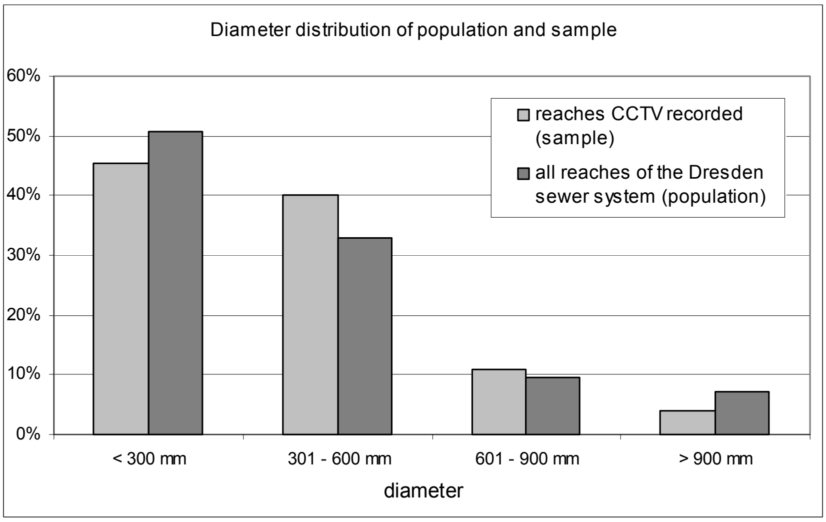

Figure 4: Diameter distribution of population and sample

The chosen groups represent the population of the Dresden sewer system rather well. Only the amount of reaches decreases with increasing diameter. Still, the amount of reaches with diameters larger than DN600 is sufficient to perform a statistical analysis.

A third criterion is the age of the sewer. The age is more or less a synonym for the construction period including historical development, technological process and the change of existing rules and regulations/standards regarding the quality of construction. The construction periods are classified as follows:

- until 1899
- 1900 – 1916
- 1917 – 1928
- 1929 – 1945
- 1946 – 1989
- since 1990

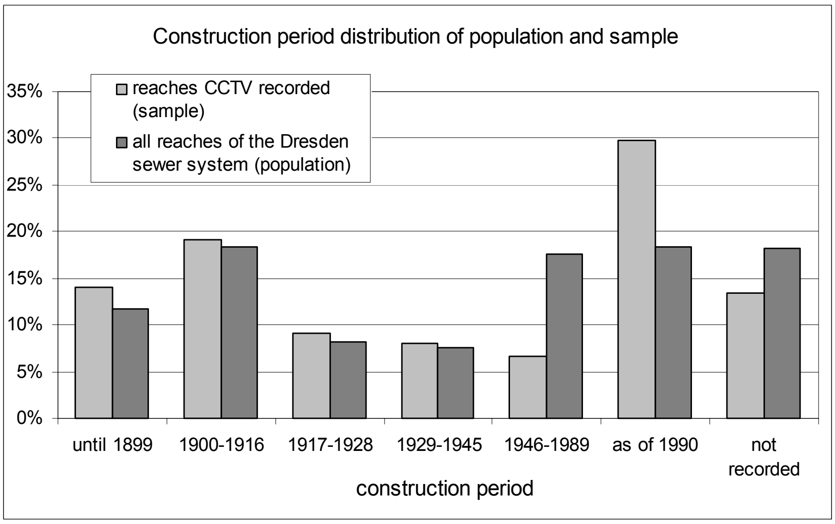

Figure 5: Comparison of the dataset of the whole sewer system and the sample (construction period distribution)

Comparing the two datasets an almost identical distribution is detectable until the year 1945. The number of constructed sewers in the years 1945 until 1990 and after 1990 until today is very similar (approximately 18 %). But only 7 % of the reaches built in GDR times are CCTV recorded. In contrary almost 30 % of the reaches built in the last years are recorded. Thus, the sample does not represent the data of the entire sewer system. Based on the initial assumption that sufficient data are available and the CCTV records are randomly distributed over the sewer system a statistical analysis is still possible, a further analysis with more data is proposed.

In addition to these observations, the distribution of each material according to the construction period was analysed, underlining these results. With these remarks the independency of the samples (first and second requirement of the u-test) were shown. The other two requirements of the u-test are:

3. The measurement scale is at least ordinal: Sachs [1997] put this assumption into perspective. He postulates that nominal scales (material) as well as rank scales (construction period and dimension) are appropriate for the u-test.
4. Both samples show a similar distribution function: To prove the fourth requirement the condition class distributions according to each criterion are illustrated in Figure 6 to Figure 8. Thereby condition class V has the heaviest defects and conditions class I only a few small defects.

As concrete and clay are the most important materials used in sewer system (see also Figure 3) we concentrate on them. According to Figure 6 both materials show a similar distribution. Concrete and PVC/PE peak at condition class IV, still the upward trend from class V to class I is obvious for all materials.

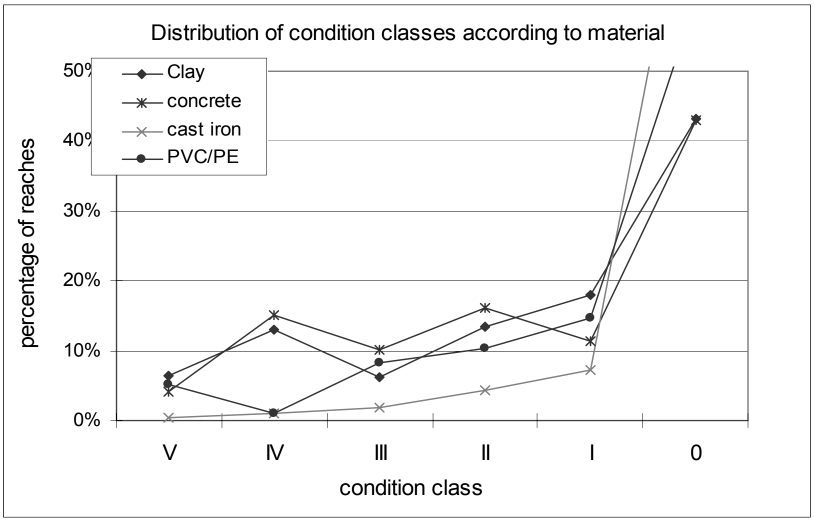

Figure 6: Distribution of condition class with respect to material

The distribution of the different construction periods appears to be rather similar as well (Figure 7). The shape of the black line (sewers constructed after 1990) is significant different. This was expected, as those sewers are recently constructed and should have a better condition.

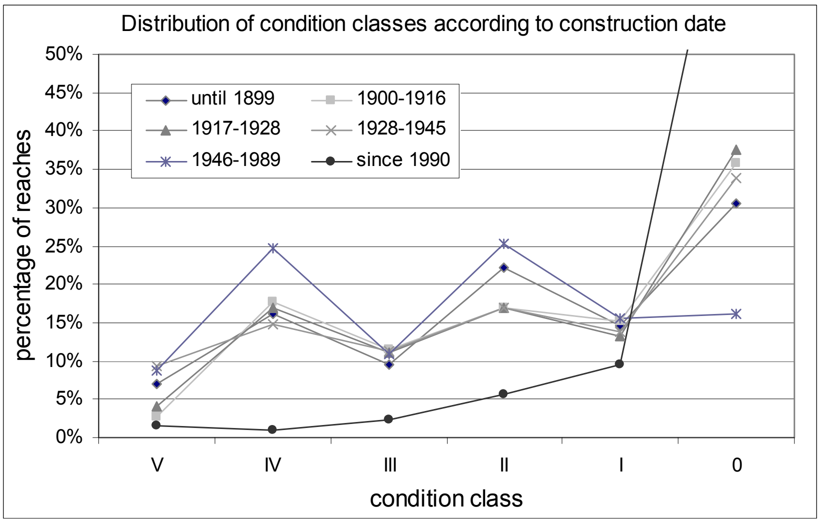

Figure 7: Distribution of condition class with respect to the construction period

Regarding the distribution of the dimension all categories follow a similar trend. Whereby, the amount of reaches recorded decreases with increasing diameter. Still, is can be seen that the amount of reaches increases with decreasing condition class (Figure 8).

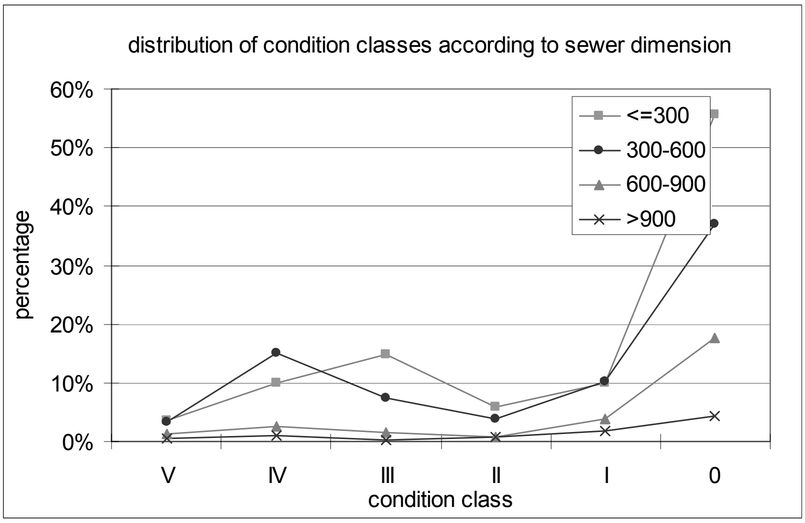

Figure 8: Distribution of condition classes with respect to dimension

2.1.2. Test of relevance

The relevance of the criteria material, dimension and construction period on the condition class of the sewer was investigated. Therefore the different specifications of the criteria are listed in Table 4.

Table 4: Compilation of criteria for the relevance analysis

material		dimension		construction period	
specification	number	specification	number	specification	number
concrete	1	< 300 mm	1	until 1899	1
clay	2	300 - 600 mm	2	1900 - 1916	2
		600 - 900 mm	3	1917 - 1928	3
		> 900 mm	4	1929 - 1945	4
				1946 - 1989	5
				since 1990	6

The u-test is demonstrated for the criterion material and its treatments concrete (number 1) and clay (number 2). All possible combinations in diameter and construction period for the treatment concrete are compared with all possible combinations for the treatment clay. The obtained levels of significance are shown class-wise as cumulative function in Figure 9 (dark line).

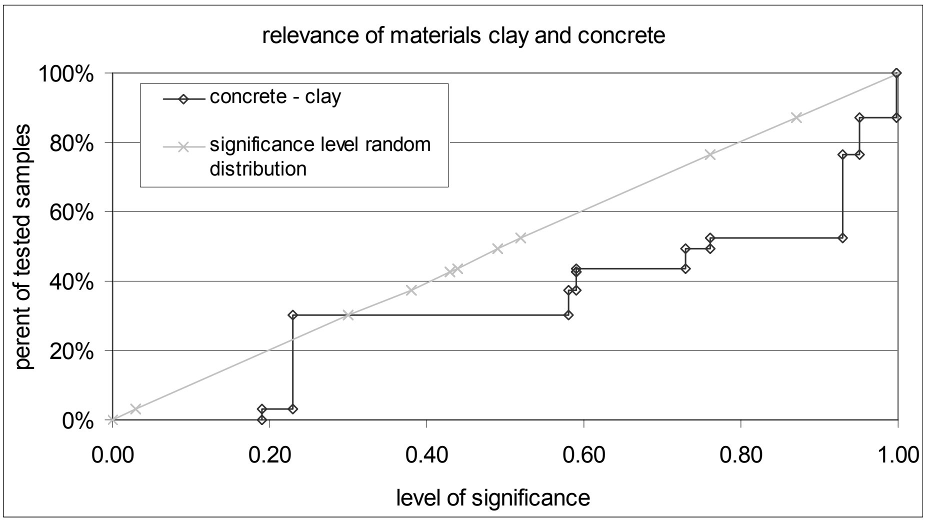

Figure 9: cumulative function of the significance levels for the criterion material

The bisecting line represents the cumulative function for the significance levels of infinite comparisons of two random samples. The further down and the further right the location of the cumulative function the more relevant is the criterion. In our example the sum line is mainly situated below the bisecting line with a quite large distance. Expressed as numbers 47,8 % of the tested reaches obtain a significance level of more than 90%. The differences of the condition class distribution do not seem to be coincidental.

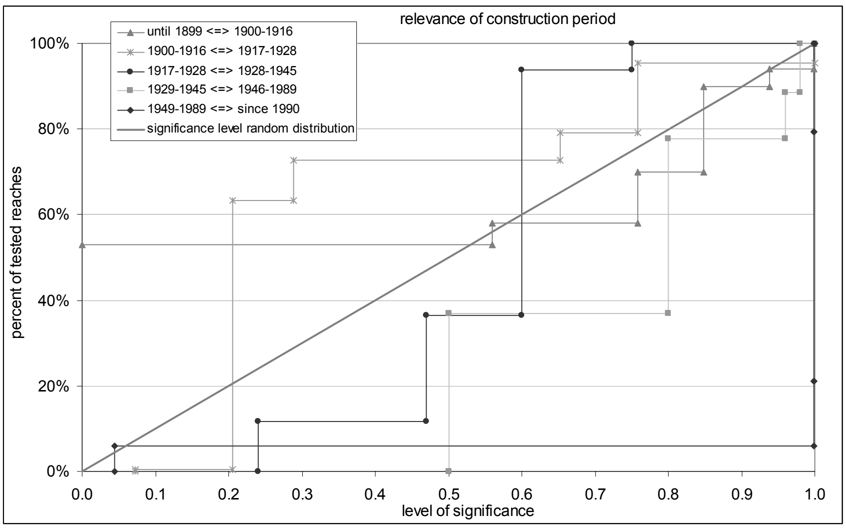

Figure 10: Relevance of construction period for condition classes

Within the analysis of the construction period shown in Figure 10 an obvious difference is observed between the construction period of 1946 to 1989 and 1990 to today and tendentially the periods 1929 to 1945 and 1946 to 1989. The sum lines of the construction times up to 1945 do not show a high relevance for further observations concerning extent and manner of the influence. The results have to be proved with a larger dataset and more classes.

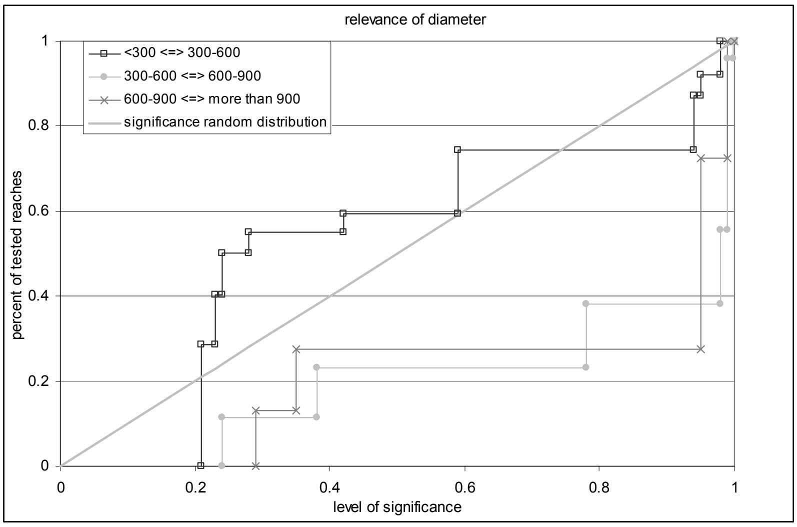

Figure 11: Relevance of pipe diameter for condition classes

The sum line of the diameter smaller than 600 mm does not show any relevance on the condition class in contrary to the larger diameters (see Figure 11). There is no difference in the defect frequency between small sewers (< 300 mm) and medium sewers (300-600 mm).

2.1.3. Conclusions

The data availability in Dresden allowed to link the whole set of CCTV records to the pipe characteristics material, construction period and diameter. The preliminary investigations resulted in the applicability of the Wilcoxon-(u)-test. Analysing the relevance of material, only concrete and clay had a sufficient high amount of data. A difference between the two materials according to their defect frequency was detected. It can be postulated that the material has to be considered a relevant parameter for further investigations.

Concerning the construction period relevance was expected also due to the categories chosen by historical developments. But only two sum lines indicated a significant difference between neighbouring periods. A further gradation would lead to other results. The dimension of the sewers gets relevant regarding the leakage with diameters larger than 600 mm.

The CCTV records, which were supposed to give very detailed information about the condition of sewers, will not be the only important source of information. The data availability is improving and with a large dataset and finer resolution the content of information will increase. The CCTV records are still the most important data to look at the sewer in detail, above all to interpret measurements of ex- and infiltration.

2.2. Leakage approach for the estimation of infiltration [Karpf and Krebs, submitted]

2.2.1. General

The investigations deal with the effects of the Dresden sewer system during and after the flood event in August 2002, when the groundwater level rose to a maximum level since data were recorded. To estimate and predict the drainage effect a hydrological leakage model is calibrated and used. Furthermore, the leakage of sewers has been assessed. As these investigations met each other in the determination of sewer leakage some cross-correlated work was managed with the following results.

The leakage approach can be traced back to the equation of Torricelli. It is widely used for modelling hydrological interactions between aquifer and surface water. The leakage approach is related to the wetted area of the riverbed and the difference between groundwater and surface water level. Furthermore, a specific leakage factor is essential for the calculation of infiltration rates, representing a specific resistance. As an integrative parameter the leakage factor describes various attributes of the soil layer of the riverbed and thereby the potential of exchange between the compartments ground- and surface water. According to GUSTAFSSON [2000] the Leakage-model can be modified for the simulation of groundwater infiltration into sewer systems (Equation 1).

$Q_{Infiltration} = k_L \cdot A_S \cdot (h_G - h_S)$ (requirement: $h_S < h_G$) (Equation 1)

$Q_{Infiltration}$	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})

The groundwater level, which is needed to calculate the groundwater-influenced surface of the sewer system, can either be modelled or interpolated based on measurements. The water level in the sewer pipe can be modelled as well, however, it is also feasible to simply estimate it. The leakage factor has to be calibrated. This was realised on the basis of wastewater flow and groundwater level measurements of preceding months and years [Karpf and Krebs, submitted].

It was shown by Wittenberg and Brombach [2002] that sewer systems behave similar as watercourses with regard to infiltration of groundwater.

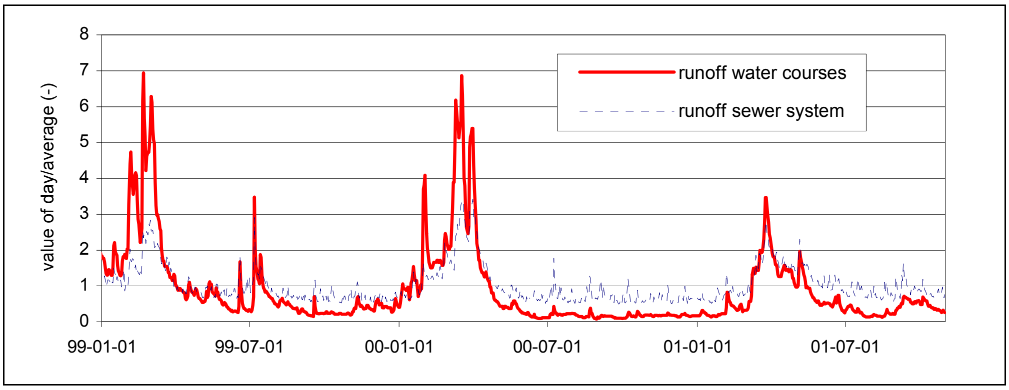

Figure 12: Normalised flow rate measurements of water courses and sewer system in the City of Dresden

For the catchment of the City of Dresden it could be shown that the behaviour of the sewer system on the one hand and that of rivers and creeks in the city on the other hand is similar. In Figure 12 plots of the normalised flow rate of the rivers and the wastewater treatment plant inflow are compared. The plots show a clear synchrony of the hydrographs.

The main reason for the correlation is the similarity of groundwater exchange processes with the surface water and sewer pipes. Groundwater effects to sewer pipes can be identified by correlating the dry-weather flow in the system to the groundwater-influenced length of sewer pipes. Figure 13 shows the respective correlation.

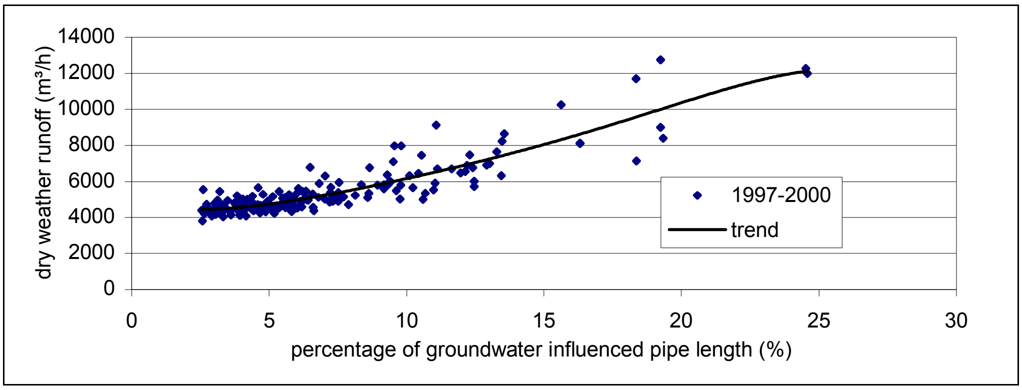

Figure 13: Correlation between percentage of groundwater-influenced length of sewer pipes and dry-weather runoff

2.2.2. Leakage factors

The calibration of the leakage factors of the Dresden sewer pipes was based on Equation 2.

$$k_{L,T} = \frac{Q_{Infiltration,T}}{\sum_{i=1}^{n} \left[\left(h_{G,i,T} - h_{S,i,T} \right) \cdot A_{S,i,T} \right]} \qquad \text{(Equation 2)}$$

$k_{L,T}$	integral leakage factor at time T
$Q_{Infiltration,T}$	balanced infiltration of groundwater at time T
$H_{G,i,T}$	groundwater level at the sewer pipe i at time T
$H_{S,i,T}$	water level in the sewer pipe i at time T
$A_{S,i,T}$	groundwater-influenced pipe surface of pipe i at time T

The estimation of the groundwater level at each pipe and the groundwater-influenced pipe surface of the sewer are based on the interpolation of groundwater measurements. The dynamics of water levels in the pipes were estimated according to measurements of water levels in the system. The infiltration was balanced by calculating the difference of wastewater flow and the average consumption of drinking water. Because of uncertainties associated to balanced drainage rates (KARPF and KREBS, 2003) the variation of infiltration rates ($Q_{Infiltration}$) was smoothened.

The leakage factor calculated with equation 2 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 had been carried out for 240 time spots from 1995 to 1999 and represents a kind of a calibration under various groundwater conditions. Thereby, the leakage factor of each groundwater-influenced pipe was approximated to be some weighted average of all calibration cases.

In Figure 14 the infiltration into sewers classified by pipe dimension is illustrated. Sewers with a profile height larger than 1,200 mm and the respective house connections cause 80% of the parasite water inflow.

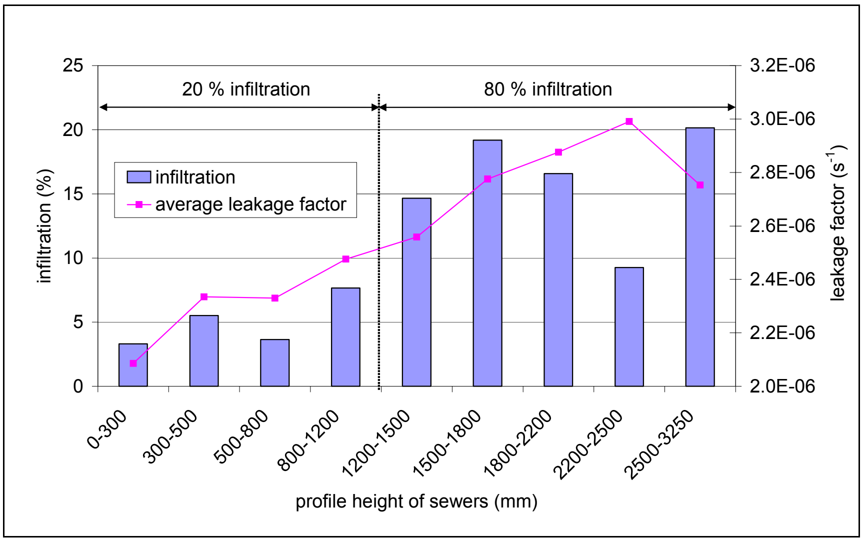

Figure 14: Infiltration and leakage factors depending on the profile height of sewers in the City of Dresden

The leakage approach is based on the groundwater level and the sewers as drainage system observed over a long period. It gives only little information on the processes at pipe scale. One of the main statements is that the smaller sewers induce a less important infiltration contribution. The Dresden sewerage system consists of more sewers with small diameters (Figure 15). A further investigation can therefore be focused on the smaller number of large sewers.

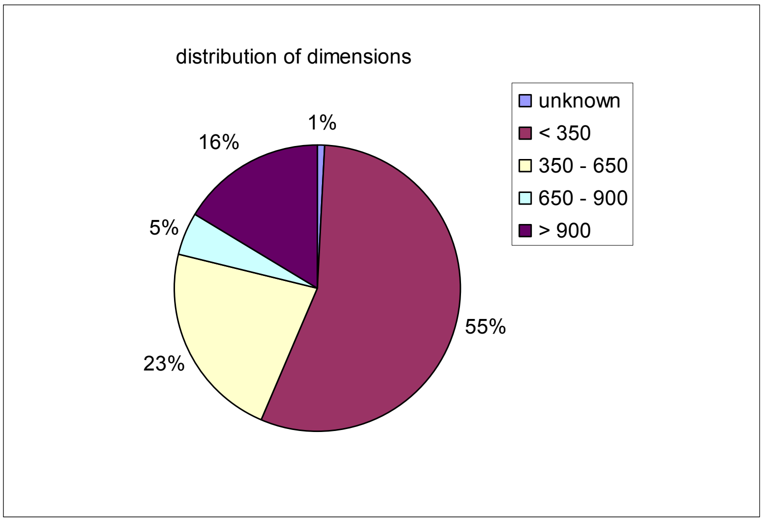

Figure 15: Distribution of diameters in the sewerage system of Dresden

2.3. Further development within the APUSS project

2.3.1. Development of a model to describe exfiltration [Neitzke, 2002]

A first simple model tries to express the exfiltration rate Q_{exf} as a function of the wastewater flow Q_I (or water height and velocity) using two parameters α and β:

$$Q_{exf} = \alpha * Q_I^{\beta}$$

This kind of model takes neither geometry and structural state of the pipe into account nor hydraulic properties of sewer trenches and surrounding soil. However, correlations between the value of the parameters and other input data (construction date, slope, height of sediments...) are to be explored. The model complexity will thus depend on the diversity and on the available data.

The input data should therefore be known with some precision for all the sewers, where measurements are to be carried out. Especially for sewer age, this information is not always available in sewer databases. To calibrate the model parameters extensive measurements in sewers are necessary and probably subsets (classes) of sewers with certain characteristics need to be formed to achieve calibration.

It is unlikely to find a simple correlation of ex- or infiltration rates and construction date of sewers, as sewers can be leaky right after being built. It is more likely to be able to establish relationships explaining the probability of sewers having a certain age to be in a failing condition or having a certain type of defect, which might effect leakage. Other research programs have tried to establish deterioration models based on sewer age and defect observations by inspection. This would allow selecting sewers that are likely to leak but not the prediction of an ex- or infiltration rate.

A more complex model is based on other physical parameters. Considering pipe geometry, wastewater flow height and groundwater level, some theoretical active surface (m^2) to exfiltration S_{exf} can be defined. The real active surfaces will vary according to two time scales: a seasonal variability related to groundwater level, and a diurnal and hourly variability related to wastewater flows. Then exfiltration rates will be expressed by analogy to the Darcy law using a coefficient of leakage K [$m*s^{-1}$] :

$$Q_{exf} = K * S_{exf}$$

In this case, the variability of exfiltration rates depends on the variability of the permeability coefficient K.

Moreover, it is considered that the coefficient K may depend on both surrounding soil properties and pipe structural state, and could be noted as a function of two terms:

$$K = f(K_{soil}, K_{pipe})$$

It is assumed that the value of K_{soil} depends on the surrounding soil water content or previous rain P(t) and dry weather periods. K_{pipe} is related to the pipe structural state (breaks, connections, number of pipe reaches, roots intrusion, broken joints, etc.). So one can express K_{pipe} as a function of the type and the number of leakage defects observed on the experimental pipe :

$$K_{pipe} = F(\text{defects})$$

The permeability of the pipe K_{pipe} can fluctuate, because the leakage can be sealed by suspended solids. So the pipe permeability could be expressed as the sum of two components: an average permeability component and a stochastic component. Its distribution has to be derived from experiments:

$$K_{pipe} = K_{mean} + K_{stochastic}$$

Thus, the most complex model to be tested should take the structural state of the pipe, the hydraulic state of sewer trenches and a stochastic component into account:

2.3.2. Data requirements :

To describe the active surface:

• groundwater level	piezometric measurement in vicinity
• water level in sewers	measurement during experiments
• geometry of sewers	recorded in sewer data base

Permeability coefficient:

• Type, number, size of defects	visual inspections and CCTV records
• Soil water content, permeability	in vicinity of sewer
• Sedimentation	Observation during experiments

2.3.3. Model calibration

Q_{exf} needs to be measured. The active surface can be calculated from the known data and measured water levels in the sewers. The resulting permeability is to be explained by the sewer and soil conditions. This is similar to the determination of the factor L(t)*A in the relationship of Rauch and Stegner [1994]. The three variables are:

- Permeability of pipe due to pipe condition
- Permeability due to soil characteristics
- Effect of sediments/solids

The (stochastic) influence on the variation of K can be assessed experimentally by repeating measurements in several sewers once they have been cleaned and some time after cleaning, when sediments and solids have been built up.

More difficult is the attribution of permeability variations to pipe condition and soil characteristics as no condition can be kept constant or varied independent of the other. For a specific test site the soil water content will certainly change with weather conditions, but these will also influence the sediment built up or wash out due to flow changes.

One could assume that in a certain subcatchment sewers of the same type and constructed in the same period have similar bedding and soil conditions. The variation of the permeability factor K can therefore be attributed to pipe characteristics (number, size and type of defects, number of joints). The selected sewers should allow varying the sewer condition to be able to find a relationship expressing the sewer state.

The main difficulty lies in the expression of a relationship between the permeability factor and the sewer condition because the sewer condition of the whole measured reach is to be expressed. In fact, this relationship is to be calibrated from the measurements.

The influence of soil conditions cannot really be assessed experimentally, even if they seem to be the limiting factor concerning exfiltration rates. Their influence can only be calibrated by applying the relationships of sewer condition to subcatchments/reaches with other soil conditions.

2.3.4. Strategies for calibration of a relationship between exfiltration and sewer permeability

To establish and calibrate a relationship between exfiltration, expressed as permeability factor K and the condition and characteristics of the sewers two strategies seem possible.

- Measure a large number of possible reaches in a subcatchment with equal soil conditions and explain the variation in K by number, size, type and frequency of defects/joints. Based on some a-priori knowledge of the sewer condition the extremes should be measured first to gain some experience on the differences in K. If the differences between sewers in nearly perfect condition and very bad condition are too small to be determined any extensive campaign on this space scale will be useless.
- Develop a system of “leaking potential” classification from existing knowledge (inspection protocol) and choose samples in the classes to calibrate a function between condition grade and observed K. Define a calibration function, which translates the classification into K values.

In general sewer inspection results in the attribution of a condition grade. However these condition grades do not primarily consider leakage but other aspects such as structural condition and other functions. A classification based only on leakage aspects can be developed considering the type of defects (some defects are known to be prone to leaks, such as open joints, holes), their size and frequency in the reach. The result could be a division in a set of leakage classes. For each leakage class a number of samples is to be chosen to measure the actual exfiltration rates. From the measurement results a relationship between the class and the K value is to be calibrated.

The classification scheme depends on the available data on sewer condition. If the reports or videos allow a detailed description of presumed leakage defect the scheme will be complex but well adapted to this aspect. If no other data than an overall condition grade is known, measuring samples in very good, average and very bad condition can be a first approach to learn about the range of expected exfiltration rates.

3. Measurements and input into the models

3.1. Preliminary investigations

The two subcatchments MAL and LR were subject of some preliminary investigations to check the probability of exfiltration. Groundwater data to observe the influence of groundwater were only available from hydro-geological maps. Additionally, the wastewater flow data from the last years were analysed (see Figure 16 and Figure 17).

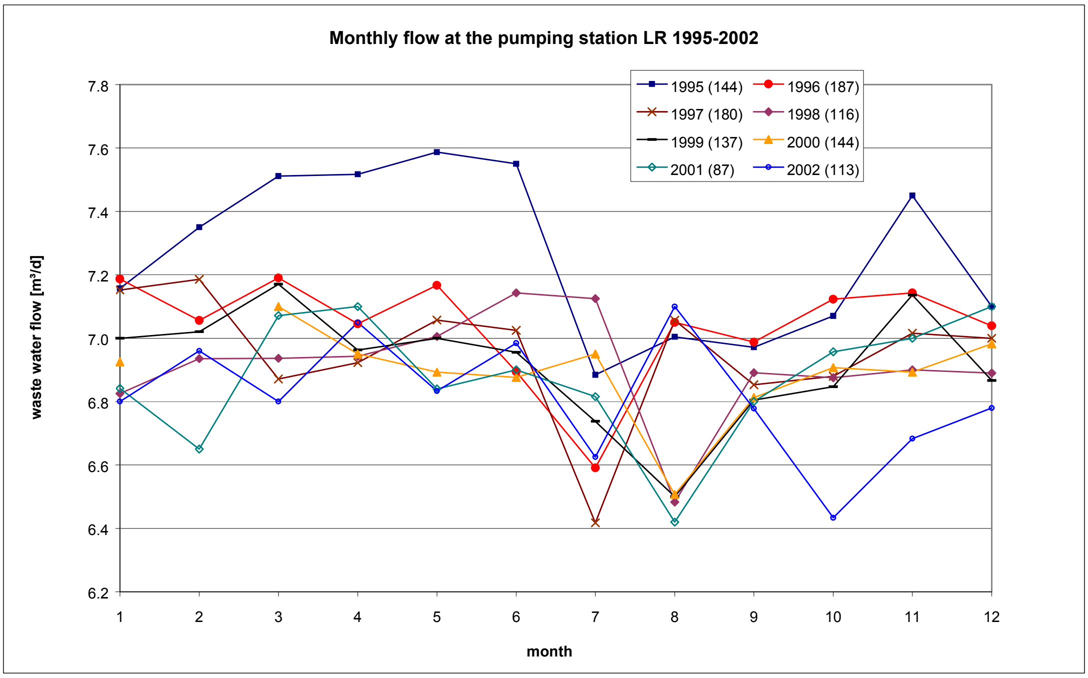

Figure 16: Waste water flow at pumping station LR

The monthly flow at the outlet of the catchment LR is illustrated by using mean values over the last 8 years. The numbers in parentheses are the dry weather days in the particular year. Except the flow in 1995 the graphs are regular. A groundwater influence in spring or autumn cannot be detected. The holiday season July and August cause the distinct decrease in flow. The influence of the wet weather in 2002 is also to be seen. Looking at the graphs in MAL (Figure 17) approved the statement. Those are even more regular. In MAL a 30 % reduction of wastewater discharge is observed, which was attributed to the decreasing water consumption since 1990.

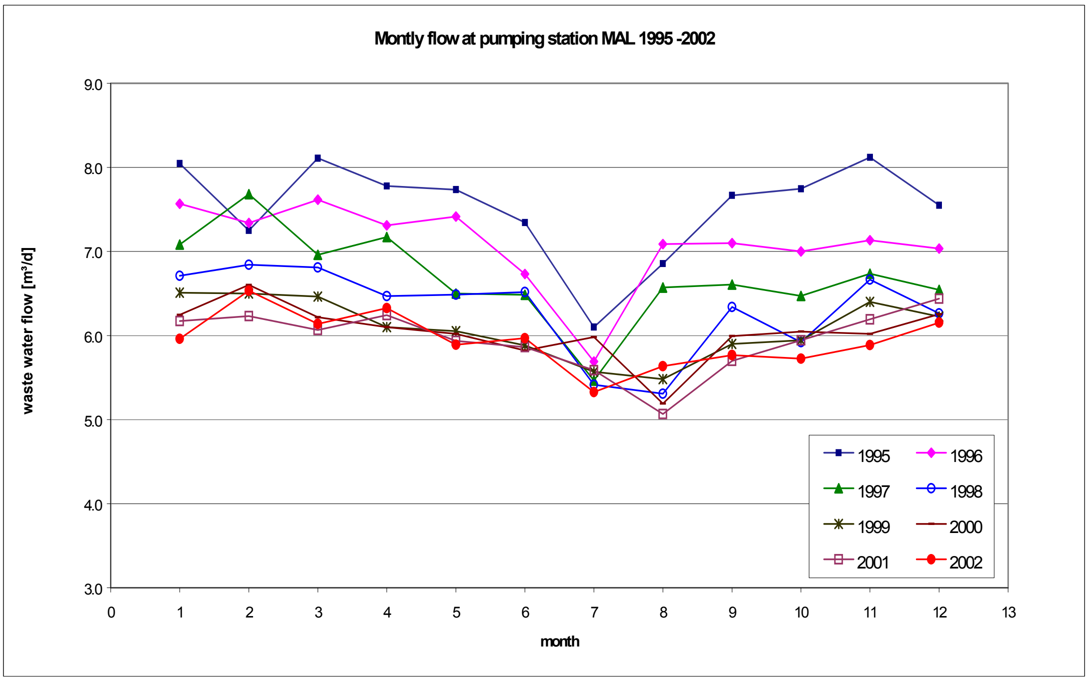

Figure 17: Waste water flow at the pumping station MAL

In MAL water consumption data were available and faced to the wastewater flow at the pumping station (Figure 18). Preliminary investigations of the local operator indicated a very low night flow compared to the number of inhabitants. Our measurements could not support this statement (dotted bar in Figure 18). The water consumption at night corresponds to our measurement. Yet, the comparison of the average flow (chequered bar) and the summarized flow (striped bar) showed a more or less similar result for the waste water flow measured by us and the pumping station and the water consumption. The absolute numbers are given in Table 5.

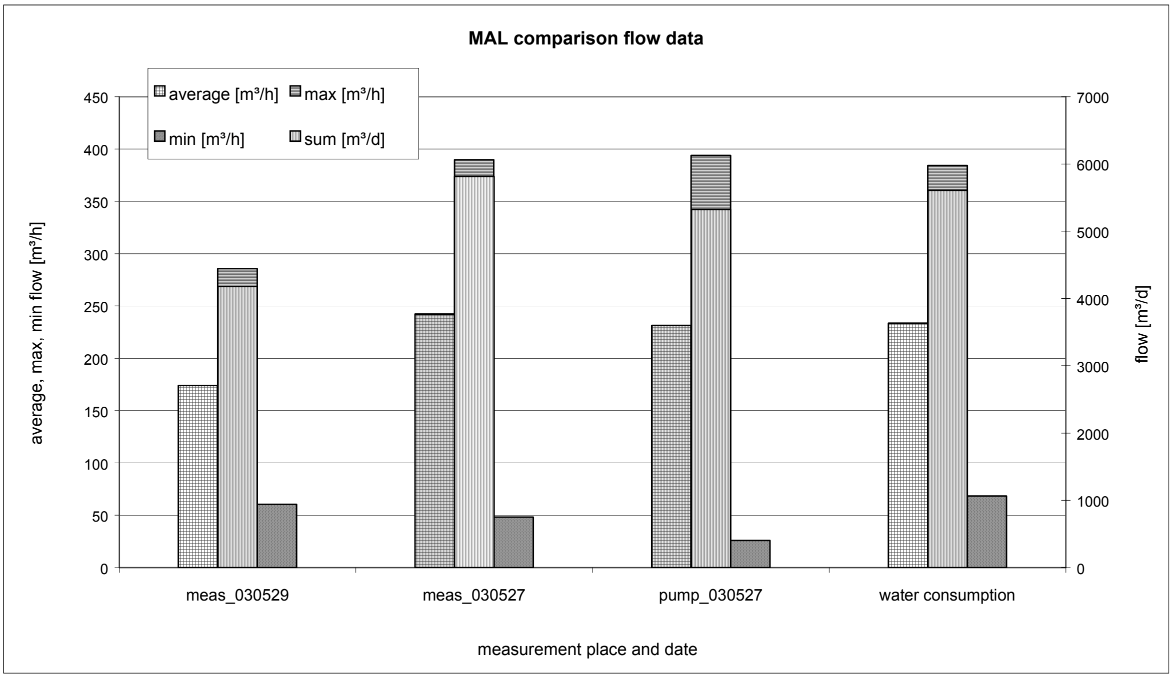

Figure 18: Comparison of waste water flow and water consumption

Table 5: Comparison of waste water flow and water consumption in MAL

	average [m³/h]	max [m³/h]	min [m³/h]	sum [m³/d]
meas_030529	174	286	60	4177
meas_030527	242	390	48	5816
pump_030527	231	394	26	5324
water consumption	234	384	68	5608

Additionally, COD measurements were conducted (Figure 19). The hydrographs shape deviates from those of other catchments. The COD concentration does not follow the flow over the day. While the matter concentration has only one peak in the morning, the flow has a second peak in the evening. This was attributed to the people's daily behaviour, as well as the extremely low minimum night flow. Due to this an enhancement of the pollution load method was achieved by Kracht [2003]. For the online COD measurements an UV-VIS probe was applied accomplished by a sampling campaign to calibrate the probe. Kracht calculated an infiltration rate/clean water content of 5 % of the waste water flow.

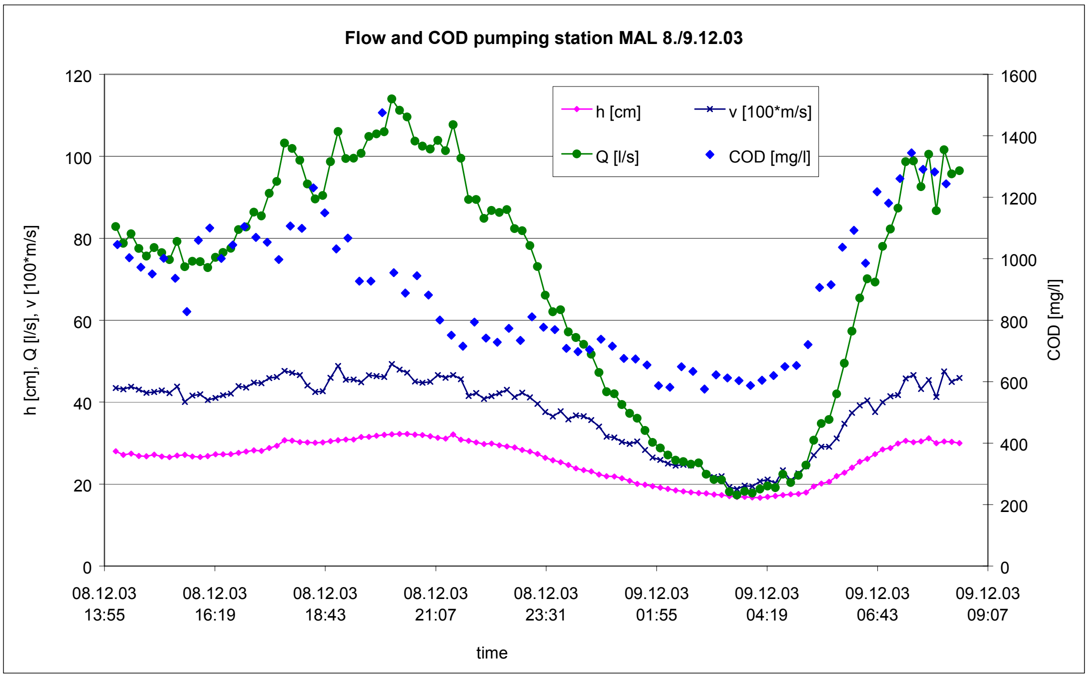

Figure 19: Flow and COD measurement in MAL

The preliminary investigations proved the absence of groundwater influence and point to a potential exfiltration. This postulation was to be proven by the exfiltration measurements.

3.2. Exfiltration measurements

Several subcatchments were selected to deliver important details to feed the model. The database was very good. Beside the structural data of the sewer system, CCTV records were available and conducted, respectively. The exfiltration rates recorded are shown in annex 1. Five groups were formed with similar characteristics and the exfiltration rates were interpreted with the help of these characteristics (Table 6).

Table 6: Investigation sites with similar characteristics

Area	Date of construction	Dimension	Material
Suburban environment	1920/25	DN 200-300	Clay
Mixed area	1908-1952	DN 300-750	Concrete
Garden town	1910	DN 250	Clay
Rural character	1930/1965	DN 200-450	Mostly clay, some concrete
High density, multi-storey buildings	1980	DN 200-600	Mixed and often changing material

To identify relevant parameters influencing the leakage of the sewer, the parameters were analysed under the assumption, that similar characteristics cause similar exfiltration rates. As indicated in chapter 1.2, a minimum number of samples/test sites would have been required to perform a statistical analysis. With the actual available measurements the similarity approach was to be proven or disproved.

Furthermore, the measured exfiltration rates need to be interpreted and to be referred to the available data of the particular sewer. An interpretation of the results is rather difficult, as an existing reference method is not applicable to compare our results with the results of another method. To interpret the results it was assumed that with a certain amount of data the uncertainty of the measurements can be reduced.

3.3. Interpretation of the exfiltration rates obtained

3.3.1. Consideration of flow

In case of little flow in the sewer section observed, a high uncertainty was detected. The reflection of absolute exfiltration rates underlines this detection. From variances in the exfiltration rate up to 70 % in case of little flow in the sewer we concluded that an interpretation of the exfiltration rates in sewers with little flow is to be handled with care. Another point is the observation of the flow over the whole sewer section. At the beginning little flow causes higher tracer concentration. Hence, the exfiltration rate over the whole distance might be overestimated. Dead zones can occur due to large amounts of sediments, thus the traced water is detained.

3.3.2. Uncertainty of the exfiltration method

Several measurements were conducted with the best possible accuracy. Unfortunately, there is no other method to verify the results.

The QUEST-method [Rieckermann, 2002] is based on conductivity measurements. The measurements were conducted in areas with a high probability of exfiltration. Groundwater infiltration was not detected. The background conductivity was rather high and in particular extremely varying. Night measurements were not possible first due to the operator's regulations and second to the insufficient flow at night. Still, the measurements could be analysed. Various evaluation approaches were used – analysis and comparison of the separated peaks and/or fitting of the peaks with different distribution functions. Due to the disturbed background conductivity instabilities in the calculation process did also occur.

The QUEST-C method [Rieckermann, 2003] limits the random error, but the uncertainty of the method is depending on an extremely accurate laboratory analysis of Bromide and Lithium concentrations. To test the plausibility of the results a few sewer sections were tested with both methods (Table 7).

Table 7: sewer sections tested with QUEST and QUEST-C

characteristics					QUEST		QUEST-C	
name	area	length [m]	DN	condition class	flow [l/s]	exfiltration	flow [l/s]	exfiltration
Krö/Cri	MAL	640	300-400	001 005 015 020 117	8	-4%	4	-74%
Krö/Rib	MAL	2000	300-600	002 005 027 056 233	40	12%	25	0%
Stein	LR	1220	200-350	001 007 071 088 086	14	15%	19	13%
Ldamm	LR	1460	350-500	010 002 030 015 116	36	13%	36	-13%

Only the result of STEIN could be confirmed. The difficulty of estimating the exfiltration rate in sewers with a low flow rate was explained already. The result of KRO/CRI was therefore considered as tolerable. The exfiltration rates of KRO/RIB and LDAMM could indicate a variance of 12 % and 26 %, respective. The condition classes underline the results obtained with the QUEST method. Still, the correctness of the one or the other method could not be postulated. Actually, the evaluation of the exfiltration rates appears to be extremely hard and depends on the observer.

3.3.3. Comparison with infiltration rates

One statement from the leakage approach was a high contribution to an infiltration rate from large sewers, as they are most likely low-lying. Within the measurements mostly small sewers were observed, also to exclude or minimize any groundwater influence. Another point is the larger flow in larger sewers. A higher water level and therefore a larger wetted perimeter may result in a higher probability of exfiltration. The question to be discussed is whether the exfiltration is influenced by the same factors as infiltration and if we thus can assume a higher exfiltration in larger sewers. With the number of measurements conducted a correlation of diameter and exfiltration rate could not be detected (Figure 20), not even in differentiating the exfiltration rate after the area.

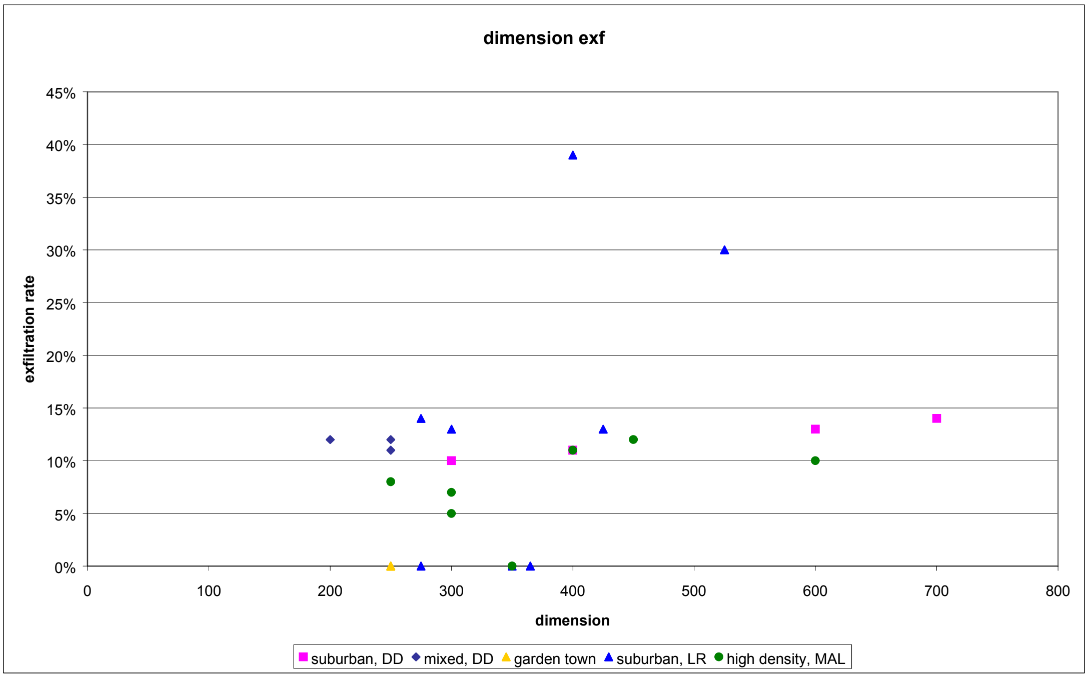

Figure 20: Comparison of diameter and exfiltration rate

3.3.4. Findings from the data analysis

Initially, the model aimed at finding a correlation between structural data and sewer leakage. Hence, experiments were carried to estimate the leakage of sewers. A subsequent step to reduce the uncertainty of the measurement results is the utilisation of available data from the catchments investigated. These are:

- Structural data
- CCTV records
- Data on ground and groundwater

A comparison of structural data and exfiltration rates does not conclude to any significant correlation (see annex X). This is caused by the small number of measurements (25) and by the insufficient amount of samples with the particular treatment, e.g. 10 sewer sections constructed in 1950. Third, there might be some interdependency of the single factors, such as quality of workmanship in different areas at the same time. The CCTV records are considered to be the best information source regarding the condition of sewers. The classification leaves out a lot of information concerning the kind and location of defects. Still, the defect severity is recorded. In Figure 21 a kind of correlation can be seen. Even though, the number of sewer sections investigated is small. With increasing number of severe defects the exfiltration rate increases as well.

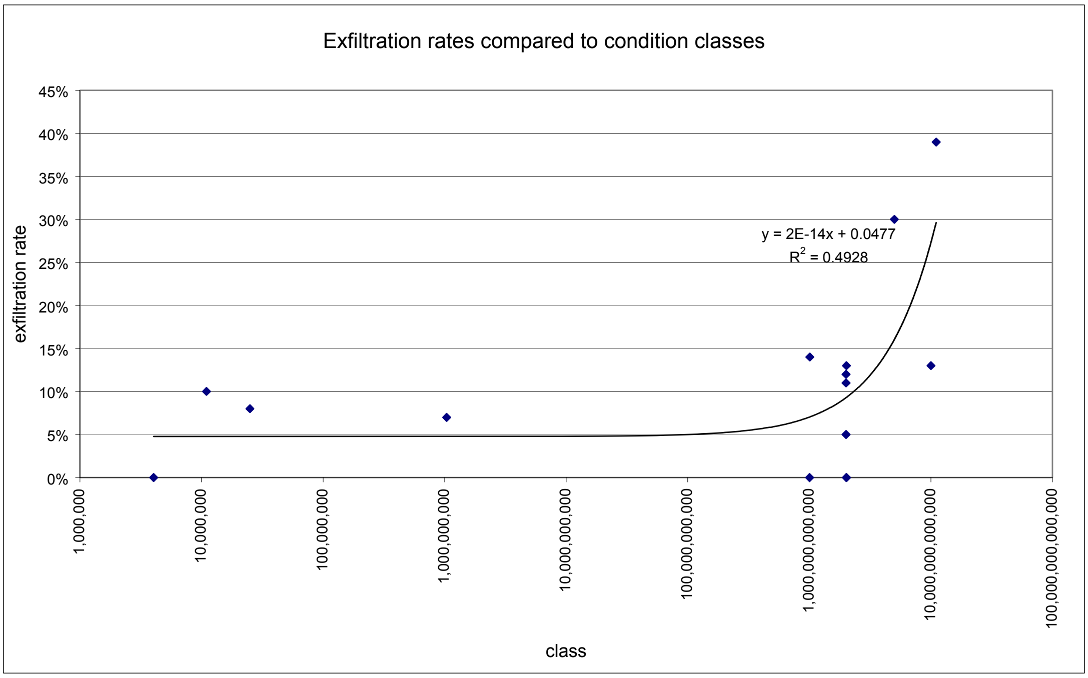

Figure 21: Comparison of exfiltration rate and condition of sewers

After these results the information content of the CCTV records is discussed critically with the local operators. A defect with a potential exfiltration cannot be differentiated from other defects. Whereby, infiltration can easily be seen in case of intruding groundwater. The CCTV information was compared with other data such as the porosity of the sewer, calculated from the wetted perimeter and the defect extent. The same crucial point was the interpretation of CCTV records regarding the exfiltration potential. But, the kind of defect was looked at in more detail.

Data on ground and groundwater are shown in Table 8.

Table 8: Data on ground and groundwater of the different investigation sites

Area	Geology	Soil	Groundwater	Housing
MAL	Barnim plateau, boulder clay as aquitard, confined groundwater, occurrence of floating groundwater	Landfill, settlement area Topsoil and subsoil: fine sand to medium loamy sand	North: 4-10 m Middle and south: 10-20 m below top ground surface	High density with multi-storey buildings
LR	Teltow plateau, boulder clay as aquitard, confined groundwater, occurrence of floating groundwater	Landfill, settlement area Topsoil: medium sand Subsoil: medium loamy sand to loamy sand, silty loam	10-20 m below top ground surface	Middle to low density One and apartment family houses with garden,
DD	River valley		Varying groundwater	Mixed housing, older buildings
HEL	River valley plateau, boulder clay as aquitard, confined groundwater, occurrence of floating groundwater		Unknown	Middle density, garden town

4. Conclusions

The substantiation of the measurement results is questioned. A comprehensive analysis of the data and exfiltration rates is not feasible, as long as the measurement results are that uncertain. The reduction of uncertainty with the available information was not successful. Still, important data such as soil need to be included to verify this statement. Assuming, the exfiltration rates are correct conclusion are:

- Diameter, year of construction or material did not tend to correlate with the exfiltration rate, also due to the insufficient number of measurements.
- The thesis that date of construction gives more information such as quality of workmanship and kind of sealing is still to be proved.
- The exfiltration rate increases with an increasing number of large defects.
- The parameters of the model proposed in chapter 2.3.4 could not be identified due to deficiency in the measurements as such and the number of measurements.
- The CCTV records appear to have the most detailed information regarding the condition of sewers. An evaluation of CCTV records in combination with structural data and ex- or infiltration will lead to reasonable results to identify the missing parameter in the model. The calculation of the leakage area over the whole length of the pipe led to a different picture than the classification including all defects.
- Several investigations of wastewater infiltration into soil (equal to exfiltration of waste water from the sewers) indicate soil clogging in the upper parts (deposit of sludge on the surface), whereby the lower parts showed a constant hydraulic conductivity for a given period. The soil clogging is said to be dependent on the amount of suspended solids. With increasing water head the increasing pressure caused by a reduction of the hydraulic pore volume can be overcome resulting in a continuation of the infiltration process. Filter recovery might occur in areas with varying groundwater level, as the exfiltration process can be interrupted by infiltration of groundwater into the sewer.

Mainly qualitative conclusions are obtained. The identification of the model parameters from chapter 2.3.1 is partly not possible yet. Water head and wetted perimeter can be modelled. Whereby it is to be questioned, which influence the water head has on the ex- and infiltration rate. An assumption of the water level in the sewer might be sufficient. The local and regional coefficient cannot be defined with those qualitative conclusions. A reduction to structural data (date of construction, material…) seems to be difficult, due to lack of measurements. The literature review led to the assumption that there is a correlation between leakage/condition of sewers and structural data. Though, even with the additional information of CCTV data a general coefficient could not be found yet.

Another drawback was the measurement results and their difficult interpretation. A possible correlation cannot be achieved as long as the measurement results vary that much.

5. Plan and objectives

It is planned to analyse the interdependencies of the ex-and infiltration process in more detail, e.g. whether the influencing factors are similar. Thereby, better information about the process in varying groundwater situations is hopefully to be obtained.

The overall porosity of soil and pipe will be investigated to identify the local leakage factor and to interpret the measurement results. Therefore, the porosity of the pipes will be connected with the soil porosity. The leakage factor [Karpf and Krebs, submitted] can be downscaled to a single pipe and the possibility of exfiltration will be estimated.

The modelling process will be continued until all measurements are conducted and evaluated to include this information. The identification of the model parameters will be accomplished with theoretical approaches in case the experiments do not deliver the required information.

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ANNEX 1: Table of sewers observed with exfiltration rates and sewer characteristics

name	date	length [m]	constr. Year	material	diameter	profile	purpose	condition class	groundwater	surrounding	Q [l/s]	Exf. quest	av. sd	Q [l/s]	Exf. quest-C	av. sd
Lug	020905	760	1952	concrete	525-750	egg	comb.		below invert	sparsely populated		13%	1%			
Fran	030919	1340	1925	clay	200-300	circular	foul		no data	mixed houses		12%	1%			
Kess	020917	1300	?	clay	200	circular	foul		no data	Village		12%	1%			
Uth	020919	1280	1920	clay	250	circular	foul		no data	Village		11%	1%			
Dör	021008	650	1910	clay	250	circular	foul		no data	garden town, 2-storey buildings		-2%	1%			
Pfarr	021010	560	1910	clay	250	circular	foul		no data	garden town, 2-storey buildings		4%	2%			
Mars	021010	1170	1910	clay	250	circular	foul		no data	garden town, 2-storey buildings		0%	1%			
War	020925	1090	1916-1936	concrete	350-600	egg	comb.		no data	mixed houses		11%	2%			
Mor	021014	690	1915	concrete	250/375	egg	foul		no data	Road	12	10%	1%			
Fal	030508	1035	1980	BGM,concr., ac	600	circular	foul	00 00 11 07 50	below invert	high density area, multistorey buildings	32-42	10%	1%			
Bies	030506	1060	1980	clay, concrete	200-400	circular	foul	00 01 39 37 102	below invert	high density area, multistorey buildings	5-7	7%	1%			
Krö/Cri	030528	640	1980	clay	300-400	circular	foul	01 05 15 20 117	below invert	high density area, multistorey buildings	8	-4%	1%	4	-74%	61%
Krö/Rib	030603	2000	1980	BGM, Clay	300-600	circular	foul	02 05 27 56 233	below invert	high density area, multistorey buildings	40	12%	1%	25	0%	10%
Sch/Ki	030527	706	1980	BGM, PVC	200-400	circular	foul	02 04 20 09 37	below invert	high density area, multistorey buildings	3	5%	1%			
Sch/Rib	030502	1490	1980	BGM,PVC,clay	200-600	circular	foul	02 04 31 27 78	below invert	high density area, multistorey buildings	45	11%	1%			
Hag/Ki	030526	780	1980	PVC, clay	200-300	circular	foul	00 00 25 09 138	below invert	high density area, multistorey buildings	3.5	8%	4%			
Stein	030806	1220	1930	mostly clay	200-350	circular	foul	01 07 71 88 86	below invert	housing estate and multistorey buildings	14	15%	1%	19	13%	15%
Altlt	030807	1450	1930	mostly clay	200-350	circular	foul	02 18 37 84 95	below invert	housing estate, family houses, gardens	10	3%	1%			
Ldamm	030808	1460	1927	mostly clay	350-500	circular	foul	10 02 30 15 116	below invert	housing estate, family houses, gardens	36	13%	1%	36	-13%	16%
Scabi	030815	1320	1965-1973	concrete	300-500	circular	foul	11 03 46 28 202	below invert	housing estate and multistorey buildings				36	39%	8%
Gerst	030819	1870	1928	clay	250-350	circular	foul	02 16 38 130 71	below invert	housing estate, family houses, gardens				4	13%	20%
Locke	030820	1475	1936	clay	200-450	circular	foul	2 16 38 130 71	below invert	housing estate, family houses, gardens				28	4%	23%
EKZLO	030821	1350	1965	reinf. Concrete	450-600	circular	foul	05 04 18 31 21	below invert	housing estate, family houses, gardens				22	30%	24%
Ketti	030822	1100	1965	ac, concrete	300-450	circular	foul	00 00 04 42 25	below invert	housing estate, family houses, gardens				4	4%	19%
Salzb	031112	840	1908	concrete	450-1000	egg	comb.		varying	mixed houses, middle density				7	14%	12%