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SPATIAL CLASSIFICATION METHODS FOR EFFICIENT INFILTRATION MEASUREMENTS AND TRANSFER OF MEASURING RESULTS

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Abstract

Keywords: exploratory data analysis, extraneous water, gauge positioning, infiltration measurements, sewer leakage, similarity approach, transfer of result

A comprehensive knowledge about the infiltration situation in a sewer system is required for sustainable operation and cost-effective maintenance. Due to the high expenditures of infiltration measurements an optimisation of necessary measurement campaigns and a reliable transfer of measurement results to comparable areas are essential. Suitable methods were developed to improve the information yield of measurements by identifying appropriate measuring point locations and to assign measurement results to other potential measuring points by comparing sub-catchments and classifying reaches. The methods are based on the introduced similarity approach “Similar sewer conditions lead to similar infiltration/inflow rates” and on modified multivariate statistical techniques. The developed methods have a high degree of freedom against data needs. They were successfully tested on real and generated data. For suitable catchments it is estimated, that the optimisation potential amounts up to 40 % accuracy improvement compared to non-optimised measuring point configurations. With an acceptable error the transfer of measurement results was successful for up to 75 % of the investigated sub-catchments. With the proposed methods it is possible to improve the information about the infiltration status of sewer systems and to reduce the measurement related uncertainty which results in significant cost savings for the operator.

Zusammenfassung

Schlagwörter: Ähnlichkeitsansatz, Ergebnisübertragung, Explorative Datenanalyse, Fremdwasser, Infiltrationsmessung, Kanalleckage, Messstellenpositionierung

Für den nachhaltigen Betrieb und die kosteneffiziente Unterhaltung von Kanalnetzen ist eine genaue Bestimmung ihrer Fremdwassersituation notwendig. Eine Optimierung der dazu erforderlichen Messkampagnen und eine zuverlässige Übertragung der Messergebnisse auf vergleichbare Gebiete sind aufgrund der hohen Aufwendungen für Infiltrationsmessungen angezeigt. Dafür wurden geeignete Methoden entwickelt, welche einerseits den Informationsgehalt von Messungen durch die Bestimmung optimaler Messpunkte verbessern und andererseits Messresultate mittels Vergleichen von Teileinzugsgebieten und Klassifizierungen von Kanalhaltungen zu anderen potenziellen Messstellen zuordnen. Die Methoden basieren auf dem Ähnlichkeitsansatz "Ähnliche Kanaleigenschaften führen zu ähnlichen Fremdwasserraten" und nutzen modifizierte multivariate statistische Verfahren. Sie haben einen hohen Freiheitsgrad bezüglich der Datenanforderung. Die Methoden wurden erfolgreich anhand gemessener und generierter Daten validiert. Es wird eingeschätzt, dass das Optimierungspotenzial bei geeigneten Einzugsgebieten bis zu 40 % gegenüber nicht optimierten Messnetzen beträgt. Die Übertragung der Messergebnisse war mit einem akzeptablen Fehler für bis zu 75 % der untersuchten Teileinzugsgebiete erfolgreich. Mit den entwickelten Methoden ist es möglich, den Kenntnisstand über die Fremdwassersituation eines Kanalnetzes zu verbessern und die messungsbezogene Unsicherheit zu verringern. Dies resultiert in Kostenersparnissen für den Betreiber.

Acknowledgement

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List of abbreviations

ANOVA	analysis of variance
APUSS	Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems (research project supported by the European Commission, EVK1-CT-2000-00072)
ATV	Abwassertechnische Vereinigung e.V. (Association for sewage technology), later DWA
ATV-DVWK	Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V. (German Association for Water, Wastewater and Waste), later DWA
CARE-S	Computer Aided Rehabilitation of Sewer Networks (research project supported by the European Commission, EVK1-CT-2002-00106)
CCTV	closed circuit television
COD	chemical oxygen demand
CSO	combined sewer overflow
DIN	Deutsches Institut für Normung e.V. (German Institute for Standardisation)
DWA	Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V. (German Association for Water, Wastewater and Waste)
dwf	dry weather flow
e	standardisation of attributes to extreme values (within four letter code)
e	Euclidean distance measure (within four letter code)
EDA	exploratory data analysis
EN	Euronorm
EPA	United States Environmental Protection Agency
EU	European Union
f	weighting with Δh as factor (within four letter code)
gw	groundwater
I/I	infiltration/inflow (equivalent to extraneous water)
LfUG	Landesamt für Umweltschutz und Geology (State office for environmental protection and geology)
LROP	Laboratoire Régional de l'Ouest Parisien (Regional Laboratory of Western Paris)
m	Mahalanobis distance measure (within four letter code)
m	group aggregation with mean distance to centroid (within four letter code)
MDS	multidimensional scaling
MP	measuring point
n	no weighting with Δh (within four letter code)
n/a	not available
PT	total number of inhabitants and population equivalents
TEPPFA	The European Plastic Pipes and Fittings Association
USGS	United States Geological Survey
v	standardisation of attributes to variances (within four letter code)
WEF	Water Environmental Federation
WRc	Water Research Center
WWTP	waste water treatment plant

x	group aggregation with mean distance to centroid of most distant reaches (within four letter code)

List of symbols

$A_{leakage}$	leakage area
$A_{surface}$	groundwater influenced reach surface
A_{wet}	groundwater influenced pipe surface (wetted area)
A_IAREA	reduced area ratio
b	coefficient
c	concentration
c	constant
$c_{COD,foulwater}$	COD concentration of foul water
$c_{COD,wastewater,model}$	modelled COD concentration of waste water
$c_{foulwater}$	concentration in foul water
$c_{I/I}$	concentration in I/I water
c_{mean}	mean concentration
c_{min}	minimum concentration
$c_{wastewater}$	concentration in waste water
$cl_{I/I}$	class of I/I rate
$cl_{I/I,predicted}$	predicted class of I/I rate
COVERAGE	coverage
d	distance
$\hat{d}$	disparity
d_{min}	minimum distance
DATE_CONSTR	year of construction
dim. i	dimension i, result of multidimensional scaling
DIST_BUILD	distance to buildings
DIST_DRAIN	distance to drainages
DIST_ELBE	distance to river Elbe (Dresden catchment)
DIST_STORM	distance to storm sewers
DIST_STREET	distance to streets
DIST_WATER	distance to surface water (not main rivers)
e	error
$F_{I/I}$	fraction of dry weather flow
FUNCTION	sewer function
G_i	cluster, group
h	homogeneity measure
IDENTIFIER	identifier
k	recession constant
K	soil permeability
k_L	leakage factor
LENGTH	reach length
MATERIAL	material
n	number, frequency
NO_JOINTS	number of joints
o	item, object
$\bar{o}$	mean item, cluster centre

$\vec{o}$	attribute vector of an item
p	significance level
$P(G_i \mid y_{o_j})$	classification probability o_j to G_i
$P_j(G_i)$	a priori probability o_j to G_i
POP_DENS	population density
POP_LENGTH	population-specific length
PROF_CIRC	profile circumference
PROF_TYP	profile type
q	specific discharge
q	factor
Q	data reduction coefficient
q_{dwf}	specific dry weather discharge
Q_{dwf}	dry weather discharge
$Q_{foulwater}$	foul water discharge
$q_{foulwater}$	specific foul water discharge, specific water consumption
$q_{foulwater,min}$	minimum specific foul water discharge
$q_{I/I}$	specific I/I discharge
$Q_{I/I}$	I/I discharge
$Q_{I/I,measured}$	measured I/I discharge
$Q_{I/I,real}$	real I/I discharge
$q_{infiltration}$	specific infiltration discharge
$Q_{infiltration}$	infiltration discharge
$Q_{infiltration,modelled}$	modelled infiltration discharge (arbitrary model)
q_{inflow}	specific inflow discharge
Q_{mean}	mean total discharge
Q_{min}	minimum total discharge
$Q_{wastewater}$	total waste water discharge
$Q_{0,intensity\_I/I}$	initial magnitude of intensity-related I/I at time t_0
r	factor
r	optimisation quality indicator, error reduction
R	correlation coefficient
reach	reach
s	empirical standard deviation
s	proximity
S	empirical covariance matrix
S_i	classification score
$S_{I/I}$	fraction of dry weather flow
sb-ctm	sub-catchment
SEW_SYSTEM	sewer system
SLOPE	slope
STREET_TYP	street type
STRESS	stress value
SUBCATCHM	sub-catchment affiliation
t	time
THICK_COHSV	thickness of cohesive layers
v	variance measure
$V_{drinkwater}$	drinking water volume

$V_{drinkwater,export}$	exported drinking water volume
$V_{drinkwater,loss}$	drinking water loss volume
$V_{drinkwater,storage}$	stored drinking water volume
$V_{drinkwater,useloss}$	drinking water loss volume during purification
V_{dwf}	total dry weather flow volume
v_{nMP}	variance measure normalised to unclustered state
$V_{I/I}$	I/I volume
$V_{wastewater,loss}$	waste water loss volume
w	weighting factor
x	set of attributes
x_i	single attribute
$\bar{x}_i$	mean attribute value
$x_{i,max}$	maximum value of x_i
$x_{i,min}$	minimum value of x_i
$x_{i,transformed}$	transformed attribute
y	dependent variable
y_j	discriminant value, discrimant function
$\hat{y}$	predicted dependent variable
z_i	standardised attribute
δ	weighting factor
Δ	difference
Δh	water head
$\Delta\varphi$	difference between similarity figures of adjacent sub-catchments
ΔL	thickness of limiting soil layer
λ	weighting factor
φ	similarity figure
φ_{max}	maximum similarity figure

1 Introduction

Sewer systems constitute a significant patrimony in cities and villages. They are a fundament for public health, for the protection against flooding in urban areas and for the protection of the aquatic environment. Their structural integrity and functional efficiency are key parameters to guarantee the safe transfer of domestic and industrial waste water to treatment plants.

A major problem of operating a sewer system is the occurence of extraneous water or infiltration/inflow, i.e. the discharge of water which is neither qualitatively influenced by any usage nor specifically collected and discharged during precipitation. Extraneous water in sewers might cause serious consequences such as increased discharges of untreated waste water to the receiving waters causing pollution and public health risks as well as a more complicated waste water treatment causing increased pumping and treatment costs. On a long term basis extraneous water is critical for a sustainable urban water management.

Operating and maintenance strategies that include extraneous water require a comprehensive knowledge about the infiltration/inflow situation in the respective catchments. The investigation of infiltration/inflow is mainly based on extensive measurement campaigns. Due to the high personnel and financial expenditures required for measurements, public and private operators need appropriate methods and techniques aiming at a cost-efficient determination of extraneous water flows.

Based on this awareness, the aim of the presented work was to develop methods which allow for

– the determination of an optimal measuring point configuration within a sewer system to receive the best information content for a given number of measurements
– the reduction of the number of measuring points without reducing the information yield
– the transfer of available measurement results to other (sub-)catchments.

Due to the restrictions of commonly used measurement methods the development of optimisation and transfer methods was focused from the outset on infiltrating groundwater as the main contribution to extraneous water and on steady state conditions, i.e. dynamic processes and long term developments are not considered.

The work is divided into four self-contained parts:

- Chapter “Extraneous Water”: This chapter contains fundamentals about extraneous water. Beside definitions, relevant sources and processes it describes measurement methods, models and practical approaches handling infiltration/inflow problems.
- Chapter “Similarity Approach”: The method development is based on the assumption “Similar sewer conditions lead to similar infiltration/inflow rates.” With this approach it is possible to look for and work with similar entities within a sewer system. The approach and its potential application is explained and verified. Furthermore, the chapter describes the data base for the development and verification of methods as well as relationships between sewer characteristics and infiltration/inflow rates.
- Chapter “Optimal measuring points”: The information yield of a measuring point is determined by reach-related differences between actual and averaged measured infiltration/inflow rates that are summarised within the respective sub-catchment. The information yield can be improved by finding measuring points representing homogeneous sub-catchments. This chapter describes the development of methods to find such optimal measuring points based on adapted cluster analysis and their verification by means of artificial and real cases.
- Chapter “Transfer of measurement results”: As far as modelling techniques are not satisfactory the evaluation of the infiltration/inflow situation of a (sub-)catchment depends on empirical knowledge. Therefore, this chapter describes the development and the verification of methods comparing sub-catchments and classifying reaches in order to transfer such knowledge and to predict the infiltration/inflow situation in similar sub-catchments without measurements.

An essential element of this work is the extensive use of statistical methods of both inferential statistics and exploratory data analysis. Explanations of these methods are given at the place of their use, thus, they can be found at different outline levels. The methods and their appearance are listed in Table 1-1.

Table 1-1. Applied statistical methods

Method	Chapter	Page
Cluster analysis	4.2	107
Crosstabulation	3.3.2	79
Discriminant analysis	5.3.1	162
Exploratory data analysis	3.3.3.2	85
Kruskal-Wallis analysis of variance	3.3.2	79
Multidimensional Scaling	3.3.3.2	87
Multiple linear regression	3.3.3.1	82
One-way analysis of variance	3.3.2	79
Post hoc tests	3.3.2	79

2 Extraneous Water

2.1 Definition

The definition of extraneous water or infiltration/inflow (I/I) is inconsistent due to vying standards and regulations, respectively. Very widely extraneous water can be defined as any contribution to the waste water flow whose occurrence is not compatible with the basic functions of sewer systems. Therefore, its occurrence has a large influence on waste water transport and treatment: quantitative as additional load and qualitative since the quality of extraneous water generally does not require a treatment.

German legal regulations do not define the technical term “extraneous water” explicitly (Mock and Nisipeanu, 1994). Mostly, for judicial purposes the DIN 4045 (DIN, 1999) is used: extraneous water consists of groundwater (gw) infiltrating into sewers, wrongly connected drainage or storm water as well as surface water flowing into foul water sewers. Competing definitions are made e.g. by the Waste Water Charges Act (N.N., 1994) which excludes rain derived extraneous water.

The regulations by the German Association for Water, Wastewater and Waste (DWA) as main technical authority use primarily the definition of DIN 4045. Further comparisons are given in Decker (1998) and Hennerkes (2006).

European standard DIN EN 752-1 (DIN, 1996a) defines extraneous water only as unwanted discharge in sewer systems. The attribute “unwanted” is subjective – e.g. extraneous water may be favourable for sediment transport – and allows individually adapted interpretations.

On a broader international level extraneous water or I/I is defined according to EPA (1973) as the water entering a sewer system from the ground through defective pipes, pipe joints, connections or manhole walls as well as the water discharged into a sewer system from roof leaders, cellar, yard and area drains, foundation drains, cooling water discharges, drains from springs and swampy areas, manhole covers, cross connections from storm and combined sewers, storm waters, surface runoff, street wash waters or drainage. This definition is used in technical and legal context (infraguide, 2005).

Based on European standards and legal regulations, ATV-DVWK (2003) gives a mandatory and favourable definition: extraneous water is water discharged in sewer systems which is neither qualitatively influenced by domestic, industrial, agricultural or other usage nor specifically collected and discharged during precipitation. Extraneous water demands no treatment, it burdens unnecessarily sewer systems and aggravates waste water treatment and it is unwanted under the aspect of water protection.

The amount of I/I discharge is specified in relation to the waste water discharge (relative value) or to sewer/time dimensions (absolute value). Typical measurands are (Decker, 1998):

1. The fraction of dry weather flow $F_{I/I}$ refers the I/I discharge to the total dry weather flow (dwf). Thus, $F_{I/I}$ ranges from 0 to 100 %. This measurand is normally used in the case of available discharge measurements. It is calculated with

$$F_{I/I} = \frac{Q_{I/I}}{Q_{dwf}} = \frac{Q_{I/I}}{Q_{foulwater} + Q_{I/I}} \qquad \text{Equation 2-1}$$

with $Q_{I/I}$ I/I discharge
Q_{dwf} total dry weather flow
$Q_{foulwater}$ foul water flow (domestic and industrial waste water)

2. The surcharge to foul water flow $S_{I/I}$ refers the I/I discharge to the foul water flow. Thus, $S_{I/I}$ can be larger than 100 %. The advantage of this measurand is the linear relationship between $Q_{I/I}$ and $Q_{foulwater}$. It is normally used while planning and calculated with

$$S_{I/I} = \frac{Q_{I/I}}{Q_{foulwater}} = \frac{Q_{I/I}}{Q_{dwf} - Q_{I/I}} \qquad \text{Equation 2-2}$$

3. The specific I/I discharge rate $q_{I/I}$ refers the I/I discharge to various parameters like connected area, inhabitants, reach length or reach surface. Thus, relevant units are e.g. $L/(s\cdot ha_{red})$, $L/(P\cdot d)$, $L/(m\cdot d)$ or $L/(m^2\cdot d)$. Only the latter two characterise the structural state of the sewer.

Conversion factors are given in Table 2-1 for a comparison of the different parameters describing I/I.

Table 2-1. Conversion table (adapted from Hennerkes, 2006)

Base unit	Conversion	Specific I/I rate
50 % $F_{I/I}$	$q_{I/I} = F_{I/I} \cdot q_{foul} / (1-F_{I/I})$ → nonlinear relationship	120 L/(P·d)
50 % $S_{I/I}$	$q_{I/I} = S_{I/I} \cdot q_{foul}$	60 L/(P·d)
0.1 L/(s·ha_{red})	with 34,2 P/ha_{red}	253 L/(P·d)
0.1 L/(s·km)	with 6,2 m/P	54 L/(P·d)

Assumptions for Germany (Statistisches Bundesamt, 2006):

- inhabitants connected to sewers: 77,961,898
- public sewer length: 486,159 km
- area: 2,281,050 ha_{red}
- specific water consumption $q_{foulwater}$: 120 L/(P·d)

2.2 Origins and classification

The total discharge of extraneous water consists of several components. Basically they can be distinguished from each other by the origin of the water:

- groundwater which infiltrates from the surrounding through defective pipes, joints, connections and other assets or which is collected by drainages.
- rain derived surface water which is directly discharged from connected surfaces or via manhole covers (foul sewer only) and rapidly percolating storm water which infiltrates into sewers
- surface water from springs, streams and from anthropogenic sources like cooling systems or building sites.

The spatiotemporal characteristics of the components depend on the type of origins. The spatial distribution can be either from point or diffuse origin. Point sources are local discharges of surface water. With a more restricted definition these discharges include only non-rain derived surface water, i.e. water from springs, streams or plants. They are normally permitted and should be easily locatable. Diffuse sources are ground or surface waters which infiltrate through defect assets. With a broader definition these sources include storm water which is discharged in foul sewers through wrong connections or other cross connections due to their unwished character.

The time distribution can be temporary or permanent. Temporary sources are rain derived, only. Their occurrence and variation depend mainly on rain intensity and previous rain heights. Permanent sources have no or only seasonal variations. Thus, they contain infiltrating groundwater and point surface sources.

LROP (1981) gives a more sophisticated allocation based on the response time on rain and time scale of flow variations, respectively (Table 2-2).

Table 2-2. Allocation of extraneous water based on flow variations (LROP, 1981)

Response time	Description	Origins
From few minutes to 1 or 2 hours	Stochastic contributions	Wrong connections
From few hours to few days	Pseudo-permanent contributions	Infiltration of groundwater with a variable level
From seasonal and annual to infinite periods	Permanent contributions	Infiltration of groundwater with a constant level

Based on the origins and characteristics several classification approaches for extraneous water exist. Nute (1980) determines a classification by means of the origin:

- infiltration: water entering a sewer system through defective pipes, joints, connections or manhole walls
- inflow: water discharged into a sewer system by surface runoff, drainage, cooling water discharges, drains from springs and manhole covers, cross connections from storm and combined sewers, street wash waters
- intensity-related I/I: storm water which rapidly percolates through fissures or highly permeable soil and infiltrates into sewers through defective pipes, joints or connections during high intensity periods.

Gustafsson et al. (1999) use a similar allocation and define the components as base flow, overland flow and interflow. Based on Pecher (1998) and Kauch (1996), a competing classification by means of the origin is given in

Table 2-3. Ranchet et al. (1982) describe a classification by means of the spatio-temporal behaviour (Table 2-4).

Table 2-3. Classification of I/I by means of the origin (Pecher, 1998; Kauch, 1996)

Type	Origin	Characteristics
Groundwater	Infiltration through defective sewers and house connections, drainages	Eventually higher nitrate concentrations due to manuring
Stream and ditch water	Inflow of surface water, flooding of waste water assets	Partly peak flows, entry of suspended solids
Storm water in foul sewers	Wrong connections, inflow through manhole covers	Peak flows, entry of suspended solids

Table 2-4. Classification of I/I by means of spatiotemporal behaviour (Ranchet et al., 1982)

Source	Permanent occurrence	Temporary occurrence
Diffuse	Infiltration during low groundwater tables (permanent impoundage of the reach)	Infiltration during changing groundwater levels
Point	Spring and stream waters, drainage, cooling water	Storm water in foul sewers

Belhadj (1994) applies a simplified classification by means of the spatiotemporal behaviour, too:

- point, (quasi-)permanent sources: spring and stream waters, drainage
- point, temporary sources: storm water from impervious surfaces
- diffuse, permanent or seasonal sources: groundwater through defects, slow drainage
- diffuse, temporary or event-based sources: rapidly percolating storm water, fast drainage.

Due to the different functions of sewers, waste water components belong to I/I in dependence of the sewer type, e.g. non-polluted storm water belongs to I/I in foul sewers, but it does not belong to I/I in combined sewers provided that it is discharged purposeful. ATV-A 118 (ATV, 1999a) and ATV-DVWK (2003) give a classification by means of origin in combination with the sewer type (Table 2-5).

Table 2-5. Classification of I/I by means of origin in combination with sewer type (ATV-DVWK, 2003)

I/I component	Combined	Foul Sewer	Storm
Groundwater infiltrating through leakages	X	X	X
Drainage	X	X	X[1]
Spring and stream waters	X	X	X[1]
Cooling waters	X	X	
Wrong connection of storm water		X	
Discharge of storm water over manhole covers		X	
Surface waters from outer areas, which should not be collected in the sewer system	X	X	X

[1]It is to be proved individually whether a discharge is acceptable.

2.3 Processes and influencing factors

2.3.1 Infiltration

2.3.1.1 Relevant elements

Infiltration of groundwater through leakages of sewerage assets is the main contribution to extraneous water (ATV-DVWK, 2003; Jardin, 2004; Karpf, 2002; Kroiss and Prendl, 1996). It is basically driven on the one hand by the water head Δh between the waste water level inside the pipe and the groundwater level outside and on the other hand by leakages of the pipe.

The infiltration process occurs between the native soil and the internal space of the pipe. Thus, the definition of inside and outside of the pipe have to be expanded (Davies et al., 2001a): due to the typical kind of building and operating a sewer (ATV, 1995; Stein, 1998) the expanded definition of sewerage systems consists of the elements (Figure 2-1):

- groundwater
- waste water
- native soil
- foundation, bedding and backfill

– pipe wall and pipe joints
– lateral connections
– sediment deposits.

All these elements with their spatiotemporal variability and their long-term development have to be considered to describe infiltration.

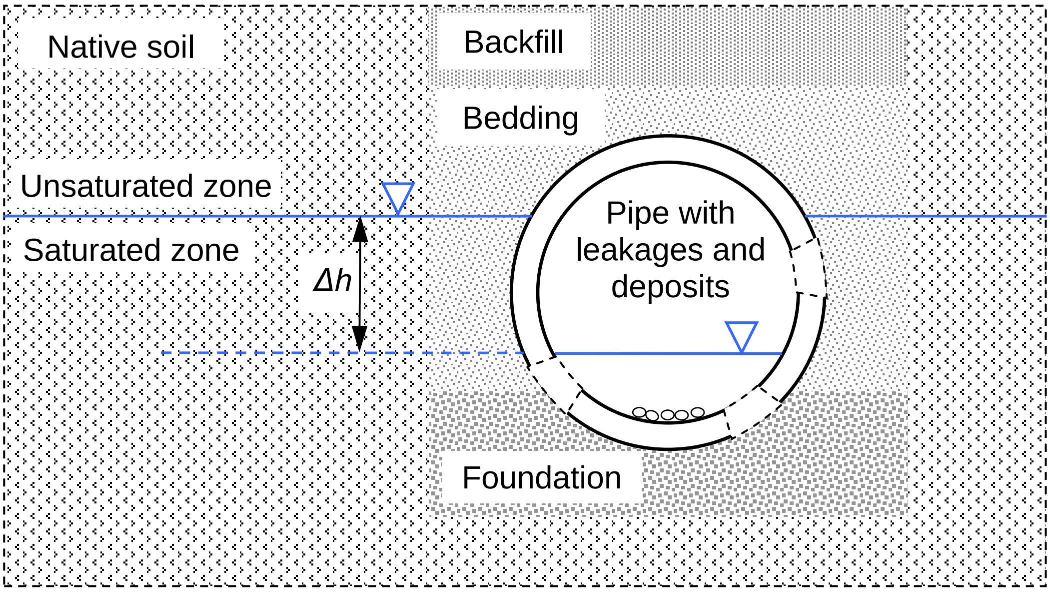


Figure 2-1. Expanded sewerage system, schematical

Although public and private sewers are similar in their construction and mounting, they should be considered separately. Private sewers and house connections, respectively, play an important role concerning infiltration due to

– their generally worse state: they are built without strict supervision, in most cases they are not maintained; Ballweg (2002) reports an untightness rate of 92 % according to pressure tests in a quarter of Göttingen/Germany, Hoffmann (2003) reports on a rehabilitation rate of 75 % due to closed-circuit-television in a quarter of Frankfurt/Germany
– their length: in Germany, the length-related fraction of private sewers amount to approximately 66 % (Berger and Lohaus, 2005).

However, the fraction of groundwater influenced pipes should be smaller compared to public sewers due to their generally lower depth. Furthermore, the interaction surface between the internal space of the pipe and the ground it is buried in is much smaller due to the smaller diameters.

House connections might significantly contribute to infiltration. Yet, it is not clear whether they dominate infiltration (Stein, 1998) or not (Karpf and Krebs, 2004a). Furthermore, operators normally have no access to and no information about private sewers. Pragmatically, they are excluded from investigations and in many studies due to lacking data.

2.3.1.2 Water head

The water head is the difference between the groundwater level outside and the waste water level inside the pipe. Both levels are rather easy to measure (e.g. Heath, 1983; Weyand, 2001) and to model (e.g. Sanford, 2002; Schütze et al., 2002).

The water head is the "driving force" of infiltration. Therefore, it is a major factor for infiltration processes. Neglecting the waste water level, Dohmann et al. (2002) show the basic relationship between the groundwater table and the I/I discharge of two individual measuring points. In Figure 2-2 a strong correlation can be observed. The differences between the measuring points result from other influencing factors like soil conditions or the structural state of pipes. For a whole sewer system, Schulz et al. (2005b) show a similar behaviour – increasing discharge with rising groundwater table – between the variables dry weather flow and groundwater influenced pipe length (Figure 2-3). The latter is determined by the groundwater table.

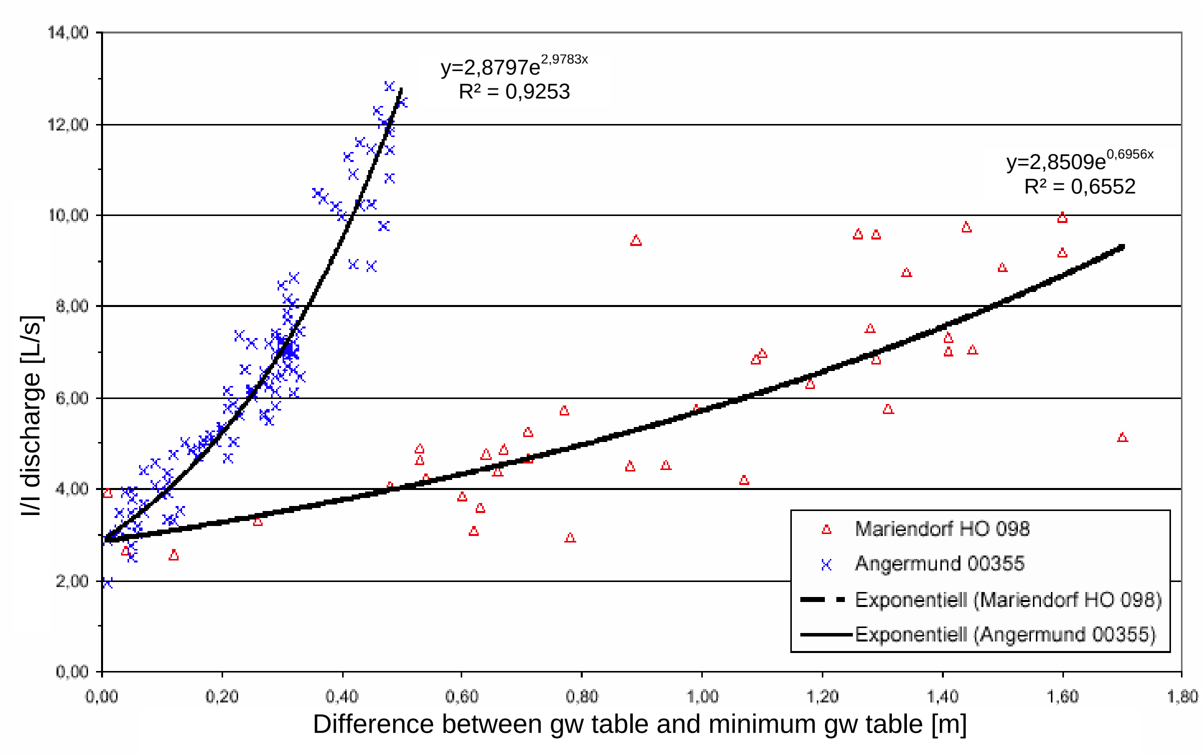


Figure 2-2. Relationship between groundwater table and I/I discharge (Dohmann et al., 2002)

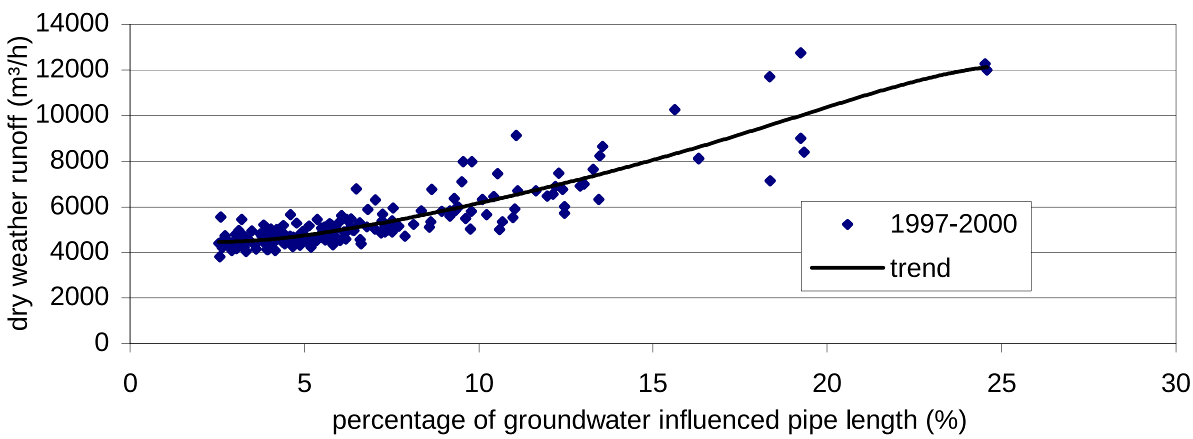


Figure 2-3. Relationship between percentage of gw influenced pipe length and dwf (Schulz et al., 2005b)

The waste water level is very dynamic due to the variability of the foul water flow and the storm runoff. It is defined by the actual discharge and the hydraulically relevant sewer features profile type, size, roughness and slope. High water levels in the pipe can reduce or even prevent infiltration.

Groundwater flow systems are determined by climate, topography and geology of the catchment (Winter, 2001) and interactions with adjunctive compartments. The natural groundwater flow pattern results from the configuration of the groundwater table, the distribution of the hydraulic conductivity in the soil and the groundwater recharge situation. The pattern consists of multiple flow systems of different orders of magnitude with a nested hierarchical order (Sophocleous, 2002).

The groundwater recharge is driven by climate and precipitation, respectively. Principal recharge mechanisms are defined by Lerner et al. (1990):

- direct recharge: vertical percolation through the vadose zone in excess of soil-moisture deficit and evapotranspiration
- indirect recharge: percolation through the beds of surface waters
- local recharge: an intermediate form of groundwater recharge resulting from the horizontal (near-)surface concentration of water in the absence of well defined channels.

Normally, combinations of the various types occur. An overview about processes and estimation of the recharge can be found in de Vries and Simmers (2002) and Sanford (2002).

The hydrogeological properties of the soil determine the flow paths and velocities. Basically, zones with a high permeability serve as drains which cause gradients. Differences of gravity potential often mirror the topography. Under uniform conditions the groundwater table is a smoothed replication of the earth surface. The multitude of movement processes in saturated and unsaturated zones is described e.g. in Heath (1983). The relevance of soil properties concerning I/I was shown e.g. by Wanaars et al. (1999).

Resulting from the natural processes the dynamic behaviour of the groundwater level is slow. There are long lasting variations which are overlaid by seasonal ones. Single storm events are locally of importance, only. In moderate climates, the highest recharge rates and rising groundwater levels can be observed during periods of high rainfall and low evapotranspiration, i.e. between November and April for the northern hemisphere (Cremer, 2000). A typical hydrograph of a shallow aquifer is shown in Figure 2-4. Due to the little depth influences of storm events can be observed as short term variations which are still small compared to seasonal variations.

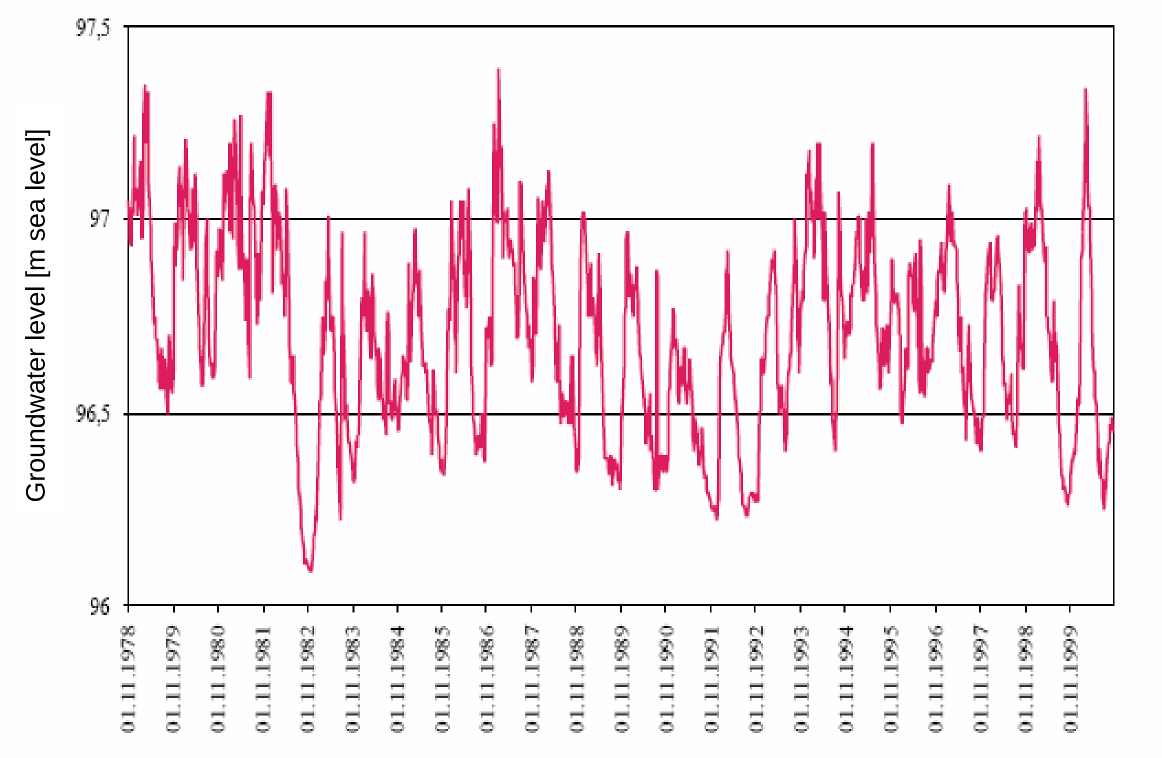


Figure 2-4. Hydrograph of shallow aquifer in Saxony/Germany (LfUG, 2002)

Due to the fact that large cities are mostly situated at rivers, the interaction between groundwater and surface waters has a predominant influence on the groundwater table in urban areas. These interactions occur by subsurface lateral flow through the unsaturated zone and by infiltration into or exfiltration from the saturated zones. Also, in the case of karst or fractured terrain, interactions occur through flow in fracture/solution channels (Sophocleous, 2002).

Depending on the water head between surface and groundwater the water bodies gain or lose water. The flow direction can change in short-term run due to single storm events causing focused recharge near the bank or flood peaks. Figure 2-5 shows an example of a groundwater hydrograph close to a main river. The multitude of occurring processes are described e.g. in Winter et al. (1998).

Consequently, infiltration is also driven by flow characteristics of streams and floods over a wide area. At main rivers the flood-influenced zone can reach several kilometres lateral to the water course (Karpf and Krebs, 2004b).

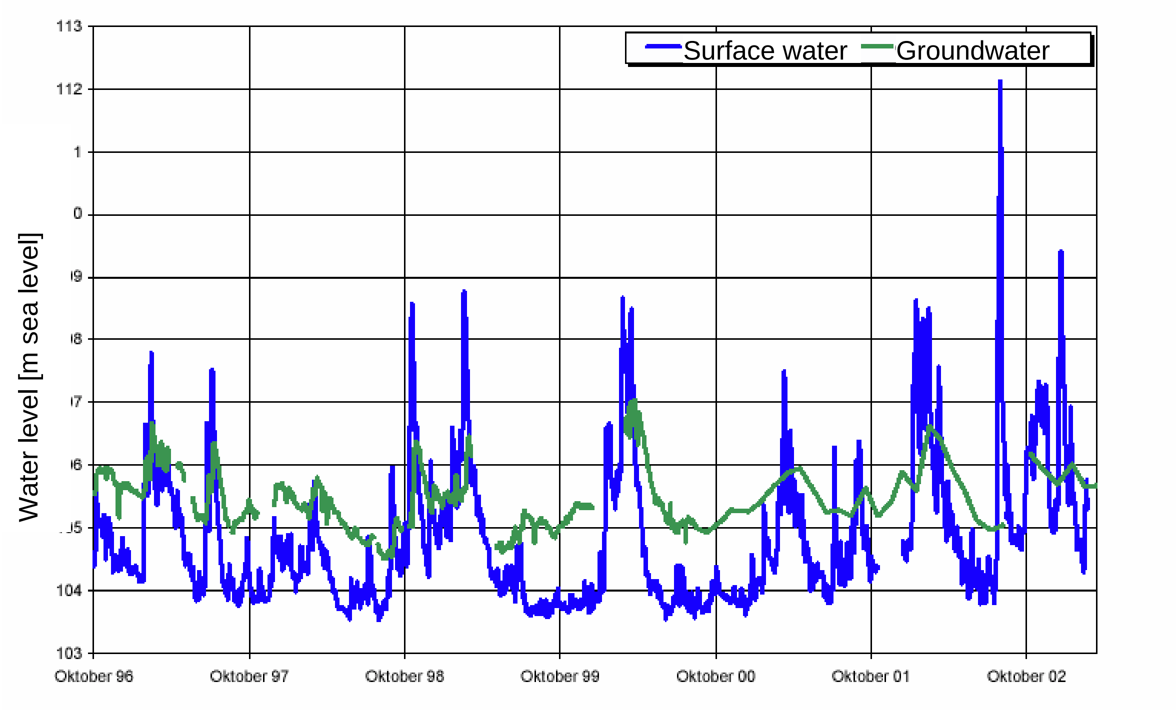


Figure 2-5. Relationship between ground and surface water level, example of Saxony/Germany (LfUG, 2002)

Groundwater table and flow paths are influenced by human activities. On a regional scale e.g. mining leads to massive disturbances of the natural water balance. E.g. Freytag and Kendziora (2002) describe groundwater funnels over an area of 2,100 km² with drawdowns of 80 m in the coal-mining district of Lusatia/Germany.

In dwelling areas, anthropogenic structures like sewers, drainages and wells affect the groundwater. They lower the groundwater table locally by drainage effects or water extraction. Furthermore, building activities and surface sealing as well as the clogging of river beds (Brunke and Gonser, 1997) reduce the recharge and change the recharge pattern in the catchment.

Gustafsson (2000) compares the measured groundwater table which is disturbed by sewers and the natural, modelled groundwater table of a small Swedish village. Figure 2-6 shows the different groundwater depths of the two conditions and thus the substantial drainage effects of the sewer system. Reichel and Getta (2000) use a groundwater model to determine the effects of sewer rehabilitation in a catchment of the city of Bottrop/Germany. They calculate an increase of the groundwater table up to 4 m and identify massive drainage problems as a result of sewer rehabilitation.

Sub-surface structures which drain intentionally or unintentionally urban areas are often older than the above-situated buildings, especially in war-affected cities. Normally, these buildings were built without considering the undisturbed groundwater conditions. Thus, a reduction of the water extraction through stopping infiltration or closing of wells can result in damages at buildings and other dwelling structures. Kofod (2001) describes such effects due to rising groundwater levels in several large European cities. Furthermore, the rising groundwater table can lead to boosted lixiviation of contaminated sites (Getta et al., 2004).

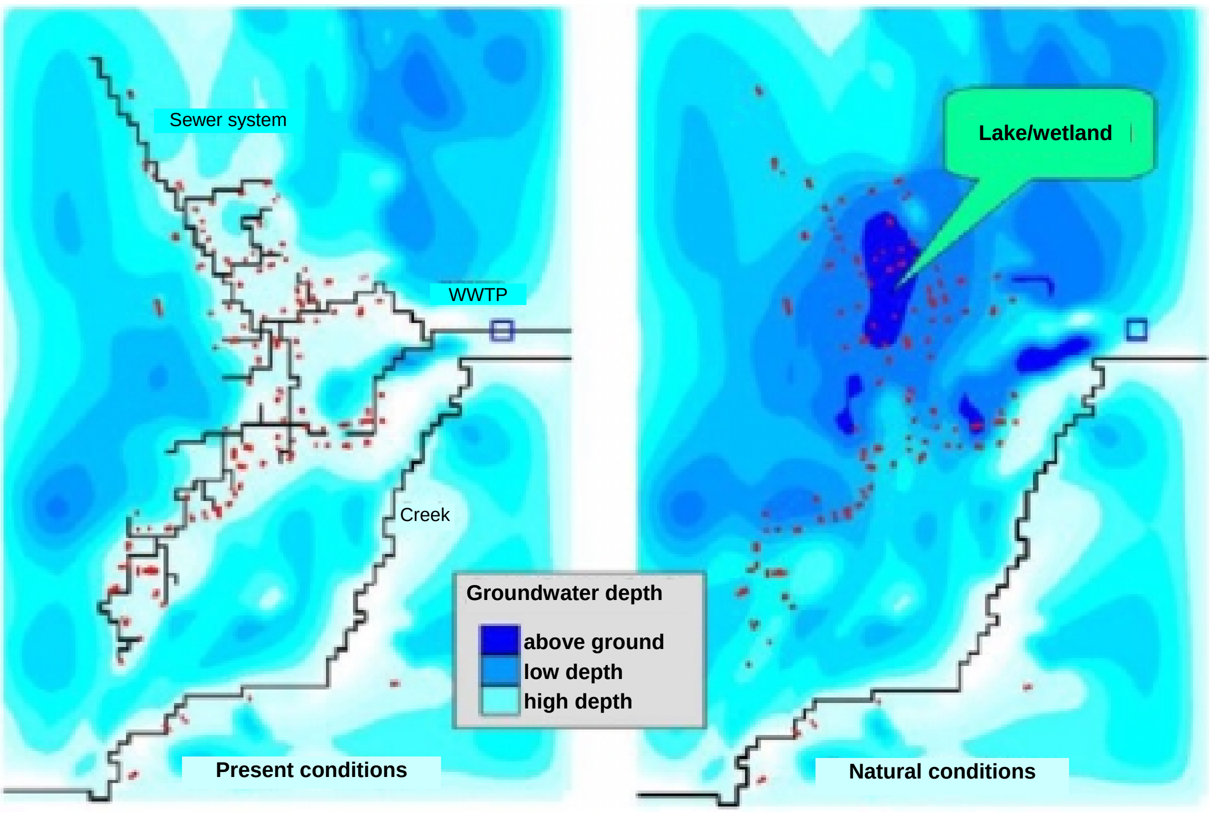


Figure 2-6. Comparison of disturbed (left) and natural (right) groundwater table (Gustafsson, 2000)

2.3.1.3 Conduit zone

The basic principles of configuration and mounting of the zone around sewers are described and regulated e.g. in ATV (1995), Stein (1998), DIN EN 1610 (DIN, 1997b), ATV-DVWK-A 127 (ATV-DVWK, 2000) and ATV-DVWK-A 139 (ATV-DVWK, 2001).

Before the 1990s nearly all sewers were built with an open construction method, i.e. with an open trench (Stein, 1998). The width of the trench amounts to external pipe diameter plus 0.4 to 1.0 m, measured at the trench invert (DIN EN 1610). According to ATV-DVWK-A 139 the following materials are suitable to fill the trench:

- sand
- sandy gravel with maximum particle size of 22 mm, sand fraction > 15 %
- one grain gravel
- broken stone with maximum particle size 11 mm
- water-bound materials, lean concrete
- recycling materials, excavated soil.

The building material is chosen depending on pipe material, profile type and size as well as native soil and groundwater characteristics, further on the trench zone in relation to the pipe (Figure 2-1):

- foundation: supports directly the pipe and the joints
- bedding: above the foundation, supports the pipe
- backfill: above the bedded pipe.

Trenchless construction methods gain importance with the recent technological development, not just for special cases like crossings of other infrastructures. Depending on the individual construction procedure like pipe jacking, heading or tunneling, the zone around sewers built with trenchless construction methods consists of displaced soil, jacket pipes or wooden or concrete sheeting (Stein, 1998).

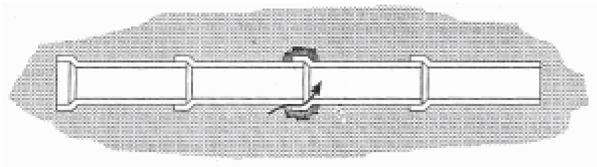
Due to the numerous historic and current construction procedures and the diversity of building practices which do not always follow the regulations all possible kinds of soils and materials with different states can be found in conduit zones. Furthermore, in European cities the upper layers of the native soil are often disturbed due to the long lasting building history and war effects. Thus, the underground conditions around sewers are very complex and vary in a wide range.

The hydrogeological properties of the system soil/conduit zone determine the groundwater flow to sewer leakages on a local scale. In principle, there is a difference of permeability between native soil and conduit zone; backfill and bedding usually have a higher permeability. Thus, the conduit zone acts as a shunt, leading the groundwater flow along the sewer over long distances (Weiss et al., 2002).

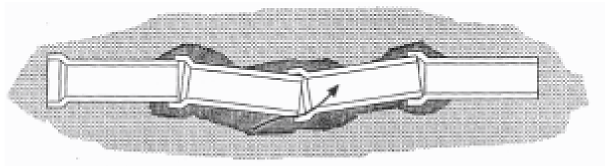
The soil around the pipe transfers the external loading pattern to the pipe. Thus, the construction and the state of the conduit zone have a direct influence on sewer failures. The surrounding ground improves the load carrying capacity of pipes (Olliff, 1992) and avoids displacement of pipes. The loss of such support resulting from soil shift promotes progressive deformation of defect sewers (WRc, 2001). An example for the development of the structural state of pipes affected by soil loss is shown in Figure 2-7.

The relevant processes – suffosion in non-cohesive and erosion in cohesive soils – and their influencing factors are described e.g. in Schaef (1995) and Jones (1984), some sewerage-specific aspects in WRc (2001). The soil loss around sewers is mainly driven by infiltration (WEF, 1994). Thus, groundwater flow, infiltration and the structural state of pipes and conduit zones are strongly related to each other.

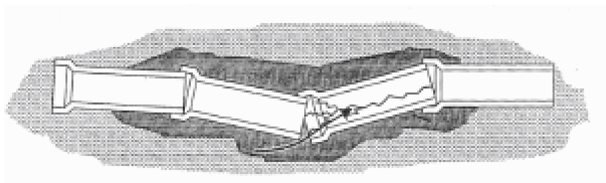
The density differences between the native soil and the conduit zone support root intrusion. Root growth follows primarily density gradients into conduit zones, but not humidity or oxygen gradients (Stützel et al., 2004). Therefore, even tight sewers are affected by root growth which can lead to root intrusion into sockets and destruction of sealing material.



Stage 1: Sealing defect at a joint or a lateral connection; visible defects: open joints, infiltration



Stage 2: Increased infiltration and exfiltration, destabilisation of trench involves displacement of pipes; visible defects: disconnection, slope inversion, depression, infiltration



Stage 3: Unequal loads due to displacements involve cracking and deformation of the pipes; visible defects: open and displaced joints, cracks, fractures, depression, inversion of slope.

Figure 2-7. Development of the structural state influenced by infiltration (WEF, 1994)

2.3.1.4 Structural state of pipes

The basic principles of construction and the mounting of pipes are described and regulated e.g. in Butler and Davies (2000), ATV (1995), Stein (1998), DIN EN 752-3 (DIN, 1996b) and ATV-DVWK-A 139.

The structural state of pipes and the sewer tightness, respectively, are the main factors for the infiltration potential. Principally, sewers are defect and not tight. In Germany some 95,300 km of sewers (19.6 % of all public sewers) have to be rehabilitated in a short or mid term run, further 104,500 km in a long term run (Berger and Lohaus, 2005). In the UK some 27,300 km of sewers (9 %) are in the poorest conditions (extracted from Ellis and Revitt, 2002). 7,300 km of them are classified as critical sewers which are of strategic importance for the correct functioning of the sewerage system and which have high economic consequences of failure.

A significant change of this situation is unlikely mainly due to the inappropriate financing. In Germany the total needs for sewer rehabilitation are estimated to approximately 50 bn EUR while the annual amount spent is 1.6 bn EUR (Berger and Lohaus, 2005). In the UK less than 1,700 km of the critical sewers were renovated or replaced between 1990 and 1998. This is equivalent to a calculative lifespan of 350 years. Operators claim that there is at least a difference of 30 % between what should be spent on capital and operational maintenance and the sum the regulation authority has set (Ellis and Revitt, 2002).

Failure detection and structural investigation of sewers are based on visual inspections. Typical methods are closed-circuit-television (CCTV), man entry and the use of mirrors and cameras; the most important method is CCTV. The analysis of the inspection results yields a classification of single reaches due to their current state.

There are numerous classification systems, not only nationwide but also operator-specific. Normally, the classification systems distinguish between 4 and 6 condition classes. Within one condition class either different types of structural defects, or functional deficiencies and their environmental impacts, or both are aggregated. Class limits are defined by threshold values or fuzzy logic (Baur et al., 2005). The classification varies between a simple assignment to inspection codes and recommended scoring models like ATV M-149 (ATV, 1999b) or the UK industry grading system (WRc, 2001). Generally, a reach is classified according to its most severe damage or its overall condition in order to determine the urgency for rehabilitation or the sewer's actual monetary value. Schulz et al. (2005a) verify a certain correlation between the distribution of I/I and the sewer classification for the catchment of Dresden/Germany. A comprehensive overview and a comparison of classifications systems are given in CARE-S, 2003.

In common classification systems leakages and infiltration, respectively, are only accounted if penetrating water is observed through the inspection. Rutsch and Uibrig (2003) propose a classification system focused purely on leakages. With this system the inspection codes are evaluated by defect type and size emphasising a potential leakage of the individual defect. Severity and number of defects per reach are aggregated in one figure, which can be analysed under different aspects.

As a main resource, DIN EN 13508-2 (DIN, 2003) defines and classifies structural failures. TEPPFA (2005) determines the leakage and infiltration potential for defect types which are relevant for infiltration. Flow rates for each single defect type were calculated considering the smallest and the biggest defect extent possible. Additional factors like soil permeability were not regarded. The bandwidth of potential flow rates was split into five categories ranging from very small to small, medium, big up to very big. For each defect type the results were discussed and revised amongst experts. Additionally, the defect types were assigned to certain leakage types to describe their leakage likelihood. The results are listed in Table 2-6.

The structural state of a pipe is not constant. The deterioration from a minor defect to collaps is a long lasting process. It follows a three-stage process (Davies et al., 2001a; compare Figure 2-7):

1. An initial defect: Collapse of a sewer normally originates where an initial, often minor, defect allows further deterioration to occur. Such defects are caused by design errors, poor construction practice, subsequent overloading or disturbances like third party interferences or maintenance damages. Visible defects: cracks at soffit, invert and wall.
2. Deterioration: In- and exfiltration cause migration of soil particles. Side support is lost and allows further deformation so that cracks develop into fractures. Side support may be also insufficient due to poorly compacted or unsuitable backfill. Softening and erosion of pipe or joint materials through chemical or mechanical attacks occur. In most cases pipes are subjected to multiple defects and hence several deterioration processes happen consecutively. Visible defects: fractures, slight deformation, infiltration.
3. Collaps: Loss of side support allows side of pipe to move further outwards and the crown to drop. Collaps is often triggerd by some random event that may not be related to the cause of the deterioration. Therefore, it is not possible to predict when a sewer will collapse. However, it is feasible to estimate whether a sewer has deteriorated sufficiently for collapse to be likely. Visible defects: fractures and deformation, possibly broken.

Studies of the effects of construction standards and asset age analyses lead to the concept, that the failure probability of a pipe follows a "bath tub" type curve over the time (Figure 2-8).

Table 2-6. Leakage behaviour of defect types contributing to infiltration (TEPPFA, 2005)

Defect type according to DIN EN 13508-2		Leakage type	Leaking Potential		
			Minimum	**Average for rigid pipes**	**Maxi-mum**
Fissure	Crack	Likely	Very small	Small	Very big
	Fracture	Always	Small	Very big	Very big
Break / Collapse	Break	Always	Medium	Big	Very big
	Missing	Always	Small	Big	Very big
	Collapse	Always	Very big	Very big	Very big
Defective Brickwork	Displaced	Likely	Very small	Medium	Very big
	Missing	Always	Medium	Big	Very big
	Dropped invert	Always	Medium	Very big	Very big
	Collaps	Always	Very big	Very big	Very big
Missing mortar		Likely	Very small	Medium	Very big
Surface damage	Missing wall	Always	Small	Big	Very big
Defective connection	Gap	Always	Small	Big	Very big
	Partial gap	Always	Small	Medium	Very big
	Damaged	Likely	Very small	Medium	Very big
Intruding sealing material (sealing ring)	Displaced, not intruding	Likely	Very small	Small	Very big
	Hanging above horizontal centreline, not broken	Always	Small	Medium	Very big
	Hanging below horizontal centreline, not broken	Always	Small	Medium	Very big
	Broken	Always	Small	Medium	Very big
Displaced joint	Longitudinal	Likely	Very small	Small	Very big
	Radial	Likely	Very small	Medium	Very big
	Angular	Likely	Very small	Medium	Very big
Defective repair	Missing wall	Always	Small	Big	Very big
	Defective patch	Always	Small	Small	Very big
Other obstacles	Protruding through wall	Always	Small	Medium	Very big
	Wedged in joint	Always	Small	Medium	Very big
	External pipes or cabels	Always	Small	Big	Very big

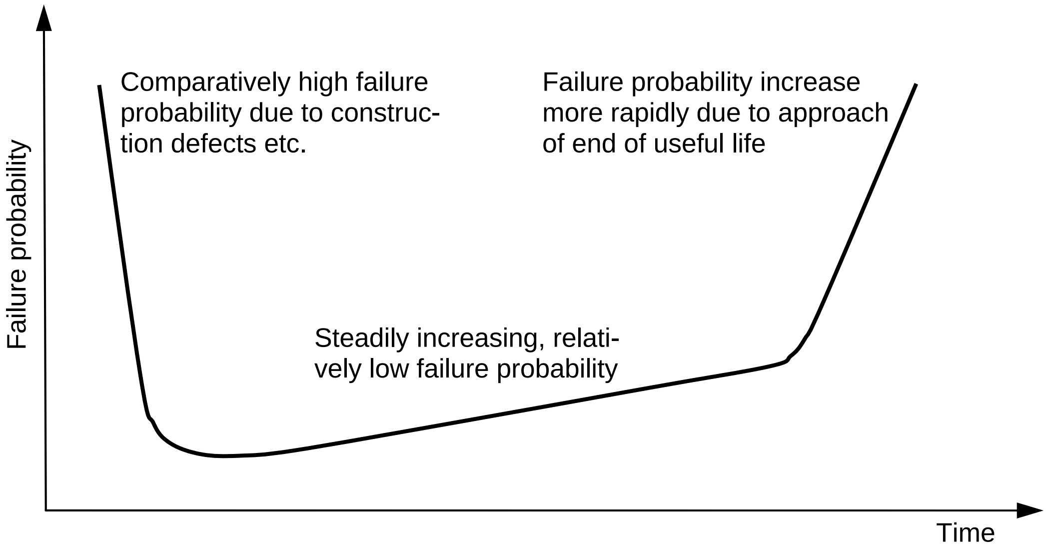


Figure 2-8. Bath tub curve (Davies et al., 2001a)

The causes of the deterioration of pipes are numerous and complex. A comprehensive overview is given in Stein (1998), Davies (2001) and HR Wallingford (2002). Factors which influence the deterioration process are specified in Table 2-7.

Table 2-7. Factors influencing the structural deterioration of sewers (Davies, 2001; Davies et al., 2001a)

Construction features	Local external features	Other factors
Installation method	Surface use	Sewage characteristics
Standard of workmanship	Surface loading	Inappropriate maintenance
Sewer size	Surface type	Investment history
Sewer depth	Traffic characteristics	Sewer age
Bedding arrangement	Water main burst/leakage	Sediment level
Sewer pipe material	Ground movement	Discharge
Joint type and material	Other utility maintenance	Presence of rodents
Pipe section length	Groundwater regime	
Connections	Infiltration/exfiltration	
	Soil/backfill type	
	Root interference	

The main reasons for untight sewers are poor standard of workmanship and construction errors, respectively (EPA, 1977; Stein, 1998; Bütow et al., 2001). These factors have influence on nearly all possible types of defects. Beside the use of defect components like concrete pipes with rock pockets, pipes with residual stress or damaged pipes the installation of the components is crucial. Especially pipe joints and house connections are vulnerable due to

- missing, displaced or damaged sealing rings
- wrong application of sealing materials
- non-centrical merge of pipes
- unstuffed headings
- supporting pipe sockets on bricks or blocks
- pried pipe walls for embedding house connections, not sealed and without saddle piece
- non-flexible joints between sewers and other assets.

Design errors include – beside the under-design for internal or external loads and wrong assumptions on the ground situation – the choice of inappropriate materials. The choice of materials for pipes and sealings is based on load, interactions of different materials (e.g. slip agents and elastomer sealings), sewage characteristics and soil properties. The existing material mix in a common sewer system has to be considered within the historical development of sewer technologies. A brief history of construction technologies is given in Stein (1998), Davies et al. (2001a), Bütow et al. (2001) and De Silva et al. (2001). A condensed overview about the development of pipes and sealings is shown in Figure 2-9.

Conceiving that old building technologies like butted joints, clay sealings or tar rings are not sufficient for the today's requirements, they are an important contributor for infiltration. E.g. Bütow et al. (2001) state that only joints of stoneware pipes built after mid of the 1950s and joints of concrete pipes built after the 1960s are sufficient and considered to be potentially tight due to changed joint and sealing types.

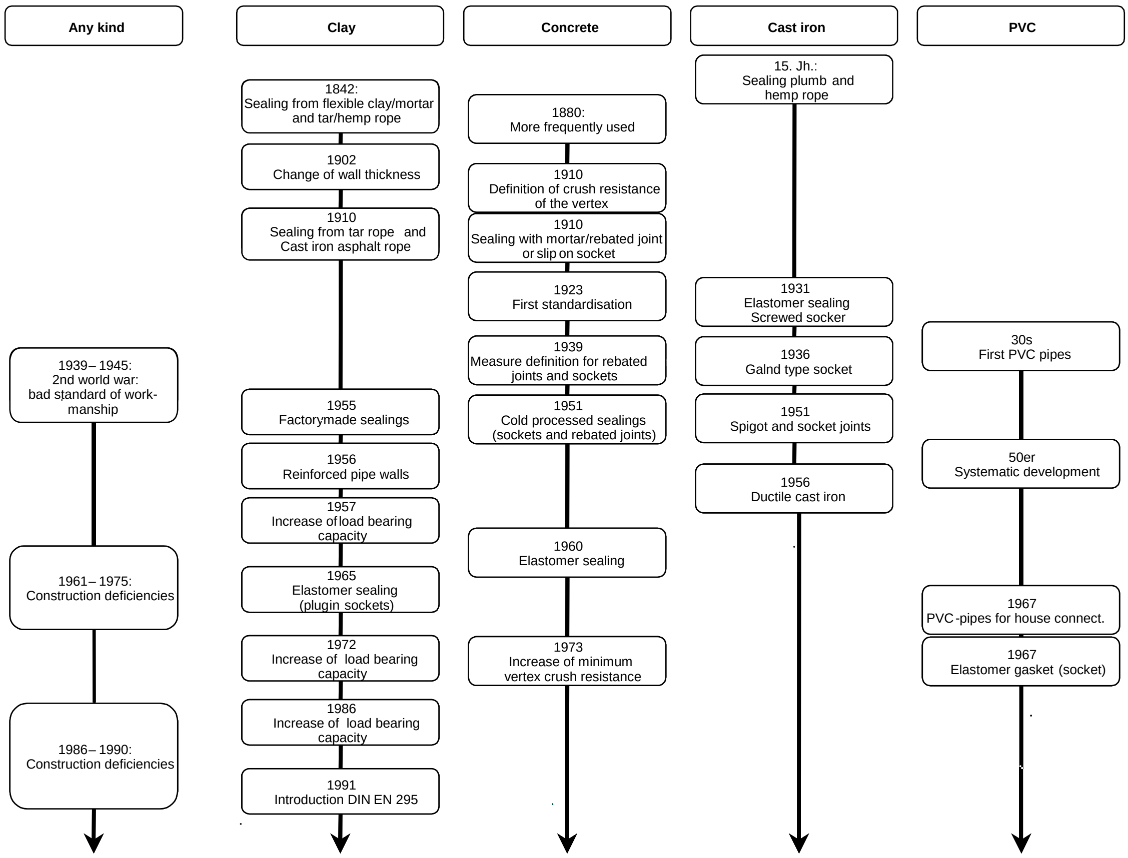


Figure 2-9. Historical development of sewer construction (Rutsch, 2006)

Other factors which cause indirectly the untighness of sewers are (Stein, 1998):

– root instrusion
– abrasion as a result of sediment transport, cavitation and use of inappropriate cleaning methods
– corrosion with and without mechanical exposure, pipe deformation.

Considering the factors which influence the structural state and the deterioration of pipes Davies et al. (2001a) draw the conclusions, that the factors are numerous and widely varied in nature and that detailed knowledge of the processes and the interactions of factors is relatively limited. Thus, statistical investigations of mechanical, chemical and biological processes are reasonable due to their complexity.

O'Reilly et al. (1989) analyse the distribution of defects in some 180 km sewer in southern England. The defects were identified with CCTV inspections. The results were 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 sewers are:

- Structural defects increase with increasing age.
- The number of faulty connections and joints do very slightly decrease with age.
- The highest defect rate was associated with vitrified clay pipes.
- The average fault rate increases with increasing pipe diameter.
- The number of structural defects decreases with smaller roads above the sewer.
- A very high incidence of defects in gardens was recorded.
- The average structural defect rate slightly decreases with increasing depth of sewers.
- Storm water sewers have a higher potential of structural deterioration.
- Structural defects increase with a rising number of connections per length unit.

Concerning the age it was shown, that sewers constructed since 1945 have a much lower rate of structural defects than older sewers. Sewers built before 1850 differ only marginally from those constructed between 1876 and 1917. The overall defect rate of vitrified clay pipes constructed before 1944 is two to three times higher than of those built in the post war period. Reasons are supposed to be the poorer quality of earlier clay pipes and the effects of new connections made to existing sewers; the number of connections and joints is much higher in older sewers. Furthermore, there is a decrease in defect number of concrete pipes built in the 1918-1944 period. The incidence of faulty connections to concrete pipes is higher than for clay pipes.

Davies (2001) uses a multivariate logistic regression model in order to investigate the relationship between 18 explanatory variables and the structural state of pipes. 10 factors were found to be statistically significant on a 5 % significance level:

- debris
- sewer pipe section length

- sewer size
- sewer use/purpose
- soil fracture potential
- soil corrosity
- sewer location
- groundwater regime
- sewer material
- bus flow.

Additionally, expert sewerage practitioners were interviewed. Combining the two methods the factors connections/sewer pipe length, sewer diameter/sewer size, sewer location/surface use and soil were found to be of above-average influence. But, it was not possible to pinpoint factors as being of outstanding importance.

Müller (2002) determines the relevance of influencing factors in evaluating the damage occurred within a reach. A very comprehensive data base was provided with four sewer systems and their complete data including CCTV inspections. All available factors were included in statistical ranking tests resulting in Table 2-8. The ranking is basically usable for house connection pipes, too.

Table 2-8. Relevance of factors influencing the structural state of pipes (Müller, 2002)

Factor	Relevance	Comments
Date of construction (age, standard of pipes, sealings and workmanship)	Very high	Investigated since 1940
Dimension	High	No statement for reaches with bigger diameters
Sewerage system (combined, storm, foul sewers)		
Depth of cover		Depending on conduit zone, cover depth less than 2 m
Soil		
Sewer material		
Traffic load	Low	Depending on conduit zone
Bedding arrangement		
Profile	No statement possible	
Groundwater level		
Catchment		

2.3.2 Inflow

The inflow of extraneous water originates from several sources and therefore from a number of processes. The sources are precipitation, floods, point surface water sources and groundwater. Beside wrongly discharged storm water due to cross-connected storm and foul water sewers or wrongly connected impervious areas the inflow of storm water over vents in manhole covers is relevant. Karpf and Krebs (2005) state for five separated sewer systems, that 18 % of the total annual I/I flow enter the system over manhole covers. Additionally, 10 % of the impervious area is connected to foul sewers influencing the runoff volume heavily and causing an overload of the waste water treatment plant (WWTP). For two separated sewer systems, Pecher (1998) estimates the fraction of the impervious area which is drained over manhole covers to 3 to 9 %.

Such inflow depends on the three-dimensional formation of the water body on the street, the location of the manhole and the configuration of the vents (Pfeiff, 1998). Kölsch (2000) developed a quantification model depending on rain intensity, number of manholes, vertical and horizontal location of manholes in the street, slope and cross slope of the street. The application of the model on a rural separated sewer system yields a 27 – 56 % fraction of inflow over manhole covers during rain events.

In flood-affected areas surface water can enter sewer systems over combined sewer overflows (CSO) or vents in flooded assets like storage tanks. Considering long time periods the contribution of this flow path is marginal (< 1 %), but during floods it can dominate the total I/I flow (Karpf et al., acc.).

Extraneous water from point sources like anthropogenic (e.g. cooling water) and natural surface water (e.g. spring water) is simply discharged into sewers. The groundwater borne inflow over drainages connected to sewers is equivalent to infiltration except the fact that drainage pipes are intentionally leaking.

2.4 Quantity and variability

2.4.1 Quantity

Infiltration/inflow is characterised by strong variations in space and time. Most study results and statistical inquiries about I/I are aggregated and describe average situations, only. Due to different measurands and used methods the results are not directly comparable. Furthermore, inquiries based on operator's self-monitoring – a main data source – tend to result in smaller values than real ones (Fuchs et al., 2003; Brombach, 2002). Therefore, detailed I/I investigations exist only for individual cases or specific conditions.

Ministerium für Landwirtschaft, Naturschutz und Umwelt (2005) states, that one fifth of the waste water treated in Germany is extraneous water. Michalska and Pecher (2000) estimate the mean I/I flow in Germany to 2.3 L/(s·km). Statistical inquiries on the level of the German federal states give results from 0 % to 100 % of the mean surcharge to foul water flow (Figure 2-10). However, the smaller values have to be questioned. Weiss et al. (2002) quantify for 34 combined sewer systems a mean I/I share of 35 % compared with 35 % storm water and 30 % foul water volume. Jardin (2004) determines a mean partitioning of 45 % I/I, 23 % storm water and 32 % foul water volume for the sewer systems of the Ruhrverband. Lucas (2003) estimates the mean surcharge to foul water flow in Baden–Württemberg to 119 % for the year 1998. For the same year, Pecher (2003) determines a mean dwf of 306 L/(P·d) for 807 municipal WWTPs in North-Rhine Westphalia. Assuming a specific water consumption of 125 L/(P·d) this is equivalent to 145 % surcharge to foul water flow. The maximum dwf values of this study exceed 1,000 L/(P·d). For the year 2000, inquiries of 1,461 municipal WWTPs in Germany show a mean value of fraction of dwf from 0 % to 90 %, whereas 90 % of the WWTPs have a fraction of less than 50 % (ATV-DVWK, 2003).

Beside these aggregated data there are a lot of data about individual catchments, e.g. Lucas (2003), Weiss et al. (2002), Jütting (2000), Michalska and Pecher (2000), Ernst (2003) or Karpf (2002). To demonstrate the variety of single cases, specific I/I rates with their standard deviations of several German cities are shown in Figure 2-11. The data based on the DWA exchange of experiences for large cities indicate specific I/I discharge rates ranging from 0.005 L/(s·ha_{red}) to 1.0 L/(s·ha_{red}), i.e. a ratio of 1÷200.

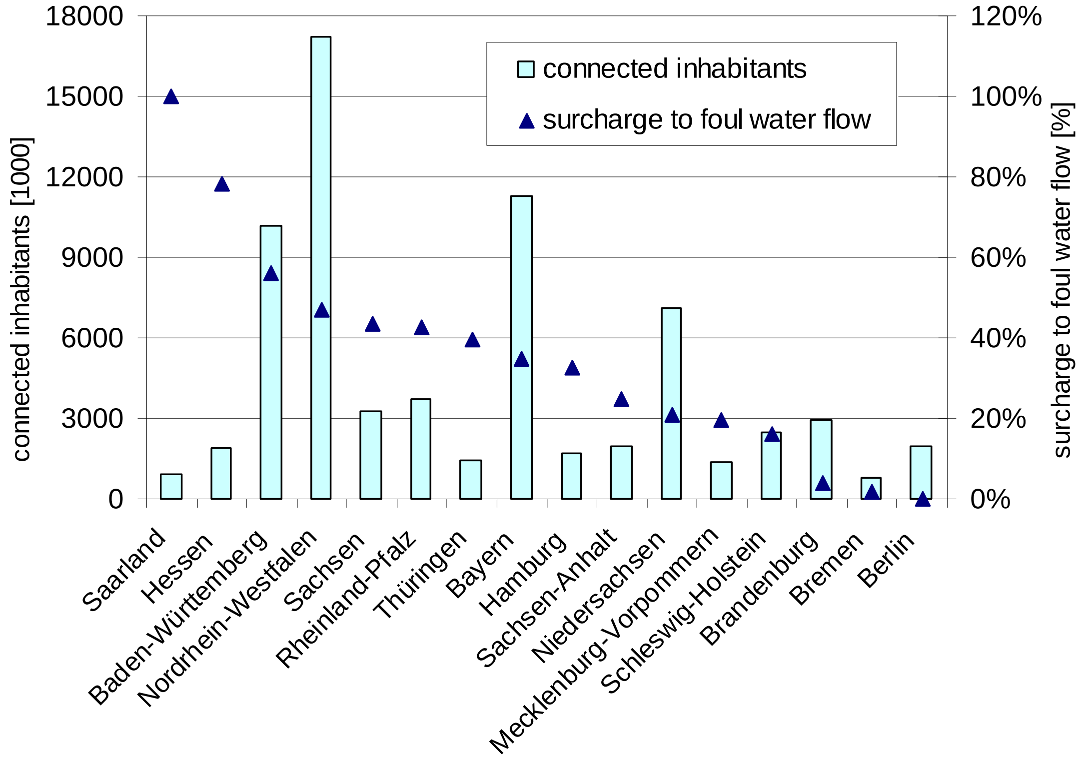


Figure 2-10. Extraneous water as surcharge to foul water flow, itemised for the German federal states (based on values given in Statistisches Bundesamt, 2001)

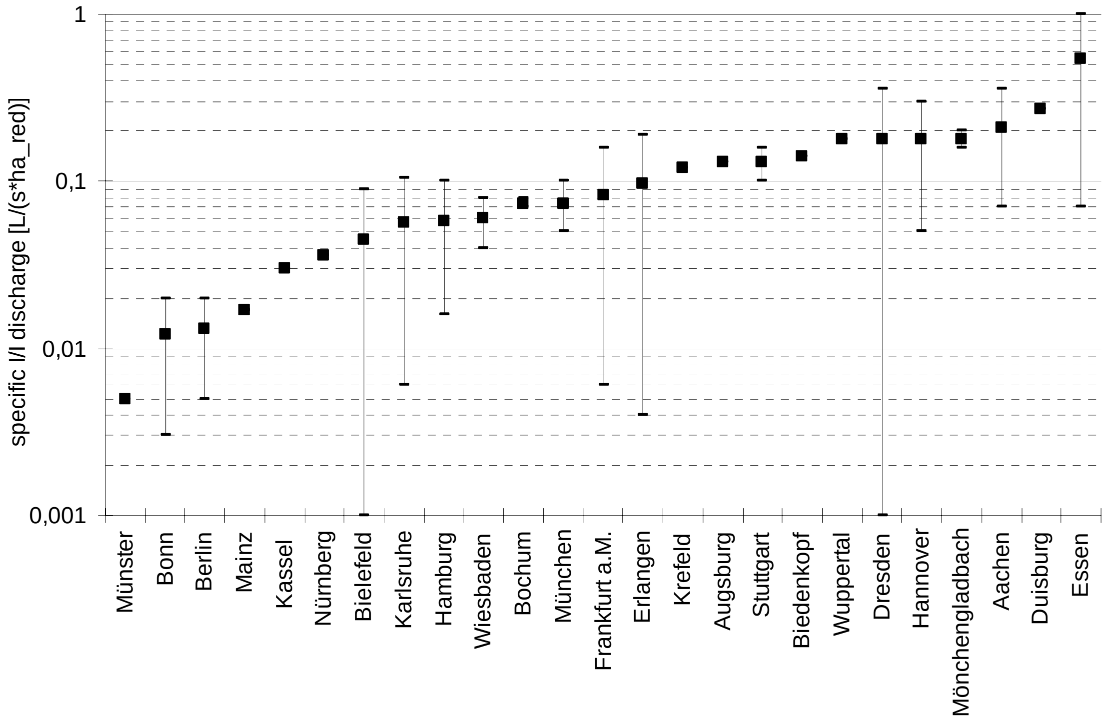


Figure 2-11. Specific I/I rates with standard deviations of German cities (adopted from Hennerkes, 2006)

On an international level, Decker (1998) estimates the extraneous water flow in foul water sewers in the USA to 1 L/(s·km). In the UK infiltration rates range between 15 % to 50 % fraction of dwf (White et al., 1997) or 10 % to 20 % fraction of total wet weather flow (Heywood and Lumbers, 1997). Gujer (2002) estimates the mean surcharge to foul water flow in Switzerland to 47 %.

A complete reduction of I/I is not possible due to technical and financial reasons. The determination of an acceptable I/I rate is very difficult due to different boundary conditions. In Germany, regulations which determine such rates are based on the Waste Water Charges Act. In several federal states only sewer systems with a mean fraction of dwf of 25 % to 50 % are exempted from financial punishment. Detailed information is given e.g. in ATV-DVWK (2003) or Hennerkes (2006). On a European level DIN EN 752-4 (DIN, 1997a) states, that the design of sewers should take into account extraneous water until a limit which justifies rehabilitation. But, this limit is not defined. The EU Wastewater directive 91/271 (EU, 1991) demands, that the design, construction and maintenance of collecting systems shall be undertaken in accordance with the best technical knowledge not entailing excessive costs, notably regarding the volume and characteristics of urban waste water and the prevention of leaks.

Indicators for increased I/I rates which are derived from technical regulations are given by Hennerkes (2006) and displayed in Table 2-9.

Table 2-9. Indicators for increased I/I rates (Hennerkes, 2006)

	Reference	Indicator
Germany	Fischer (1990)	$F_{I/I} > 50$ %
	Sitzmann (2000)	$q_{I/I} > 0.15$ L/(s·ha$_{red}$)
	Schmidt (2000)	$q_{dwf} > 240$ L/(P·d)
	ATV-DVWK (2004)	Storage tanks: increased hydraulic load – overflow days ≥ 30 a^{-1} – overflow time ≥ 150 – 300 h/a – emptying time ≥ 24 h WWTPs: increased hydraulic load and decreased inflow concentrations of pollutants – $F_{I/I} > 50$ % – $q_{dwf} > 300$ L/(P·d) – $c_{COD} < 400$ mg/L – $c_{NH4\text{-}N} < 35$ mg/L – $c_P < 6$ mg/L – $c_{NO3\text{-}N} > 5$ mg/L
Other countries	EPA (1991)/USA	$q_{dwf} > 240$ L/(P·d) as 7d- to 14d-mean $q > 1{,}000$ L/(P·d) during rain events
	infraguide (2005)/Canada	$q_{infiltration} > 500$ L/(d·mm$_{diameter}$·km$_{sewer}$) $q_{inflow} > 1000$ L/(P·d)

2.4.2 Spatial variability

The values given in chapter 2.4.1 demonstrate the supra-regional spatial variability of I/I. The reasons for this variability are different boundary conditions which are described in chapter 2.3. But, it is not evident whether the dominating factors among them are of natural/regional or of artificial/local nature.

Based on statistical investigations of sewerage systems in Baden-Württemberg, Lucas (2004a) states that there are no relations between I/I rates measured at WWTPs and the size of the sewer system, the size of the WWTP or the number of connected inhabitants (compare Figure 2-10). Similar results are given by ATV-DVWK (2003). Assuming that I/I processes are ubiquitous this result is comprehensible. Furthermore, Brombach (2000) shows, that there is no relation between I/I classes and the population density.

Based on the intersection of geological data and I/I measurements, Lucas and Fuchs (2003) trace back I/I classes mainly to the particular hydrogeological situation. Therefore, the regional spatial variability of I/I should be dominated by landforms. But, artificial factors can behave like natural or regional ones, too. An example is the distribution of combined and separated sewer systems within Germany, which appears to correlate with the I/I distribution (Figure 2-12). Assuming a comparable distribution of leakages and a similar groundwater table – which is indeed not likely for the whole country – the I/I contribution of combined sewers are larger than those of separated ones due to the deeper position, i.e. a higher water head, the greater dimensions, the higher probability of illegal connections and the lower problem awareness by the operator. Thus, a multitude of natural and artificial factors seems to be responsible for the regional variability of I/I. This conclusion is supported by the results of chapter 2.3.1.4 and by ATV-DVWK (2003).

Within catchments the same variety of mechanisms occurs. Thus, I/I rates can differ enormously even in a small scale. Figure 2-13 shows an example of 14 dwf measuring points within a separated sewer system with a size of 130,000 PE. Consequently, a homogeneous distribution of I/I in a catchment can never be assumed (ATV-DVWK, 2003).

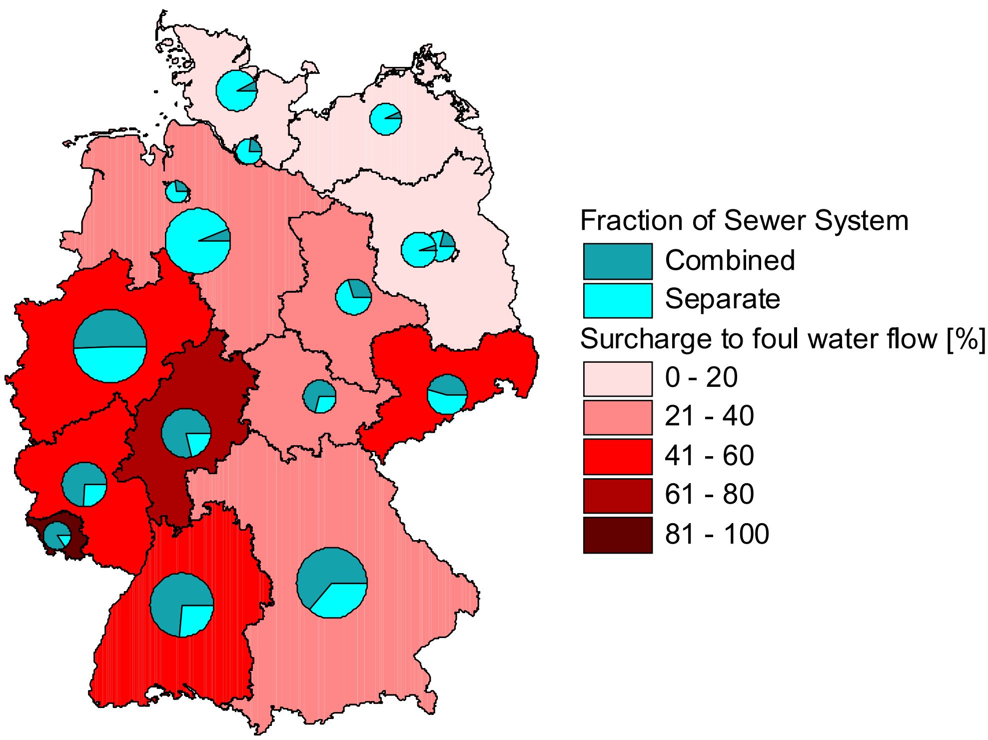


Figure 2-12. Distribution of I/I rates and fractions of sewer systems, itemised for the German federal states (based on values given in Statistisches Bundesamt, 2001)

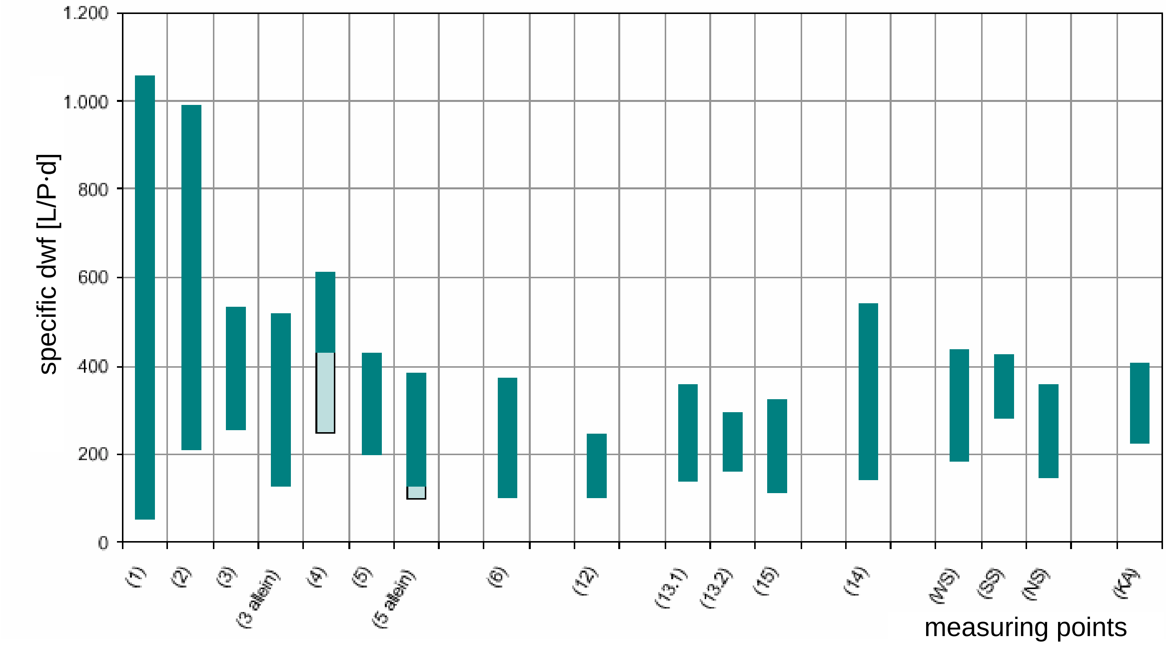


Figure 2-13. Range of specific dwf in several sub-catchments of a large German city (Pecher, 2001)

2.4.3 Temporal variability

Due to the temporal variability of the sources of extraneous water the I/I flow varies over time. Thereby, the ratio of minimal and maximal values can exceed several orders of magnitude. E.g. Lucas (2004a) reports for a WWTP in Baden–Württemberg a ratio of 1÷10 between mean summer and winter values of surcharge to foul water flow. Considering smaller timesteps, the ratio is even higher.

The variability occurs on different time scales. Yearly periods with high I/I flows in winter time and low I/I flows in summer time are a result of the varying groundwater table and the underlying recharge processes (chapter 2.3.1.2). A typical example is shown in Figure 2-14. The periods differ from each other due to the particular hydrological situation whose effect is shown in Figure 2-15. The deviation of the annual precipitation from the long lasting mean is compared with the deviation of the numbers of WWTPs belonging to three $F_{I/I}$ classes from the mean of the hydrologically moderate years 1998-2000. With a rising annual precipitation the fraction of WWTPs with a high fraction of dwf increases, too.

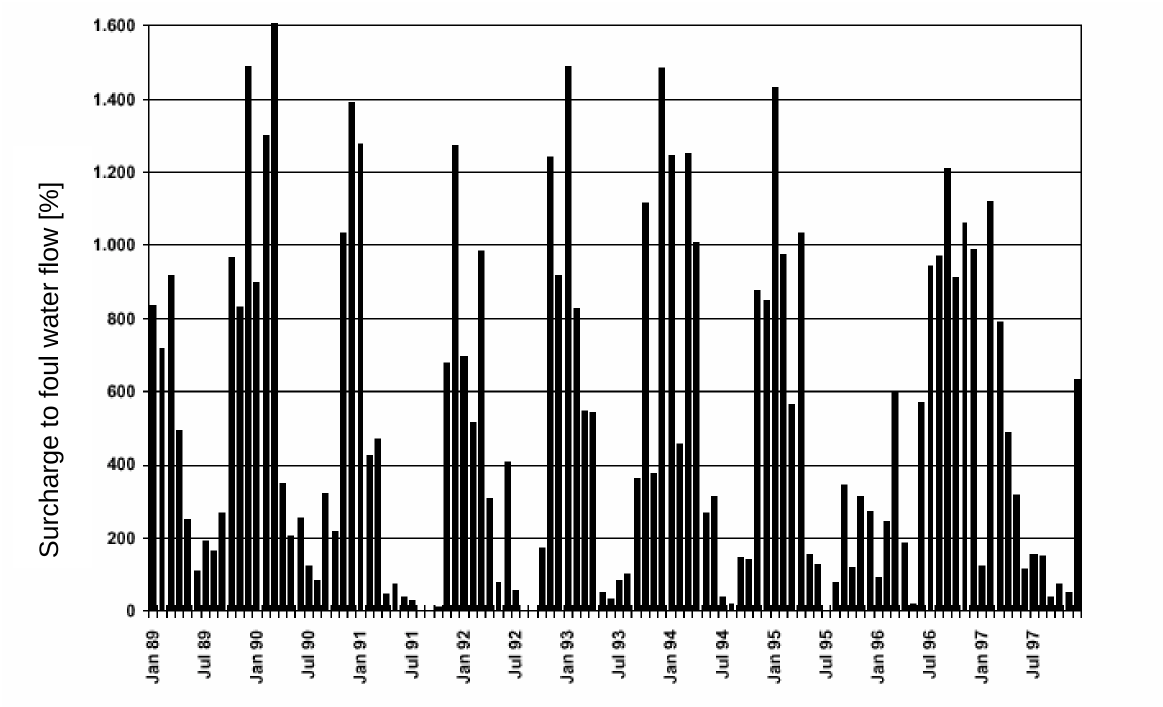


Figure 2-14. Monthly $S_{I/I}$-values of a combined sewer system in North-Rhine Westphalia (Pecher, 2001)

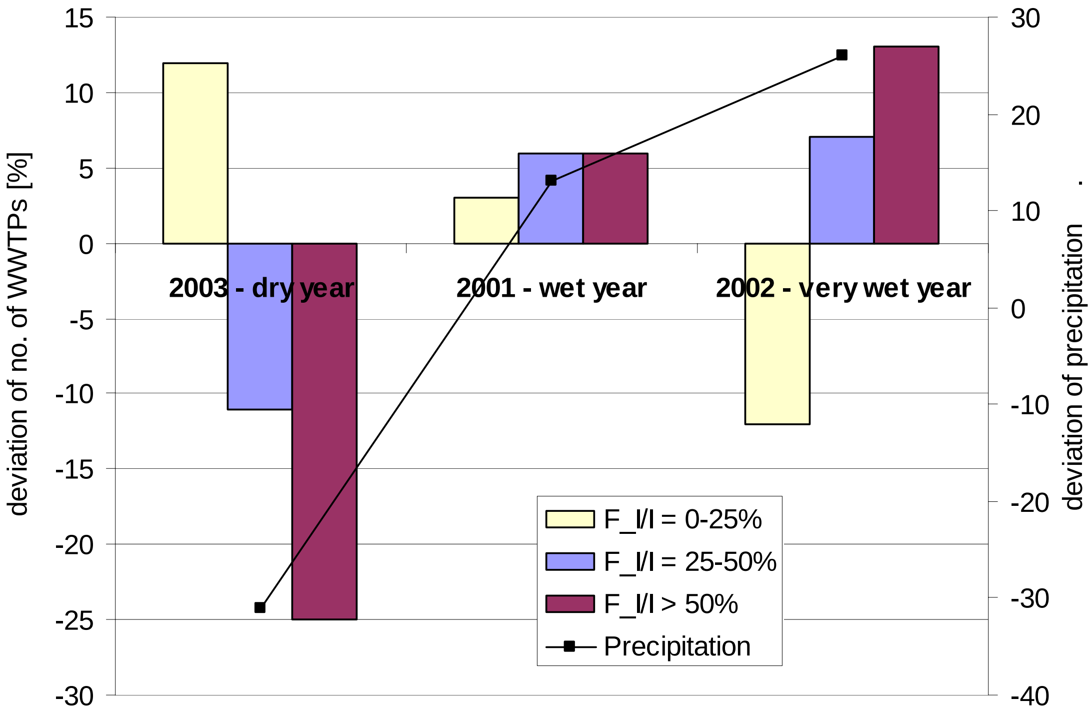


Figure 2-15. Relation between precipitation and $F_{I/I}$ at municipal WWTPs (adopted from Hennerkes, 2006)

Due to the interaction between groundwater and surface waters the I/I flow is influenced by fluctuations of the river discharge and floods. Such correlations were observed e.g. by Zimmermann (1997) for the Elbe river and Eisener (2002) for the Leine river, both in Germany. But, it has to be considered that high ground water recharge rates occur at the same time as winter floods. Thus, the river body and the aquifer must be directly connected to use such correlations.

In a short-term run, rain events influence the I/I flow over direct discharge or intensity-related I/I. The influence of the latter can last much longer than the surface runoff since the groundwater table reacts more slowly on the rainfall. Figure 2-16 shows a typical example for a rain-affected WWTP inflow. After wet weather periods, the inflow is increased for several weeks due to I/I.

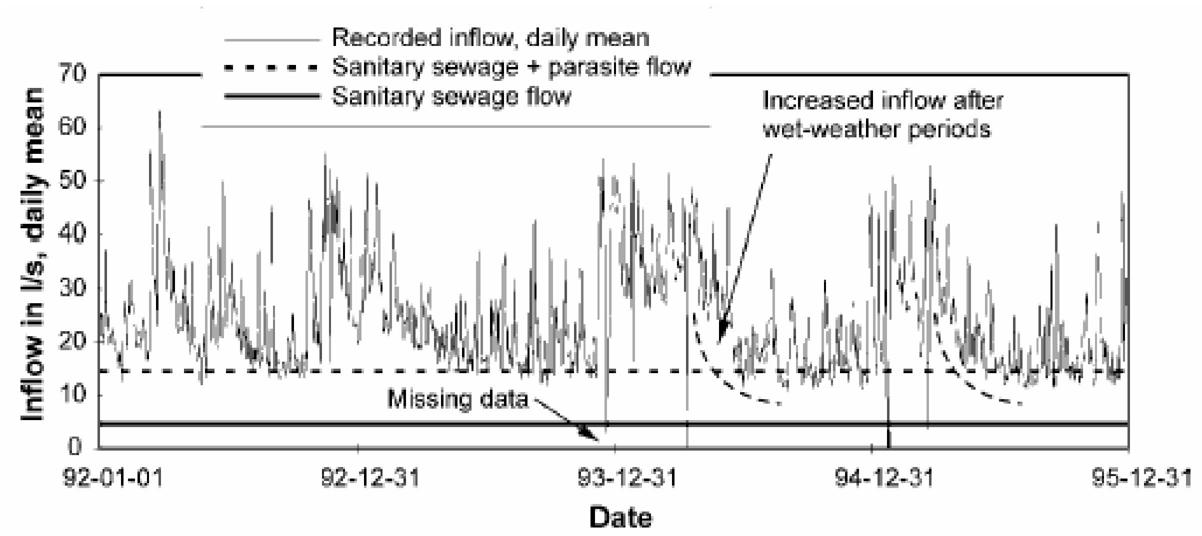


Figure 2-16. Rain-affected WWTP inflow (Weiss et al., 2002)

2.5 Impacts on the urban water system

2.5.1 General remarks

Infiltration/inflow increases the quantity and changes the quality of the waste water flow. For this reason, it influences both negatively and positively the functionality of nearly all sewerage assets and consequentially their dimensioning and operation. The occurence of I/I can change the structural stability of buried assets. Therefore, extraneous water has major operational and financial consequences for the operator and is a decision factor for the development of maintenance strategies.

I/I influences directly the groundwater table due to drainage (chapter 2.3.1.2) and indirectly surface and receiving water, respectively, over the leakages and junctions between the sewerage system and the surrounding environment.

A very comprehensive analysis of the effects of extraneous water can be found in Decker (1998).

Measures for the reduction of I/I are basically the restoration of water tightness of sewerage assets (Stein, 1998; Ministerium für Landwirtschaft, Naturschutz und Umwelt, 2005) and the decoupling of point sources. Thereby, the negative consequences of such a reduction like rising groundwater (chapter 2.3.1.2) or lower discharge in the sewer (chapter 2.5.2) must be considered and minimised e.g. with additional drainages or sewer flushing (Getta et al., 2004; Hennerkes, 2006).

2.5.2 Impacts on sewers

The main consequences of the additional discharge of water are a lessened transport and storage capacity and flushing effects. An insufficient transport capacity causes hydraulic overloads like backpressure, impoundage or activation of emergency overflows. Foul water sewers are especially vulnerable. Deposits in the sewers are possible due to permanent backpressure (Kauch, 1996). In combined sewers overloaded throttles cause more frequent and longer lasting overflow times (Brombach and Wöhrle, 1997).

A permanent full or partial filling of assets leads to a decreased storage capacity of the whole system for storm water and thus to higher overflow rates to the receiving water (Lucas, 2004b). Furthermore, connections of additional areas to the sewer system are limited.

Overloaded pumping stations can cause the discharge of untreated waste water into the receiving water, too. Furthermore, they have an increased energy consumption and a lower lifetime expectancy due to the higher number of switching operations (Flögl, 1987).

Normally, I/I involves a soil shift from the conduit zone into the sewer. Beside the loss of load support (chapter 2.3.1.3) this shift promotes the occurence of deposits as well as abrasion due to deposit transport.

Extraneous water has a higher oxygen and nitrate content than foul water. Thus, it leads to pre-degradation of easy-degradable organic substances and reduces the risk of biogenous sulphuric acid corrosion. The stronger flushing supports this reduction due to sediment transport (Michalska and Pecher, 2000). But, structural deterioration of pipes can be forced by corrosion due to lime-aggressive extraneous water (Decker, 1998).

Sewers must be dimensioned larger due to the higher discharge. In Germany, ATV-A 118 recommends measurements or the use of measurements in comparable sub-catchments to determine the I/I flow. Apart from this, either a surcharge to foul water flow of 100 % or an area-specific I/I rate $q_{I/I}$ = 0.05 to 0.15 L/(s·ha) is assumed. On a European level DIN EN 752-4 states only, that the design of sewers should take into account extraneous water.

2.5.3 Impacts on waste water treatment plants

The main consequences of I/I are hydraulic overload and dilution of foul water. The hydraulic overload reduces the efficiency of mechanical treatment assets like racks, grit chambers, primary and secondary clarifiers as well as the transport capacity of pipes. If quantity fluctuations caused by I/I are not considered, then problems could occur with waste water distribution and aeration (Kroiss and Prendl, 1996). Furthermore, the residence time of the waste water at the whole plant is decreased.

Extraneous water has got changed physical and chemical properties compared to foul water. It

- is colder
- has a higher oxygen content
- can have an increased nitrate content and lower pH values depending on the origin
- has lower concentrations of substances relevant for waste water treatment.

Extraneous water causes a reduced activity of activated sludge due to lower temperatures. The content of easy-degradable organic substances is decreased due to pre-degradation in the sewer system. Thus, organic acids are less available and problems during the enhanced waste water treatment, i.e. denitrification and biological phosphorus removal, can occur. Lower pH values caused by I/I can inhibit the biological treatment (Kroiss and Prendl, 1996). Furthermore, I/I decreases the efficiency of chemical phophorus removal (Hostettler, 2003).

The dilution of foul water results in a declined efficiency of the WWTP. Thus, load-based effluent thresholds can be exceeded. In cases of concentration-based tresholds, a dilution acts positively. This effect is especially important for catchments with a very low water consumption. In those catchments the foul water concentrations are very high and even with a highly efficient treatment concentration-based thresholds are easily exceeded.

Other positive effects of I/I are the damping of concentration peaks, a buffering of low pH values in case of hard extraneous water and the smaller fraction of organic matter in the sand removed in the grit chamber (Kroiss and Prendl, 1996).

The asset dimensioning based on hydraulics must be adapted to the higher discharge and the shorter residence times caused by I/I. This is relevant especially for pipes, pumps and mechanical treatment. A potential temperature decrease due to I/I can be neglected, thus only dilution is relevant for the dimensioning of biological treatment assets. Depending on the treatment objectives, tank volumes decrease with concentration-based and increase with load-based thresholds (Kroiss and Prendl, 1996). For the enhanced treatment a volume adaptation is not necessary. Further details are given in Decker (1998) and Hennerkes (2006).

2.5.4 Impacts on the receiving waters

The discharges from sewerage systems via CSOs, storm sewer outlets and WWTPs influence directly the water quality and the structural state of receiving waters. Due to lower concentrations and higher discharge rates both caused by I/I acute chemical impacts are reduced, acute hydraulic impacts are increased. The hydraulic stress can lead to sediment shifts and population losses, which affect the ecological integrity of the receiving water ecosystem (Borchardt and

Sperling, 1997). Additionally, increase of turbidity and remobilisation of pollutants accumulated in the sediment are possible. Thereby, oxygen depletion and a change of the biocenosis may be induced.

In a mid- and long-term run, a load increase can damage the receiving water due to accumulation of persitent pollutants. A condensed overview of the impacts of extraneous water on receiving waters is given in Table 2-10.

Table 2-10. Impacts of I/I on receiving waters (Decker, 1998)

Factor	I/I effects	River Section	Impacts
Chemical	Dilution, concentration decrease, load increase	Rhitral	– Acute impacts due to pollutants, nutrients and toxins decreases – Oxygen demand increases or decreases
		Potamal	– Mid- and long-term impacts due to accumulation increases – Oxygen demand decreases
Physical	Discharge increase	Rhitral	– Hydraulic stress and oxygen demand increase – Physical aeration can be increased – Erosion, sediment shift and population loss is possible
		Potamal	– Physical aeration remains stable – Erosion, sediment shift and population loss is possible – During erosion increase of turbidity and decrease of biogenous aeration – Remobilisation of sediments

2.5.5 Financial consequences

Resulting from the impacts mentioned above, I/I causes additional costs both capital and operational. Exemplarily, Decker (1998) calculates for a sewerage system with 100,000 P a 15 % increase of investment costs and a 7 % increase of operating cost due to a triplication of I/I flow. The fundamental financial consequences of I/I are shown in Table 2-11.

Table 2-11. Financial consequences of I/I (Michalska and Pecher, 2000)

Asset		Investment costs		Operating costs
Sewers				
Foul water	+	Larger dimension if $S_{I/I} > 100$ %	-	Flushing effects, esp. in upstream reaches
Storm water	o		o	
Combined water	o		-	Flushing effects, esp. due to high discharges
Pumping stations				
Foul water	+	Larger capacity if $S_{I/I} > 100$ %	++	Operating costs linearly correlated to $S_{I/I}$
Storm water	(+)	continuous operation of pumps if low I/I discharge during dwf	++	High operating costs at permanent I/I
Combined water, throttled	++	Necessary capacity linearly correlated to $S_{I/I}$	++	Operating costs correlated to $Q_{I/I}$
Combined water, not throttled	+	Larger capacity for dwf pumps	++	Operating costs correlated to $Q_{I/I}$
Storm water tanks				
Rain storage tank	o		o	
Rain spillway tank	++	Necessary volume linearly correlated to $S_{I/I}$	o	
WWTPs				
Hydraulics	++	Necessary capacity linearly correlated to $S_{I/I}$	++	Operating costs correlated to $Q_{I/I}$
Pollutants	--	Necessary volume smaller with concentration-based thresholds	--	Lower operating costs due to dilution
	++	Necessary volume larger with load-based thresholds	++	Higher operating costs due to worse efficieny

- cost decrease
o normally no effects
\+ cost increase

2.6 Estimation methods

2.6.1 General principles

The estimation of I/I flow is difficult and relatively uncertain. Extraneous water cannot be measured directly due to its mixing with other waste water components inside the sewer. Exceptions are several point sources like spring and cooling water or building sites drainages.

Usual measurement methods determine the characteristics, i.e. discharge or pollutant concentrations, of the waste water components and the resulting total flow (Figure 2-17). The amount of I/I is then estimated by difference and dilution calculations, respectively.

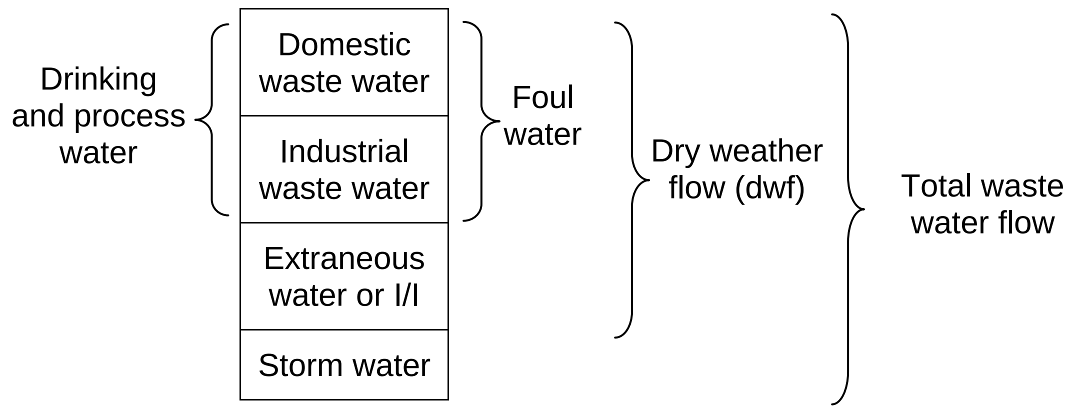


Figure 2-17. Components of the total waste water flow, schematical

Point permanent sources of extraneous water should be normally known. Their discharge can be measured outside the sewer system. A simple quantification of the storm water flow as a result of overland flow (direct discharge) is not possible due to the number of relevant processes and influencing factors of the rain-runoff-process. Only complex modelling techniques are able to quantify this component (chapter 2.7). Therefore, the measuring of infiltration is generally restricted to dwf conditions, where rain-derived water has not to be considered. For the special case of storm water in foul water sewers this component has to be estimated additionally, e.g. by distinguishing dry and wet weather periods.

The determination of dry weather days is difficult due to the interflow or intensity-related I/I. This component can be observed a certain time-span after rain events (Figure 2-16). The recession gradient of interflow varies strongly due to individual hydrogeological conditions. Thus, the determination of the resulting regressing interflow time is subjective and a higher base flow can be interpreted as interflow and vice versa (Landesamt für Umweltschutz Baden-Württemberg, 2001).

An important source of information about dry weather days and regressing interflow time are operational journals of WWTPs. However, the possibility of a wrong interpretation is given. Therefore, these records require a critical evaluation. ATV-DVWK (2003) describes an alternative graphic method: The minimum daily values of a hydrograph are connected by a polyline. This line is increased by 20 %. All days whose values lie below the increased curve are considered as dry weather days. The resolution of the hydrograph has an influence on the shape of the resulting polyline and the result. Wittenberg and Brombach (2002), Vaes et al. (2005) and Karpf et al. (acc.) propose more sophisticated filter methods to separate I/I components from each other.

During dwf conditions, I/I is in principle equal to the difference between the measured total flow and the calculated foul water flow. Considering time-depended variations, the foul water flow can be determined by means of

- the mean discharge of foul water based on the annual drinking and process water consumption
- the mean discharge of foul water depending on the catchment size (Hager et al., 1985)
- the number of inhabitants and reference values of inhabitant-specific sewage discharge
- the estimation of a residual night flow based on the catchment characteristics or waste water flow measurements in low water periods (Fischer, 1990; Renault, 1983)
- continuous or daily measurements of pollutants concentration and reference values of inhabitant-specific pollutant discharges (Renault, 1983).

The optimal point in time for measurements depends on the considered I/I sources (Table 2-12).

Table 2-12. Optimal point in time for I/I measurements (Hennerkes, 2006)

Boundary conditions	Optimal point in time for measuring		
	Rain derived I/I	Groundwater derived I/I	Total I/I
Dry weather flow		X	
Wet weather flow (foul water sewers only)	X		X
High gw table in summer	X		
Low gw table in winter		X	X

Two types of I/I measuring methods in public sewers can be distinguished: on the one hand flow-based or statistical and on the other hand pollutant-based or chemical methods (Table 2-13). Methods for measurements in house connections differ due to the small flows and the lack of access.

With flow measurements and knowledge about drinking and process water consumption and foul water production, respectively, the single waste water components can be balanced over a certain time period. Furthermore, I/I can be measured more or less directly during flow conditions where components can be neglected.

Pollutant-based methods assume that the pollutant load transported by I/I is neglectable. Thus, I/I causes a decrease of the pollutant concentration in the total waste water flow due to dilution. The I/I rate can be determined by calculating this dilution based on simultaneously flow and pollutant measurements. Appropriate substances are

- easy to measure (particularly direct measurements with on-line sensors)
- to a large extent persistent
- absent or in a very low concentration into extraneous and drinking water
- not influenced by industry.

Considering those criteria possible substances are the chemical and the biological oxygen demand, ammonium, the total organic and dissolved carbon and salts like Chloride or Borate. Further potential tracers are given in Ellis (2001). Usually, the chemical oxygen demand (COD) and ammonium are used.

Selecting appropriate measuring points within a sewer system, some restrictions have to be considered for successful and reliable measurements (Bosseler and Cremer, 2001; Ministerium für Landwirtschaft, Naturschutz und Umwelt, 2005). Measuring points must not be influenced by assets that change the flow characteristics like pumping stations or drop structures. The requirements of the measurement devices like proper slope have to be met. The safe accessibility of sewers must be guaranteed.

Furthermore, there are qualitative methods. With visual inspections it can be determined whether and in which order of magnitude extraneous water occurs. Additional knowledge can be gained by comparing and overlaying groundwater, rain and waste water time series. Several approaches are described in Liersch (1985) and Eisener (2002).

A comprehensive overview of measuring methods can be found in De Bénéditis (2004) and Uibrig et al. (2002). Ministerium für Landwirtschaft, Naturschutz und Umwelt (2005) provides guidelines for measurements under various conditions. In the following chapters, the most important methods are shortly described and discussed.

Table 2-13. Measuring methods for I/I (adapted from Uibrig et al., 2002)

Quantitative methods	Flow-based	Balancing by means of drinking and process water consumption and waste water production – Annual balance – Daily balancing – Triangle method Analysis of time series/hydrographs – Minimum night flow – Moving minimum
	Pollutant-based	Dilution of foul water specific substances – Swiss method – Time series of pollutographs – Stable isotopes
	Model-based	Modelling of rain events
Qualitative methods		Visual inspections Tracer use Comparisons of time series

For localisation of single I/I sources and leakage detection, respectively, CCTV is mostly used. Non-visual methods are e.g. hydrochemical probes (Held, 2003), electromagnetic and acoustic detection (Bosseler et al., 2003; Stein, 1998) and several other geophysical methods (Armbruster et al., 1992; Dohmann, 1999). The flow paths of extraneous water especially caused by overland flow and drainages can be investigated with tracers (colouring, salt) which are added to potential inflow sources and measured in sewers. Reversely, wrong connections can be found with fog released in sewers.

2.6.2 Flow-based methods

2.6.2.1 Annual balance

A balance for the system water supply and sewage disposal on an annual base is given with the following equation (Bundesamt für Umweltschutz, 1984):

$$V_{I/I} = V_{dwf} - \left(V_{drinkwater} - V_{drinkwater,export} - V_{drinkwater,loss} - V_{drinkwater,useloss} \pm V_{drinkwater,storage}\right) + V_{wastewater,loss} \qquad \text{Equation 2-3}$$

with $V_{I/I}$ I/I volume
V_{dwf} total dry weather flow volume
$V_{drinkwater}$ drinking water volume
$V_{drinkwater,export}$ exported drinking water volume
$V_{drinkwater,loss}$ drinking water loss volume
$V_{drinkwater,useloss}$ drinking water loss volume during purification
$V_{drinkwater,storage}$ stored drinking water volume
$V_{wastewater,loss}$ waste water loss volume

It is essential for applying the method, that the spatiotemporal boundary conditions of the measurements are identical. Otherwise these boundaries have to be adapted. Data of the investigated area can be collected for several levels (whole catchment vs. sub-catchments, year vs. month). Thus, a higher resolution of I/I is possible. While determining the dry weather days the regressing interflow time has to be considered.

Due to the uncertainties within data like drinking water loss and exfiltration in sewers this method appears less exactly. Nevertheless, based on appropriate data a rough estimation of the annual I/I is possible. Advantageously, the estimation is done without any knowledge about inhabitant-specific water consumption.

Related methods are described in Hager et al. (1985) and Schmidt (2000).

2.6.2.2 Triangle method

The triangle method (Landesamt für Umweltschutz Baden-Württemberg, 2001; Brombach et al., 2003) is a graphical method based on daily measurements. The daily waste water volumes, e.g. the inflow volumes of a WWTP, are ranked and standardised to the maximum observed. The result is typically an s-shaped curve (Figure 2-18). It is assumed that high volumes occur during wet weather periods. Therefore, the number of days with storm runoff is protracted from the right side to the left.

The foul water flow is supposed to be constant; it is expressed by a horizontal line. Missing measurements can be recognized by values below this line. The area between the curve and the horizontal line represents the annual volume of both storm and extraneous water. To separate these two components, it is assumed that there is no regressing interflow at dry weather days and that I/I is reduced during rain weather periods because higher water levels in the sewers inhibit infiltration. The straight line which closes the triangle reproduces this conceptual approach.

The area between the foul water line, the daily volume curve and the straight line represents the annual volume of I/I. The area between the daily volume curve and the straight line represents the annual volume of storm water.

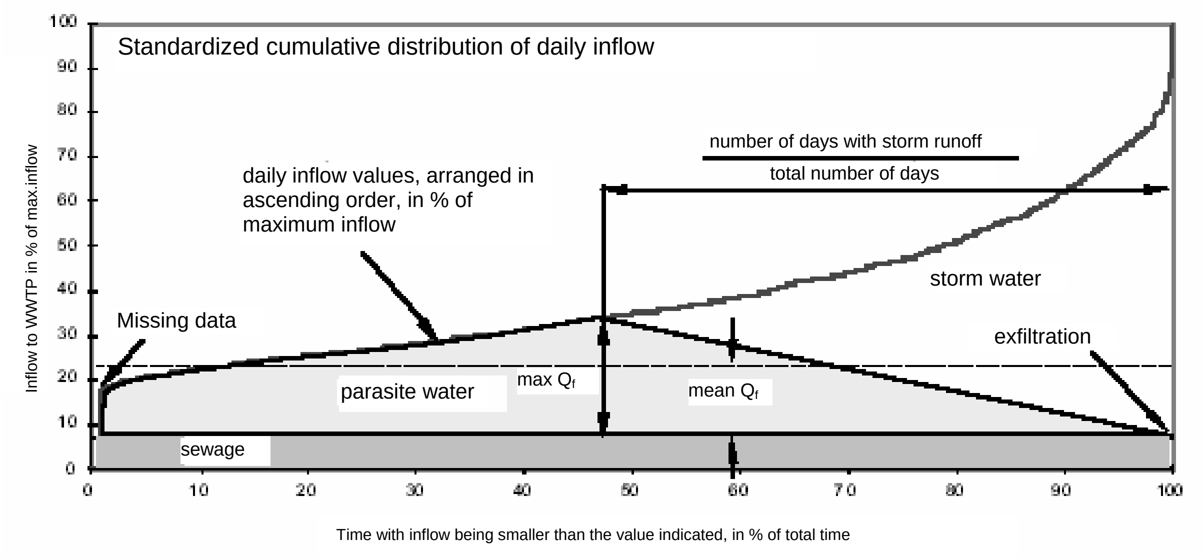


Figure 2-18. Triangle method (Brombach et al., 2003)

2.6.2.3 Minimum night flow

Due to the day-night-rhythm the minimum foul water flow is in principle very low and occurs at night. This discharge decreases with a decreasing catchment size and increasing slopes both causing a short flow time in the sewer system, as well as with no or weak influence of pumping stations and industrial discharges. Thus, the I/I rate is close to the total minimum night flow. Appropriate measurements should take place preferably between 2 and 4 a.m. and on weekends to avoid industrial influence (Hager et al., 1985). It is possible to measure I/I with a high temporal resolution. Thus, variations of the I/I rate can be identified.

Fischer (1990) determines the minimum night foul water flow depending on the catchment characteristics (Table 2-14). Alternatively, Renault (1983) gives a range of the fraction of foul water on the total minimum night flow as a function of simple catchment characteristics (Table 2-15). A comparative study about several approaches for quantifying the minimum night foul water flow can be found in Warnecke (1996).

Table 2-14. Specific minimum night foul water flow (Fischer, 1990)

Catchment		$q_{foul,min}$
Size [P]	**Other characterisitcs**	**[L/(s·1000 P)]**
< 5,000	Homogeneous, without flow time extending assets	0.3
5,000 – 100,000	-	0.5
> 100,000	Flow time > 10 h	1.0

Table 2-15. Fraction of foul water on the total minimum night flow (Renault, 1983)

Catchment size	Slope	Fraction of foul water [%]
Large	Flat	25 – 40
Small	Steep	15 – 25

2.6.2.4 Moving minimum

The method of the moving minimum (Weiss et al., 2002) is based on daily measurements, too. It is assumed that the dry weather flow is equal to the minimum total waste water flow observed during the past days. Thus, at least one dry weather day is supposed in the chosen period. The result is a step-shaped hydrograph (Figure 2-19). The foul water flow is assumed to be constant.

The lag time represents the response time of the system of increased I/I due to previous rain events. Thus, the lag filters storm water runoff and allows the isolation of foul water and infiltration components. Long term variations of I/I are traced back to base flow, short term variations with high gradients to interflow. Tests show, that a lag time of 21 days is a good compromise to exclude short-time surface runoff (ATV-DVWK, 2003). A shorter lag time leads to an overestimation of I/I.

The method has the advantage that wet and dry weather periods are likewise included and no arbitrary discrimination is necessary to select dry weather days as a reference. The determination of the temporal variation of I/I is possible due to the continuous estimation at daily scale.

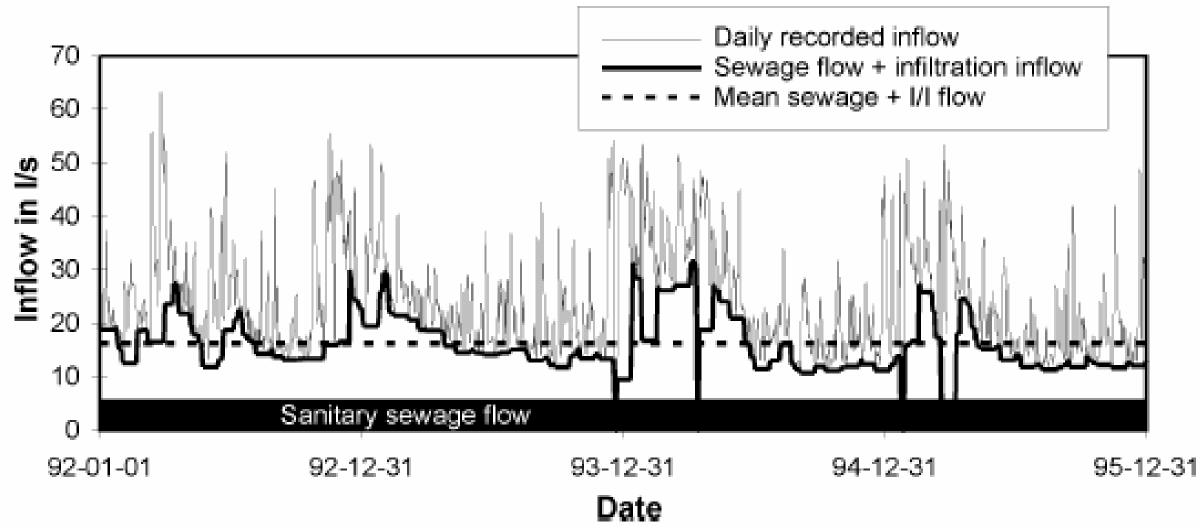


Figure 2-19. Moving minimum (Weiss et al., 2002)

2.6.2.5 Storm water in foul water sewers

Rain derived infiltration in foul water sewers is analysed by means of flow measurements during rain events with considering dry weather data (ATV-DVWK, 2003). With a comparison of hydrographs the fractions of interflow and overland flow can be separated. Thus, it is possible to calculate the area and – with a high spatial resolution of measurements – the location of wrong connected surfaces. It is essential to analyse a number of events to improve the quality of the results.

2.6.3 Pollutant-based methods

2.6.3.1 Swiss method

Hager et al. (1985) describe the following iterative approach to identify the fraction of dry weather flow based on grab samples and flow measurements:

$$F_{I/I} = \frac{Q_{min}}{Q_{mean}}\left(1 - \frac{c_{min} \cdot Q_{min}}{c_{mean} \cdot Q_{mean}}\left(\frac{Q_{mean}}{Q_{min}} - 1 + \frac{c_{min}}{c_{mean}}\right)\right)$$ Equation 2-4

with c_{mean} mean concentration

c_{min}	minimum concentration
Q_{mean}	mean total discharge
Q_{min}	minimum total discharge

The method assumes, that the I/I flow and its pollutant concentration are constant during the course of the day. The pollutograph is typically measured in 24 hours periods with a temporal resolution of 15 minutes. Variations of I/I can be quantified with measurements over a longer period. Advantageously, data about the inhabitant-specific substance load are not necessary for this method.

2.6.3.2 Time series of pollutographs

Kracht and Gujer (2005) introduced a method which avoids the assumption of constant measurement conditions. The infiltration is determined from a combined analysis of time series of COD concentrations and waste water flow. The basic requirement of this method is a very high temporal resolution of the measurements, e.g. 2 minutes.

I/I is separated in the components infiltration and intensity-related I/I and expressed with

$$Q_{I/I} = Q_{infiltration} + Q_{0,intensity\_I/I} \cdot e^{-k \cdot (t - t_0)} \qquad \text{Equation 2-5}$$

with

$Q_{infiltration}$	infiltration discharge
$Q_{0,intensity\_I/I}$	initial magnitude of intensity-related I/I at time t_0
k	recession constant
t	time

By means of measurements of the total waste water flow a time series for COD concentration can be modelled:

$$c_{COD,wastewater,model} = \frac{\left(Q_{wastewater} - Q_{I/I}\right) \cdot c_{COD,foulwater}}{Q_{wastewater}} \qquad \text{Equation 2-6}$$

with

$c_{COD,wastewater,model}$	modelled COD concentration
$c_{COD,foulwater}$	COD concentration of foul water
$Q_{wastewater}$	total waste water discharge

The parameter $c_{COD,foulwater}$ can be set to a constant value or expressed either as a polynomial function depending on foul water discharge or a frequency function depending on time of day in order to include diurnal variations of the foul water concentrations. By fitting the model to the measured time series, the unknown parameters of $Q_{I/I}$ can be estimated.

The method is very flexible and reflects the dynamics of infiltration processes. It considers natural storage and interflow processes and avoids the simplifications of other methods.

2.6.3.3 Stable isotopes

Single components of the total waste water flow could be discriminated with tracers, e.g. by labelling drinking water. However, the use of artificial tracers added to compartments of the urban water system is not possible due to environmental and legal concerns as well as practicalities. Kracht et al. (2005) show, that the stable isotopes composition of water can be used as a natural tracer.

Water is composed of several stable isotopes of oxygen and hydrogen. Transformations within the global water cycle cause a change of the isotopes composition due to different vapour pressures of the isotopes and diffusion processes. As clouds move across the land the heavy water molecules containing the isotopes ^{2}H and ^{18}O will rainout first. Thus, precipitations in coastal regions or at high altitudes (mountains) are isotopically heavier than those that rainout in inner continental regions or at lower altitudes.

If drinking and foul water, respectively, originates from a distant or higher hydrological system and the extraneous water originated from local precipitation the differences in the isotope ratios could be used to identify the fraction of infiltration with:

$$F_{I/I} = \frac{c_{wastewater} - c_{foulwater}}{c_{I/I} - c_{foulwater}} \qquad \text{Equation 2-7}$$

with $c_{wastewater}$ concentration in waste water
$c_{foulwater}$ concentration in foul water
$c_{I/I}$ concentration in I/I water

The basic requirement of this method is a significant difference in the isotopes composition of foul and infiltration water. It is necessary to identify the source of infiltration and to be able to describe the natural variations in its isotopic composition with sufficient precision. Variations in the supplied water should be low or quantifiable. Therefore, in cases with a neglectable I/I discharge it is possible to identify different drinking water sources like long-distance water supply and local wells.

2.6.4 Methods for house connections

I/I measurements in house connections are complicate due to changed boundary conditions compared to public sewers. Apart from the private character of house connections which causes access problems and limited knowledge about location and situation of the pipes, there are several technical differences to public sewers:

- smaller or zero flows
- smaller dimensions
- access possible only over revision openings or public sewers
- branching pipes without manholes or revision openings
- horizontal and vertical bends
- dimension changes within a pipe section.
- technical "obstacles" like back pressure flaps, lifting systems, separator, etc.

Especially access and small flows with a high variability are problematic. Thus, I/I measurements in house connections are practically restricted to flow-based and volumetric methods.

Flow and volume measurements are carried out over short time periods at revision openings or manholes connecting a few houses to public sewers. Foul water discharges can be avoided by blocking relevant installations. In case of very low discharges, the pipe can be blocked with balloons. Typically, infiltration is equivalent to the minimum night flow (Princ and Kohout, 2003).

Pressure tests and CCTV are suitable for qualitative assessments and for testing the tightness of house connections (Ballweg, 2002; Bosseler and Cremer, 2001).

2.6.5 Measurement Costs

APUSS (2004a) describes exemplarily costs for several measurement methods. The range of costs for pollutant-based methods and methods for house connections are given in Table 2-16. All estimated values, especially personnel expenditures, are values for prototype measurements due to the novel character of the methods. Cost reductions are expected, if such measurements are applied on a routine basis.

Flow measurements in sub-catchments are part of the operation of sewer systems. Thus, data collections for flow-based methods are side subsidised. Apart from this, APUSS (2004a) gives the following information for additional flow measurements:

- installation and demounting of a flow measuring unit: 525 EUR per site
- maintenance, readout and data analysis (14d-cycle): 850 EUR per month.

Flow measurements appear more beneficial than combined flow and pollutant ones. However, the gained information differs strongly between these method groups. Thus, statements about the cost-benefit ratio are not possible offhand.

Table 2-16. Range of costs for experiments, prototype measurements (APUSS, 2004a)

	Time series	**Stable isotopes**	**House connections**
Number of experiments/samples	1 / 20	1 / 44	2-3 / -
Measuring equipment	~ EUR 24,500 to 30,500	~ EUR 19,200	~ EUR 300 to 2,200[1]
Personnel expenditures[2]	~ 60 h to 110 h	~ 120 h	~ 80 h to 160 h
	~ EUR 1,500 to 2,750	~ EUR 3,000	~ EUR 2,000 to 4,000
Consumption costs	~ EUR 500 to 1,000	~ EUR 4,800	~ EUR 100 to 200
Costs per single experiment	~ EUR 2,000 to 3,300	~ EUR 7,800	~ EUR 2,200 to 4,100

[1]costs are calculated on rental base

[2]25 EUR / hour

2.6.6 Assessment and comparison

Ideal I/I measurement methods (extended according to Fuchs et al., 2003)

- are easily and routinely to apply
- are free of arbitrary assumptions
- measure temporal variations and average values
- identify several sources of I/I
- have low uncertainty
- have low costs.

Common methods (Table 2-17) meet these requirements conditionally only. Beside practical problems like data availability, probe mounting and costs, major problems of the methods are the reliability and reproducibility of results. Both are limited due to the method assumptions and the varying measurement and analysis conditions.

Furthermore, quantitative methods measure or use the total flow at the respective measuring point, i.e. the total flow of the upstream sub-catchment. Therefore, the determined I/I rate is a spatially mean rate for the whole sub-catchment. The minimum size of the uniformly investigated sub-catchment depends mainly on the minimum measurable discharge.

The immediate determination of I/I rates of a single sub-catchment within or and at the end of a superior catchment is not possible. A practical solution would be I/I measurements at the beginning and the end of the sub-catchment and a calculation of the difference. But, sections which should be investigated cannot be selected arbitrarily. The definition of such sub-catchments depends on the specific network topology.

There are a number of comparative studies of different measurement methods, e.g. Joannis (1994), Ertl et al. (2002), Fuchs et al. (2003), Ernst (2003) and De Bénédittis and Bertrand-Krajewski (2004). An analysis of the studies shows, that results of I/I measurements with different methods vary in a wide range of more than 25 % in average. The main reasons for this range are (De Bénédittis, 2004):

- the questionable estimation of foul water flow
- the focus on different I/I sources
- network characteristics (slope, mesh degree)

- catchment characteristics (inhabitants, industrial influence)
- the arbitrary definition of dry weather periods.

Consequently, there is no ideal measurement method but a set of methods which can be applied according to the specific study site conditions. Such conditions are described e.g. in Uibrig et al. (2002). In principle, methods based purely on measurements (moving minimum, time series, stable isotopes) appear to be more reliable (Fuchs et al., 2003; De Bénédittis, 2004).

The uncertainty of underlying measurements amount to approximately 10 % for discharge and 15 % for pollutant concentrations measurements (Bertrand-Krajewski et al., 2000). Thus, the uncertainty of single I/I measurements can reach more than 30 %. However, this strong variability seems to have a limited impact at least on the spatial definition of the I/I situation in a catchment (De Bénédittis and Bertrand-Krajewski, 2004).

Table 2-17. Comparison of measurement methods (Lucas, 2003; De Bénédittis, 2004)

Method	Factors	Assessment
Annual balance	Data	Daily waste water flow, weather definition, drinking water consumption/number of inhabitants
	Hypotheses	
	Scale	Annual
	Advantages	Simple
	Disadvantages	Only dwf is considered, arbitrary weather definition, tends to underestimate I/I
Triangle method	Data	Daily waste water flow, number of dry weather days, drinking water consumption/number of inhabitants
	Hypotheses	Constant flow of foul water
	Scale	Annual
	Advantages	Simple, graphic representation
	Disadvantages	Rough definition of I/I, constant flow of foul water
Minimum night flow	Data	Waste water flow, weather definition
	Hypotheses	Minimum night flow is equal to I/I flow
	Scale	Daily
	Advantages	Simple
	Disadvantages	Sensitive to flow transit time, arbitrary choice of measurement time

Method	Factors	Assessment
Moving minimum	Data	Daily waste water flow, number of dry weather days, drinking water consumption/number of inhabitants
	Hypotheses	Constant flow of domestic wastewater
	Scale	Daily
	Advantages	No arbitrary choices by the user, easy study of I/I variability
	Disadvantages	Influence of chosen time lag (intensity-related I/I is taken into account with short time lag), purely phenomenological
Swiss method	Data	Waste water flow, measurement of pollutants (COD, NH_4-N, others)
	Hypotheses	Pollutant content in foul water remains constant
	Scale	Daily
	Advantages	Consideration of dilution and minimum night flow
	Disadvantages	Constant pollutograph in foul water, costs of pollutant measurements
Time series of pollutographs	Data	Waste water flow, constant COD measurements
	Hypotheses	COD content of I/I is zero
	Scale	Daily
	Advantages	Consideration of dilution and minimum night flow
	Disadvantages	Measurement expenses
Stable Isotopes	Data	Waste water flow, ^{18}O measurements
	Hypotheses	^{18}O content of foul water and I/I differ
	Scale	Daily
	Advantages	Easy to apply, can determine illegal wells
	Disadvantages	Measurement expenses, drinking water source not local

2.7 Modelling

2.7.1 Modelling of infiltration/inflow

Modelling of infiltration/inflow allows for a better study of processes and impacts. Thereby, the development of management strategies for operation and rehabilitation is supported. Two types of models can be distinguished: hydrological and hydraulic models. The first ones are based on conceptual approaches and applied at catchment scale. The second ones are focused on I/I mechanisms and applied at reach scale.

Hydrological models are adapted from runoff models which represent the transformation of precipitation to runoff at a sub-catchment scale. Thus, hydrological models simulate I/I components at the outlet of a catchment starting from rainfall, evapotranspiration and additional flow data. The transformation, i.e. the temporal variability as a result of retention, is generally simulated by means of storage functions (reservoir analogy). These models are very common. However, they are not suitable for modelling changed situations e.g. due to sewer rehabilitation (Dupasquier, 1999).

The RORB model (Laurenson and Mein, 1992) simulates I/I in separate sewers. It consists of several tanks in series and distinguishes various flow components assuming that dwf corresponds with waste water flow and groundwater infiltration. During rain events inflow and fast drainage, i.e. rapidly percolating storm water, are added. Precipitation is introduced into the tank with a 10 hours delay due to the response time of the water storage in the ground. The model does not take into consideration the variability of ground moisture and permanent groundwater drainage. It is a simple approach with a small parameter set. The model obtains rather good results for single rain events (Mein and Apostolidis, 1993).

The MouseNAM model (Gustaffson et al., 1991) simulates the transformation by means of four connected tanks. It includes infiltration (slow response component) and inflow (fast response component) and is suitable for combined and separate sewers (Figure 2-20). The model delivers very good results (Gustaffson et al., 1999). However, MouseNAM has a rather complex structure and numerous parameters.

The SEPI-model (Belhadj, 1994) simulates I/I in separate sewers and consists of several tanks in series. The first one is associated with an output function for rain and describes various hydrological phenomena like interception, evaporation and surface retention. The second one connects the estimated rain volume with the waste water flow. The model does not regard the variability of I/I, it underestimates peak flows and overestimates recession velocity. It is a simple model and delivers preliminary results.

Infiltration of groundwater into sewers is similar to infiltration into drainage pipes for land improvement. The hydraulic functionality of such drainages is well studied. Thus, corresponding approaches could be used to model I/I. Basically, modelling infiltration into sewers is more complicated due to the heterogenous pipe environment in urban areas and the uneven distribution of leakages.

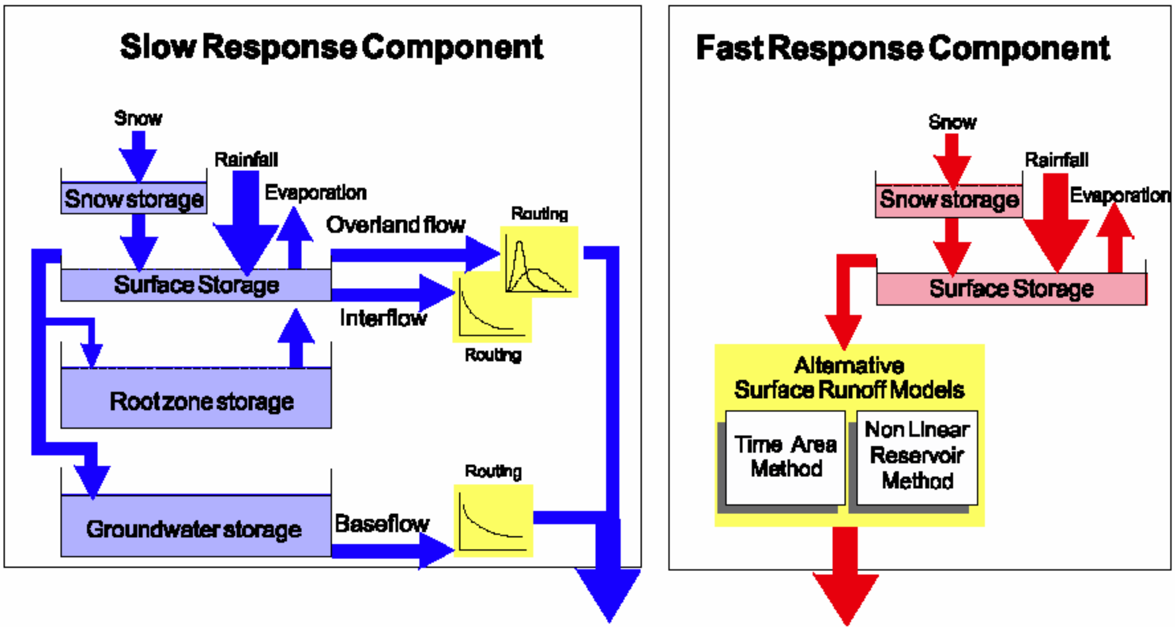


Figure 2-20. Model structure of MouseNAM (Gustafsson et al., 1999)

Dupasquier (1999) proposes a science-oriented hydraulic model. It solves Laplace's equation for underground flow in a pseudo 3D space, representing a pipe section affected by leakages, the conduit zone and surrounding soil. Only one kind of soil material is regarded. Leakages are considered as wells exporting water from the pipe surrounding. The results obtained with this model depend very much on the boundary conditions. The model points to a domination of leakage and soil characteristics for the infiltration flow. It is not suitable for sewer modelling from an operator's point of view. However, the model provides a useful basis to understand relevant processes.

For practical purposes the leakage approach to infiltration is often used. The primordial approach is based on modelling of interactions between aquifer and surface water and related to the wetted area of the river bed, the difference between groundwater and surface water level, and a leakage factor representing the permeability of the infiltration zone. According to Gustafsson (2000) and Karpf and Krebs (2004a) the approach can be modified for modelling groundwater infiltration into sewer systems:

$$Q_{infiltration} = k_L \cdot A_{wet} \cdot \Delta h \qquad \text{Equation 2-8}$$

with k_L leakage factor
A_{wet} groundwater influenced pipe surface (wetted area)
Δh water head

An extended approach, which takes into consideration regional differences and house connections, is proposed in APUSS (2004b). Furthermore, the leakage approach can link more sophisticated models like deterministic sewer and hydrogeology models (Gustafsson, 2000). Thus, it supports studying future changes in the hydrogeological system.

The crucial point of the model is the determination of the leakage factor. As an integrative parameter, it describes various attributes of the soil and the pipe and thereby the potential exchange between aquifer and sewer. The factor has to be calibrated based on time series of groundwater levels and infiltration rates (Karpf and Krebs, 2004a). However, it can be modelled on catchment scale e.g. by using neural networks (APUSS, 2004b).

The achievable spatio-temporal resolution of the model is relatively high but depends on the data situation. Theoretically, it is possible to estimate infiltration at single pipe level and at daily scale. However, the quality of modelling and predicting infiltration rates is higher for larger catchments (Karpf and Krebs, 2004a).

In a further development of the leakage approach, CARE-S (2005) replaces the integrative parameter leakage factor with physical parameters:

$$Q_{infiltration} = \frac{K}{\Delta L} \cdot A_{leakage} \cdot \Delta h \qquad \text{Equation 2-9}$$

with K soil permeability
ΔL thickness of limiting soil layer
$A_{leakage}$ leakage area

This model is purely deterministic and does not need any calibration. But, application of the model is extremely difficult due to its data need and the determination of the introduced parameters, respectively.

2.7.2 Modelling of the structural state of pipes

Of further interest for the I/I investigation are models for the structural state of pipes due to its dominating character for sewer tightness (chapter 2.3.1.4). Although there are no links between both model groups, they support the prediction of I/I under changed boundary conditions and the determination of relevant parameters and their sensitivity. A few examples are given below.

Fenner and Sweeting (1999) introduce a decision support model for sewer rehabilitation. They assume that small sections of a sewer system (grids) contain assets of similar type and age and have consistent environmental conditions. The pipe characteristics expected to influence failure are sewer type, depth, size, profile, material, gradient, age, construction type, joint type, soil type and traffic flow. As only a few of these parameters are commonly stored, the model is reduced to sewer type, size, material and event history. But, the use of these physical asset information does not produce high rank correlations.

Herz (1996) describes the cohort survival model which determines 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 sewers. With these transition functions, the most probable date of entering a critical condition class can be forecast from sewer characteristics such as material, period of construction, location, type, size and gradient. The model is to be applied to groups of pipes that are homogeneous with respect to their material and environmental/operational stress.

Physical 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. An example for such models is given in Bernal et al. (2003).

2.8 Handling of infiltration/inflow

A need for action arises from operational problems (chapter 2.5.2, chapter 2.5.3), excess expenditures (chapter 2.5.5) and regulatory punishments (chapter 2.4.1) caused by infiltration/inflow. The handling of I/I aiming at a cost-efficient reduction is normally based on a comprehensive strategy plan. The different approaches of these plans are relatively similar. Starting from noticing I/I as a problem they include analysis of available data, measurement campaigns, assessment of the current situation, planning and implementation of measures and controlling. It is useful to combine these plans with other rehabilitation actions, e.g. hydraulic rehabilitation of ageing-induced network reconstruction or street reconstruction (Karpf and Krebs, 2005).

Ranchet et al. (1982) propose a three-stage investigation strategy focused on measurements:

1. Short-term survey: Areas affected by I/I are investigated by visual inspections and short-term measurements. If the sources of I/I are not identifiable, continuous measurements are used to characterise different contributions.
2. Analysis of measurements: Data based on temporary or permanent measurements are analysed to determine the catchment–wide I/I situation and to find a spatial and source-related order of I/I contributions. With this hierarchical order it is possible to reduce the investigation effort by determining hot spots and negligible areas. The separation of sub-catchments is based on catchment characteristics (age, inhabitant structure, hydrogeological properties etc.) and the experience of the operator.
3. Localisation of sources: Single sources and damages, respectively, are localised by suitable technologies like CCTV and tracer methods.

These investigations are followed by planning and comparison of measures which reduce the I/I amount.

Nebauer (1996) developed and applied a method consisting of the stages:

1. Data acquisition: geography, topography, inhabitant and dwelling structure, water consumption, industrial discharge, situation of receiving and groundwater, asset data
2. Determination of I/I discharge: use of available data, temporary measurements at crucial points (e.g. confluence points, downstream of closed quarters, before and after endangered reaches), plausibility tests
3. Determination of potential I/I sources: focused on relevant areas, use of CCTV, fog release, expert and local knowledge
4. Planning of measures: priority due to current I/I discharge and reduction potential, costs
5. Implemantation of Measures: preferably in times of low groundwater table
6. Controlling: repeat of the measurements under comparable boundary conditions, possible iteration of the process.

Milojević and Wolf (2004) introduce a rehabilitation-oriented strategy which determines the potential I/I reduction and rehabilitation costs for every single pipe:

1. Data acquisition: flow measurements, groundwater table, sewer dimensions, structural state of pipes
2. Assessment: definition of the rehabilitation priority of single pipes based on a classification of the structural state and the mean location to the groundwater table; minimal priority and rehabilitation limit, respectively, are set by the operator
3. Localising: I/I discharges are allocated to single pipes due to a points rationing scheme based on a classification of the sewer tightness and the probability of location below the groundwater table; potential I/I reduction is related to necessary rehabilitation costs
4. Rehabilitation: determination of rehabilitation order and areas.

Other approaches and strategies can be found e.g. in Hennerkes et al. (2006), Ministerium für Landwirtschaft, Naturschutz und Umwelt (2005) or Kommunal- und Abwasserberatung NRW (2006).

Regarding the implementation of measurement campaigns and the determination of the spatio-temporal I/I distribution all strategies follow a top-down approach. Starting with an analysis of the WWTP inflow (e.g. Fuchs et al., 2003) the catchment is divided in sub-catchments with homogeneous structures (e.g. Nebauer, 1996), where additional measurements are realised. Such a hierarchical approach is used for temporal and source-related investigations, too.

2.9 Conclusion

The occurrence of infiltration/inflow has major consequences for the sewerage system, both negatively and positively, as shown in chapters 2.4 and 2.5. In principle, all branches and assets of the urban water system are affected. The additional financial and personnel expenditures for planning, maintenance and operation are significant and can reach two digit percent figures. Directly and indirectly, I/I influences significantly environmental compartments adjunctive with sewers. Due to the large dimension and the underground location of sewerage systems a complete water tightness of their assets is de facto not possible and I/I cannot be avoided. Thus, some I/I discharge must be accepted.

Although the importance of I/I is known since the beginning of modern urban water management, the knowledge about relevant processes and influencing factors is fairly limited as detected in chapter 2.3. This concerns cause-effect relationships between independent factors like pipe characteristics and the structural state of pipes on the one hand and the structural state and I/I rates on the other hand. The main reason for this gap of knowledge is the composite structure of a sewer consisting of the pipe itself, the ground it is buried in, the local environment and the great variance of these elements and their effects regarding I/I. Therefore, a detailed investigation of single processes is too intricate.

I/I is mostly considered phenomenological as described in chapters 2.7 and 2.8. The determination of the I/I situation in a catchment as well as the application of I/I models – both deterministic and empirical – are based on extensive measurements and local expert knowledge. In principle, extracted findings are catchment-specific. Their transfer to other catchments is conditionally possible, only. Thus, extensive measurements are of predominant importance for handling I/I problems.

Beside the use of routine measurements at the WWTP and major confluence points within the sewer network additional measurement campaigns are necessary to determine the I/I situation in larger sewer systems. These campaigns follow a top-down approach, where the catchment is hierarchically divided in sub-catchments with homogeneous structures as described in chapter 2.8.

Compared to other measurement problems in the field of urban water management common I/I measurement methods have two major restrictions as stated in chapter 2.6.6. First, I/I is determined indirectly, leading to relatively high uncertainty in the results which is due to the multitude of measurands and user-specific assumptions. Second, the determined I/I rate is a spatially mean rate for all sewers upstream the measuring point. As listed in chapter 2.6.1, measuring points cannot be selected arbitrarily due to restrictions of the measurement methods like a minimium flow or conditions of probe mounting.

Due to the importance of I/I measurements and their high personnel and financial expenditures as shown in chapter 2.6.5 there is an urgent need for an improved efficiency aiming at

- a reduction and optimisation of measuring points
- an increase of the information yield and a reduction of uncertainty per single measuring point
- a possible transfer of available measurement results and empirical knowledge to other (sub-)catchments.

This is investigated within the next chapters.

3 Similarity Approach

3.1 Basic assumption

Operators need measurement and modelling methods to determine the infiltration/inflow situation in urban sewer systems with a sufficient resolution in space and time at low costs. Infiltration as the main fraction of extraneous water is determined by a lot of mechanical, biological and chemical processes and corresponding factors (chapter 2.3.1). But, the knowledge about cause-effect relationships between influencing factors and I/I rates is fairly limited. Due to the enormous number of relevant processes affecting I/I and due to the general data situation of large sewer systems there is a significant lack of data. Thus, the application of existing I/I models is difficult and extensive measurements are required.

With regard to a higher efficiency in measurements and a better utilisation of investigation expenditures a different approach is needed. With the assumption "Similar sewer conditions lead to similar infiltration/inflow rates" it is possible to identify homogeneous areas and comparable sub-catchments by looking for and working with similar entities within a sewer system.

The assumption as such is not new and can be deduced from common I/I measurement procedures as described e.g. in ATV-A 118 or Nebauer (1996). But, instead of using it subjectively it is possible and advisable to adapt exact mathematical methods to the assumption, which leads to the similarity approach.

The similarity approach classifies and compares states, but it does not describe functional relationships and dynamic processes. Its implementation aiming at the applications proposed in chapter 2.9 demands for the use and adaption of several techniques:

1. Classification: Statistical classification methods are widely used within the field of sewer systems (e.g. Herz, 1996; Müller, 2002). But, the applied methods consider reaches as single items independent from each other. Due to the commonly used measurement methods a sewer classification in the frame of I/I measurements and modelling has to include both the structural

dimensionality and the functional anisotropy of sewer systems, i.e. the network topology and the flow direction.

2. Optimisation: The partitioning of a catchment in homogeneous areas, i.e. sub-catchments with a low variance in their characteristics, demands for a suitable measure for a sub-catchment's homogeneity and for an optimisation with regard to the discrepancy between the number of possible (high) and required (low) partitioning solutions. Advantageously, the optimisation algorithms should quantitatively assess different solutions.
3. Comparison: The defined sub-catchments are considered as single units aggregating the properties of all reaches within. For these units I/I rates are measurable and comparable. The units and sub-catchments, respectively, have to be arranged and compared by means of suitable measures.

3.2 Data

3.2.1 Data acquisition

For the verification of the basic assumption and the development of methods numerous data of two sewerage systems situated in Germany were acquired: the sewerage systems of the city of Dresden in Saxony and of the city of Bottrop in North-Rhine Westphalia (Figure 3-1).

The city of Dresden is the capital of Saxony with a population density of 1,490 P/km². It is situated in the broad Elbe valley. The main WWTP Kläranlage Dresden-Kaditz has a capacity of 650,000 PT. Some parts of the sewer catchment are self-contained drainage areas with an own WWTP. They are situated on the upland outside of the Elbe valley.

The city of Bottrop is part of the Ruhr agglomeration and heavily influenced by mining. It has a population density of 1,188 P/km² and is situated on the foothills of the Recklinghäuser Landrücken. The WWTP Klärwerk Bottrop has a capacity of 1.34 m PT. The considered sewer catchments are part of the Boye river area. This small river discharges to the Emscher river.

Data donors were the operators and city authorities. The data did not cover the total catchment areas. They were mainly provided as geographical and network information system. The usable data sets contained

- base maps (streets, buildings, surface water, soil type etc.)
- sub-catchment data (census, dimensioning-related values)
- sewer data (network topology, location, reach characteristics)
- groundwater data (time series, single measurements)
- I/I measurements.

The structural state of pipes expressed by detailed defect descriptions or sewer condition classes was not acquired. Due to the statistical nature of the investigation approaches, i.e. the use of black box techniques, the focus was set on I/I and direct relationships between independent reach characteristics and I/I rates.

Further details for data acquisitions related to I/I problems are given in Karpf and Krebs (2003) and Franz et al. (2004).

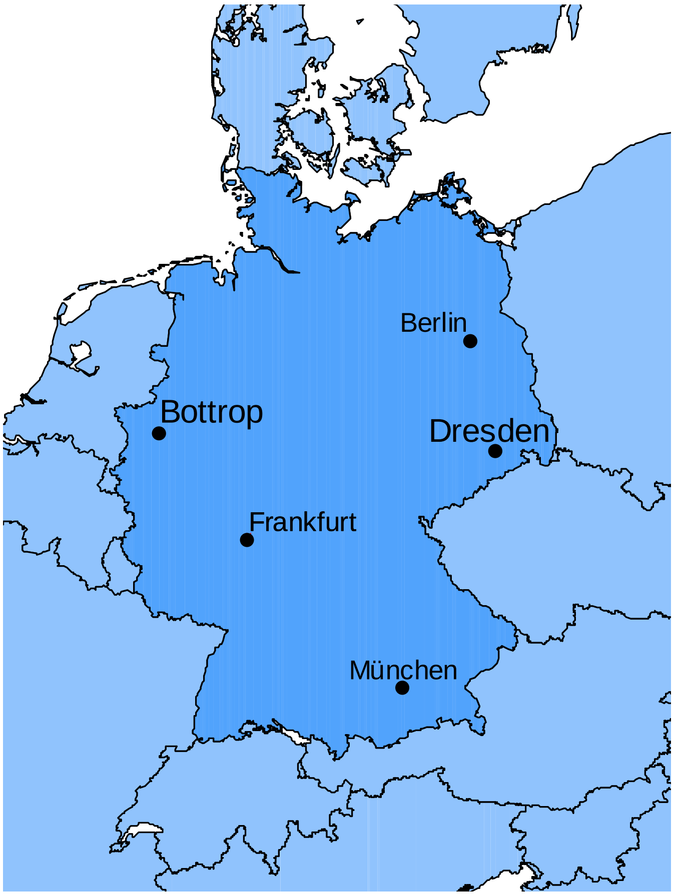


Figure 3-1. Location of the cities of Bottrop and Dresden in Germany

3.2.2 Pre-processing

The pre-processing of data can be described as a three stage process:

1. basic part: digitalisation of analogue data, conversion into the formats needed, validation
2. main part: linking of data, implementation into main software, adaptation to a consistent spatial-temporal environment
3. additional part: simplification, time series analyses, distribution transformation, etc.

The acquired data had a good quality. A basic pre-processing was not necessary except for establishing data consistency and for outlier elimination by means of visual evaluations.

Due to the investigation aim the single reach was used as spatial reference to which all data were linked. The location of sewers relative to linear and not area-wide plane surface units like streets, water courses and buildings was determined by the shortest distance between the reach centre point and the unit. Area-wide plane sub-surface units like groundwater table and soil type were linked by means of the location of the reach centre. Thereby, the groundwater table was calculated with linear interpolation between measured point values. These map-related linkages were determined by means of a geographical information system. I/I rates were calculated as mean values related to sewer length and sewer surface.

The temporal reference was one measuring period which lasted several weeks for the Bottrop sub-catchments and one year for the Dresden sub-catchments. The temporally dependent parameters I/I rate and groundwater level were averaged over the total measuring period. In Bottrop, I/I and groundwater measurements were conducted simultaneously in spring 1999. The I/I rates were determined by means of minimum night flow. In Dresden, groundwater measurements in a 14d-period were available for the complete year 2001, but not for the total area. The I/I rates were determined as a yearly mean by means of balancing.

The interpolation of the ground water tables and the determination of I/I rates were not part of this work.

All data were compiled in a simple spreadsheet. The network topology was regarded by keeping the information about up- and downstream manholes for every reach. A georeferencing of reaches was not necessary.

A reduction of items, i.e. reaches, and attributes, i.e. parameters or factors, was necessary with regard to their potential relevance for I/I. Storm water sewers and drainages were not considered, because the I/I measurements were conducted in foul and combined sewers, only. The rare pressure sewers were not considered too, because they have no influence on infiltration. The sewer dimensions nominal size, profile width and height were expressed as profile circumference. Thus, the sewer dimensions of all profile shapes could be considered within one attribute. The distance to railway tracks was not considered due to the low number of influenced reaches and the assumed sufficient coverage. The geodetic invert and surface heights themselves have no influence on I/I. Together with the profile height they were used to calculate the mean coverage. The classes of street type, sewer material and profile type were combined in order to eliminate classes with low quantities and to combine classes with similar characteristics:

- main, state, federal roads and highways to main roads
- residential and district roads to residential roads
- paths, forest and farm tracks to paths
- polyethylene and polyethylene HD to polyethylene
- grey cast iron and ductile cast iron to cast iron
- fibre glass reinforced synthetics and polymer-modified concrete were eliminated (fraction in Dresden 0.4 %, in Bottrop 0 %)
- all profile types other than circle and egg were combined (fraction in Dresden 5.7 %, in Bottrop 0 %).

An important property of an attribute is its statistical scale. At the nominal scale attribute values are different, but they cannot be ranked, e.g. names like material. At the ordinal scale the values can be ranked, but the differences between two adjacent values can vary, e.g. ranks like street type. At the interval scale values are numbers whereas the differences between the values can be measured, e.g. numbers like slope. Added to this, the ratio scale has a natural zero point, e.g. numbers like distance. The last two scales are summarised as metrical scale (Walford, 1995). The scale level of an attribute determines its information content and feasible mathematical operations and methods.

There are several options to combine attributes with different scales (Backhaus et al., 1994). Attributes with higher scales are transformed to lower ones by means of level regression methods, e.g. binary coding. That means a loss of mostly relevant information. Attributes with lower scales are transformed to higher ones by means of level progression methods, e.g. the definition of ordinal attributes as metrical ones. It is to prove carefully, whether this is acceptable.

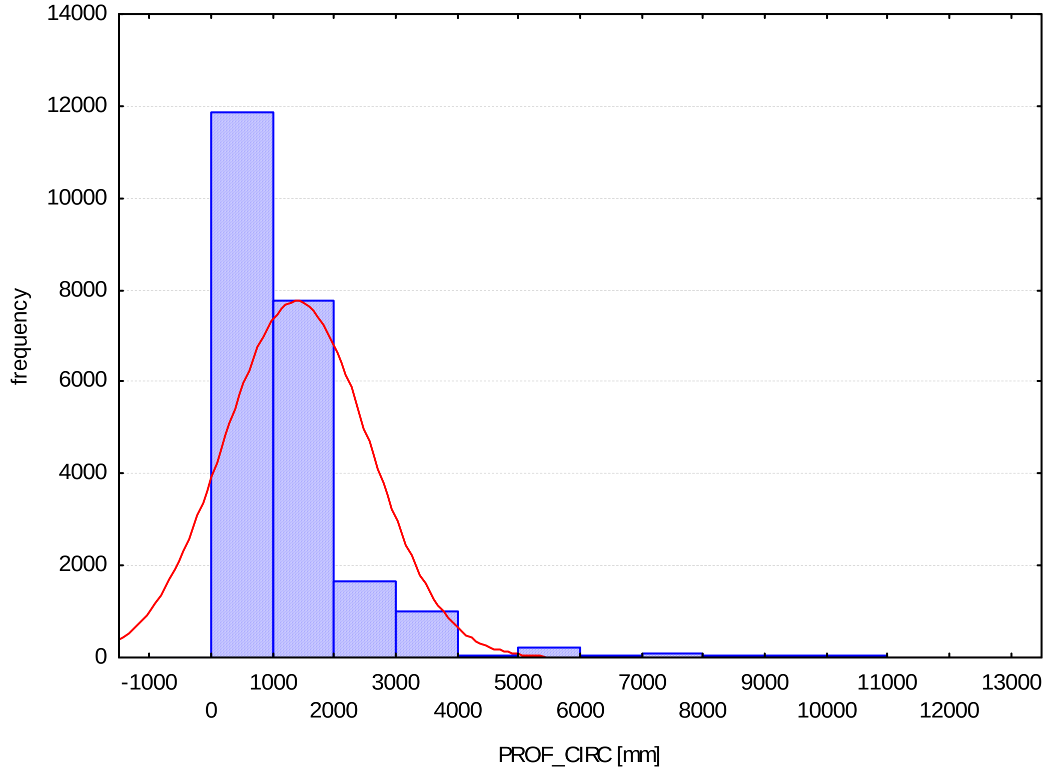
The metrical attributes were tested for normal distribution. This statistical distribution is an important constraint for the applicability of several statistical methods. In some cases the attributes were transformed, i.e. their distribution was changed by using mathematical functions, e.g. natural logarithm and square-root (Tabachnik and Fidell, 1989):

$$x_{ij,transformed} = ln(x_{ij}) \qquad \text{Equation 3-1}$$

with x_{ij} value j of attribute x_i
$x_{ij,transformed}$ transformed value j of attribute x_i

An example is given in Figure 3-2. The transformed attributes are marked in Table 3-2.

The Kolmogorow-Smirnow test (e.g. Sachs, 1993) was used as test for normal distribution. Although the test results were not always satisfying, normal distribution can be assumed for all metrical attributes due to the central limit theorem. This theorem states that the sum of a large number of independent, identically distributed random values converges against the normal distribution (Handl, 2005).



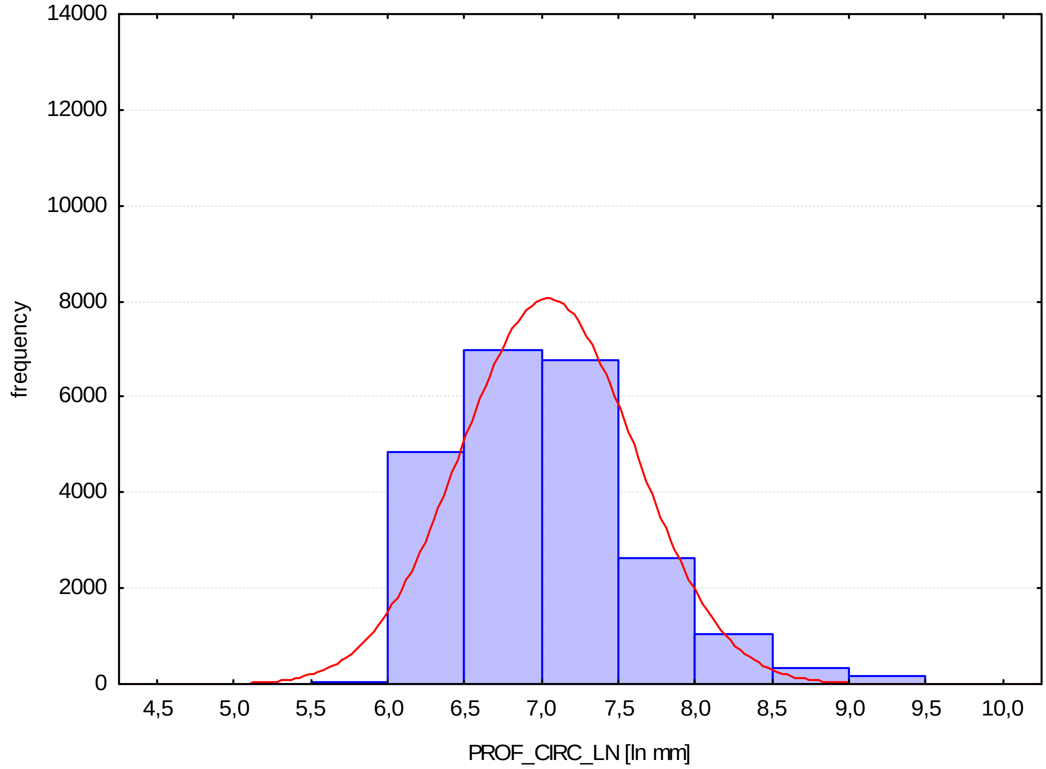


Figure 3-2. Distribution transformation of the attribute profile circumference with natural logarithm (above: natural distribution, below: transformed distribution)

3.2.3 Data base

The result of the data acquisition and the pre-processing was a data base covering 27 sub-catchments with approximately 24,000 reaches and a total sewer length of 861 km (Figure 3-3, Figure 3-4, Figure 3-5, Table 3-1, appendix). Every sub-catchment was determined by a measuring point and a mean I/I rate, respectively. The number of reach-related attributes which are independent from I/I range between 18 and 19 (Table 3-2). Detailed groundwater information and the water head linked to I/I measurements, respectively, were available for 30.6 % of the reaches, only.

Regarding the spatial and attribute coverage the data base is significantly above-average, compared both to other investigations and to the general data situation for sewer systems (Franz et al., 2004). In large part, the attributes cover the I/I influencing factors detected in chapter 2.3.1.

Regarding groundwater information as important element for investigation approaches the following data sets were available for method development and further investigations:

– 16 Dresden sub-catchments without groundwater information
– 6 Dresden sub-catchments with groundwater information
– 5 Bottrop sub-catchments with groundwater information.

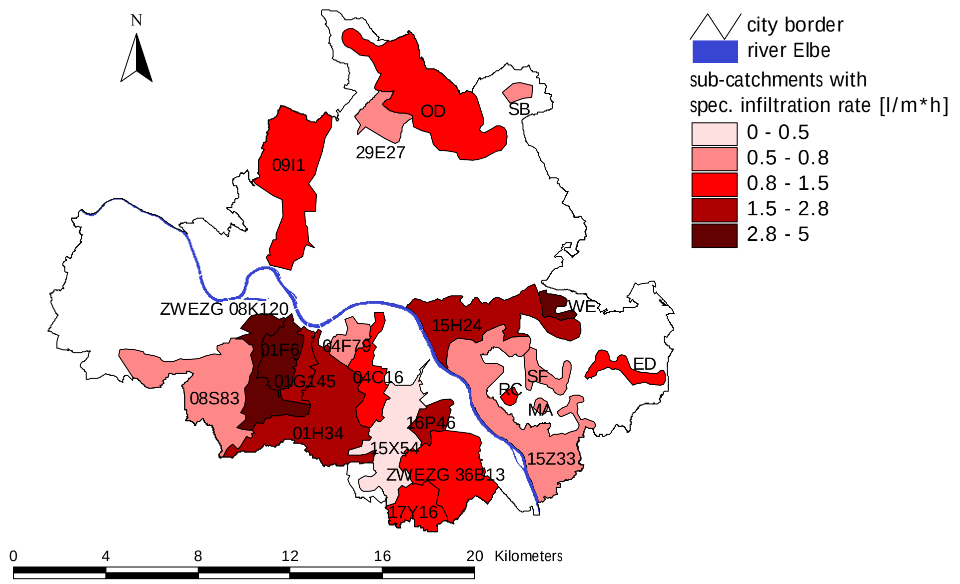


Figure 3-3. Investigated sub-catchments in Dresden with sewer length specific I/I rates

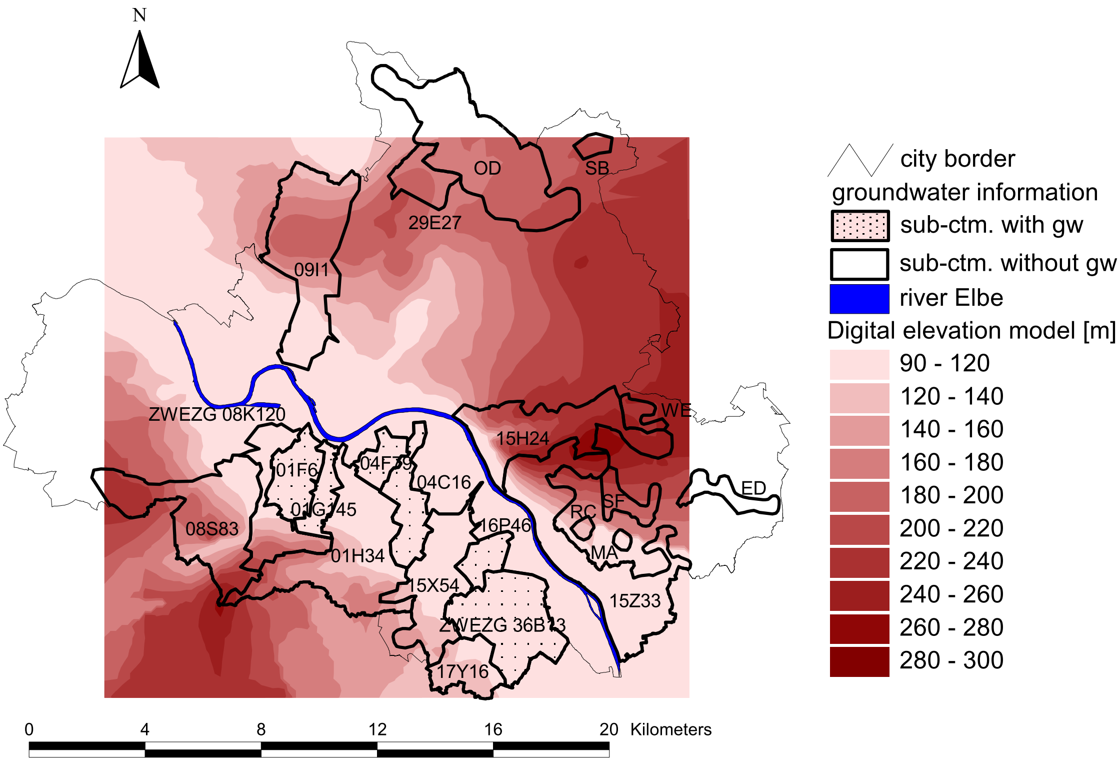


Figure 3-4. Investigated sub-catchments in Dresden with gw information availability and digital elevation model

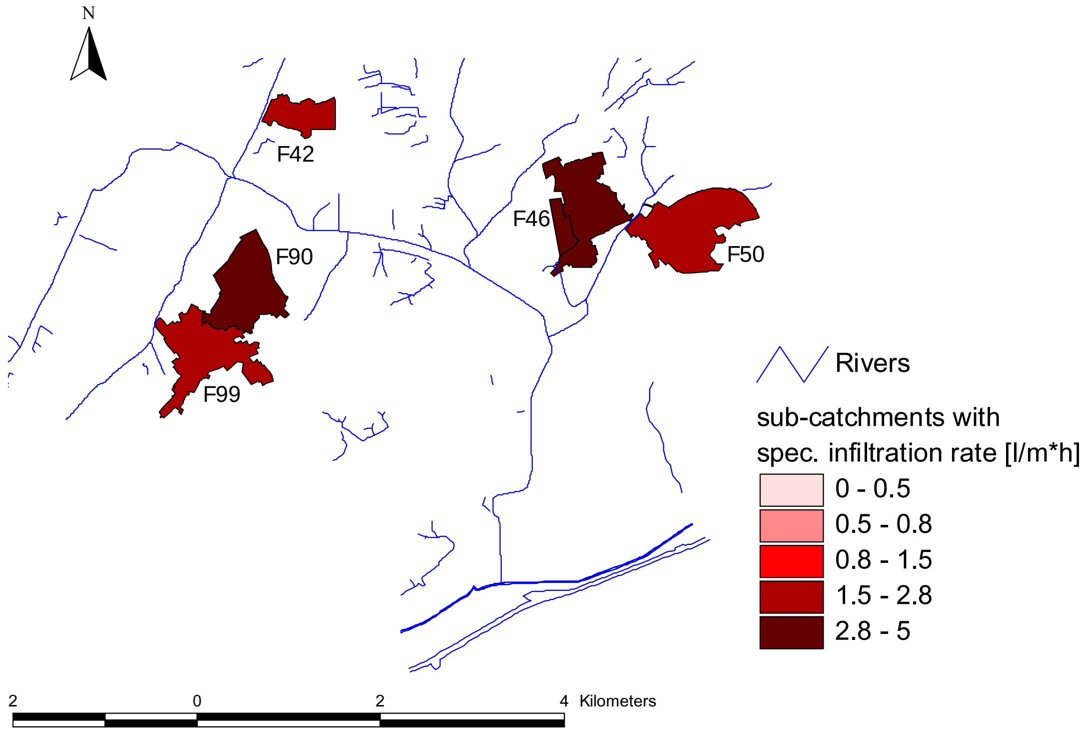


Figure 3-5. Investigated sub-catchments in Bottrop with sewer length specific I/I rates

Table 3-1. Characteristics of the investigated sub-catchments

Sub-catchment	Self-contained area	Ground-water information	Total sewer length [m]	Year of construction (mean)	Population density [P/ha]	I/I rate [L/m·h]
Dresden catchment						
29EE27			11,675	1971	14.5	0.69
ZWEZG 08K120			58,388	1924	36.4	4.44
01H34			97,381	1937	32.6	2.55
01F6		X	52,356	1910	40.4	2.83
01G145		X	36,152	1922	29.1	2.07
16P46		X	12,136	1948	36.8	2.64
ZWEZG 36B13		X	60,896	1947	34.5	1.45
15X54			67,282	1957	39.9	0.30
15H24			75,390	1930	12.3	2.41
04F79		X	24,399	1901	79.5	0.78
04C16		X	43,573	1930	59.1	1.10
15Z33			51,488	1996	5.3	0.54
09I1			54,971	1944	22.4	1.19
08S83			84,649	1935	29.2	0.74
17Y16			12,028	1940	5.8	1.25
SB	X		2,757	2000	3.5	0.69
OD	X		44,731	1999	3.8	0.85
SF	X		6,860	1997	2.7	0.67
ED	X		9,313	2001	1.3	1.02
WE	X		6,134	1998	7.6	4.79
RC	X		2,680	1995	4.5	1.01
MA	X		2,080	1996	1.3	0.58
Bottrop catchment						
F42		X	2,662	1978	27.1	1.76
F99		X	8,586	n/a	65.8	2.64
F90		X	6,725	n/a	40.6	2.84
F50		X	9,767	1959	61.0	1.81
F46		X	7,665	1982	67.0	4.78

Table 3-2. Approved attributes

Abbreviation	Attribute with values	Scale[1]	Transfor-mation[2]
Both catchments			
IDENTIFIER	identifier		
SI/I	surcharge to foul water flow		
qI/I	specific I/I rate		
SUBCATCHM	sub-catchment affiliation		
DATE_CONSTR	year of construction	M	
FUNCTION	function: regional, main, tributary	N	
MATERIAL	material: asbestos, brickwork, cast, concrete, polyethylene, polyvinylchloride, reinforced concrete, steel, stoneware	N	
SEW_SYSTEM	sewer system: combined, foul	N	
PROF_TYP	profile type: circle, egg, other	N	
PROF_CIRC	profile circumference	M	LN
LENGTH	reach length	M	LN
POP_DENS	population density	M	SQR
POP_LENGTH	population-specific length	M	SQR
DIST_WATER	distance to surface water (except main rivers)	M	SQR
DIST_BUILD	distance to buildings	M	LN
STREET_TYP	street type: main, residential, path	O	
DIST_STREET	distance to streets	M	LN
SLOPE	slope	M	LN
COVERAGE	coverage	M	
Dresden catchment only			
DIST_ELBE	distance to river Elbe	M	SQR
DIST_STORM	distance to storm sewers	M	SQR
DIST_DRAIN	distance to drainage	M	SQR
THICK_COHSV	thickness of cohesive layers	O	
Bottrop catchment only			
K	soil permeability	M	
A_IAREA	reduced area ratio	M	
NO_JOINTS	number of joints	M	

[1] M: metrical scale, O: ordinal scale, N: nominal scale
[2] LN: natural logarithm transformation, SQR: square root transformation

3.3 Verification of the basic assumption

3.3.1 General remarks

Despite the derivation of the basic assumption "Similar sewer conditions lead to similar infiltration/inflow rates" from widely accepted approaches a confirmation of the applicability of this assumption is necessary. This confirmation was performed by means of several statistical methods and was focused on the differences between sub-catchments with different I/I rates and on relationships between independent attributes and measured I/I rates.

3.3.2 Differences between sub-catchments

Due to the existent relation between independent attributes and infiltration/inflow (chapter 2.3) and due to the wide range of the observed I/I rates

- Dresden: minimum÷maximum = 1÷16
- Bottrop: minimum÷maximum = 1÷3

it seemed to be probable that the sub-catchments differ significantly from each other. The sub-catchments are characterised by the reaches with their attributes. Thus, a sub-catchment complies with a reach population and a reach with a single item. These item groups can be analysed.

Suitable statistical methods which prove a significant difference between groups of items are analysis of variance (ANOVA) and related methods. With these methods it can be investigated whether several sample populations belong to one basic population. Normally, statistical tests prove a hypothesis not positively but negatively. Thus, for this case the null hypothesis states that the samples and reach populations, respectively, belong to one basic population. To disprove this hypothesis an all-in-one test which includes all attributes is not available, because the attributes belong to different statistical scales. Therefore, every attribute has to be analysed individually. Suitable tests are listed in Table 3-3. Additionally, several post hoc tests have to be performed to verify the method assumptions and to compare sample pairs.

Table 3-3. Statistical tests for inter-group differences (Müller, 1991)

Statistical scale	Test	Post hoc tests	Requirements
Metrical	one way ANOVA	Levene test, least significance difference test	normal distribution, variance homogeneity
Ordinal	Kruskal-Wallis-ANOVA	multiple comparisons of mean ranks	continuous data
Nominal	Crosstabulation	not available	minimal frequency = 5

For metrical attributes the one-way ANOVA analyses variances to verify a significant inter-group difference of the mean values. Variances are a measure of the distribution of random variables to their expectancy value, i.e. to their mean. The observed variances are separated into a component based on the coincidental error, i.e. the within-group variability, and into a component based on different mean values. If the ratio of the components is greater than a critical value, the null hypothesis is rejected (Müller, 1991).

Beside normality the one-way ANOVA requires variance homogeneity, i.e. identical variances of all item groups. This is tested by means of Levene's test which analyses the variances of the difference to the group means for the dependent variable. Another applied post hoc test is the least significance difference test (Winer et al., 1991). It calculates the group-to-group significance level and is equivalent to a simple t-test for independent samples (Hill and Lewicki, 2006).

The Kruskal-Wallis-ANOVA is the non-parametric alternative to one-way ANOVA. Non-parametric methods do not require normality, i.e. they are suitable for ordinal attributes. They are not based on estimation of parameters like mean or standard deviation for describing the distribution of attributes. The Kruskal-Wallis-ANOVA measures the difference between the group rank and the average rank of all groups. The related post hoc test is the multiple comparisons of mean ranks which determine the mean ranks for all pairs of groups (Siegel and Castellan, 1988).

For nominal attributes crosstabulation are relevant. Crosstabulation is a combination of two or more frequency tables. Each cell of these tables represents a unique combination of crosstabulated attributes. Thus, crosstabulation allows for examining frequencies of observations belonging to specific categories. By comparing these frequencies with expected ones, relations between attributes can be identified. The Pearson χ^2 is the most common test for significance of those relationships (Hill and Lewicki, 2006). Post hoc tests are not available.

The test results are related to a certain significance level, i.e. to the probability that the observed differences occur by pure chance and do not exist. The significance level is expressed by the *p* value. It represents a decreasing index of the reliability of a result. A typical *p* value of 0.05 indicates that there is a 5 % probability that the found difference is pretended (Hill and Lewicki, 2006).

Assuming that a combination of catchments is not reasonable (chapter 2.4.2) the tests were applied separately for the catchments of Dresden and Bottrop. The test results were significant at $p = 0.05$ in both cases for nearly all attributes. Exceptions are the attributes *DIST_BUILD* and *NO_JOINTS* in the Bottrop catchment, only. Levene's test refused variance homogeneity for all metrical attributes. But, the test is not very robust especially for unbalanced designs, i.e. unequal group sizes (Glass and Hopkins, 1996). Furthermore, a comparative analysis of the metrical attributes with non-parametric methods showed same results as with one-way ANOVA. Thus, the ANOVA results could be accepted (Hill and Lewicki, 2006) and the null hypothesis that the reach populations belong to one basic population was refused for both catchments; the existence of significant differences between the sub-catchments can be assumed.

For the Dresden catchment, the results of the post hoc tests calculating the group-to-group significance levels for metrical and ordinal attributes are condensed in Figure 3-6. It is the representation of a matrix in which the number of not significant test results between two certain sub-catchments is summarised. If a post hoc test result is not significant, then there is no significant difference between the reach populations and sub-catchments, respectively, for the respective attribute. Thus, those sums stand for a similarity degree to which all attributes contribute equally.

In most cases the reach populations differ in more than two-thirds of the attributes. For the other cases the comparison of Figure 3-3 and Figure 3-6 indicates that the observed pairwise similarities represent more a geographical proximity than a similar I/I behaviour. The main reason for this result is the absence of groundwater information as essential factor for infiltration. Assuming that a large sub-catchment size as well as – due to the influence of the Elbe river (Karpf and Krebs, 2004b) – a sub-catchment shape orthogonal to the main valley lead to an inhomogeneous and not comparable groundwater situation within the sub-catchment good and bad relationships between pairwise similar sub-catchments and their measured I/I rates become more clear. As shown in Table 3-4, the difference between the measured I/I rates of a similar pair of sub-catchments decreases with an increasing comparability of the respective groundwater situations.

High similarity degrees are concentrated on the self-contained catchments with an own WWTP (lower right corner in Figure 3-6). Their measured I/I rates have a comparable magnitude except for the catchment WE. All of those catchments are situated at the upland outside the Elbe valley. Their infrastructure was built mainly after the German reunification (Table 3-1). Therefore, the observed strong similarities of attributes and I/I rates can be traced back to constructive and hydrogeological factors. An exclusion of these catchments in further investigations is indicated in order to avoid weighting effects.

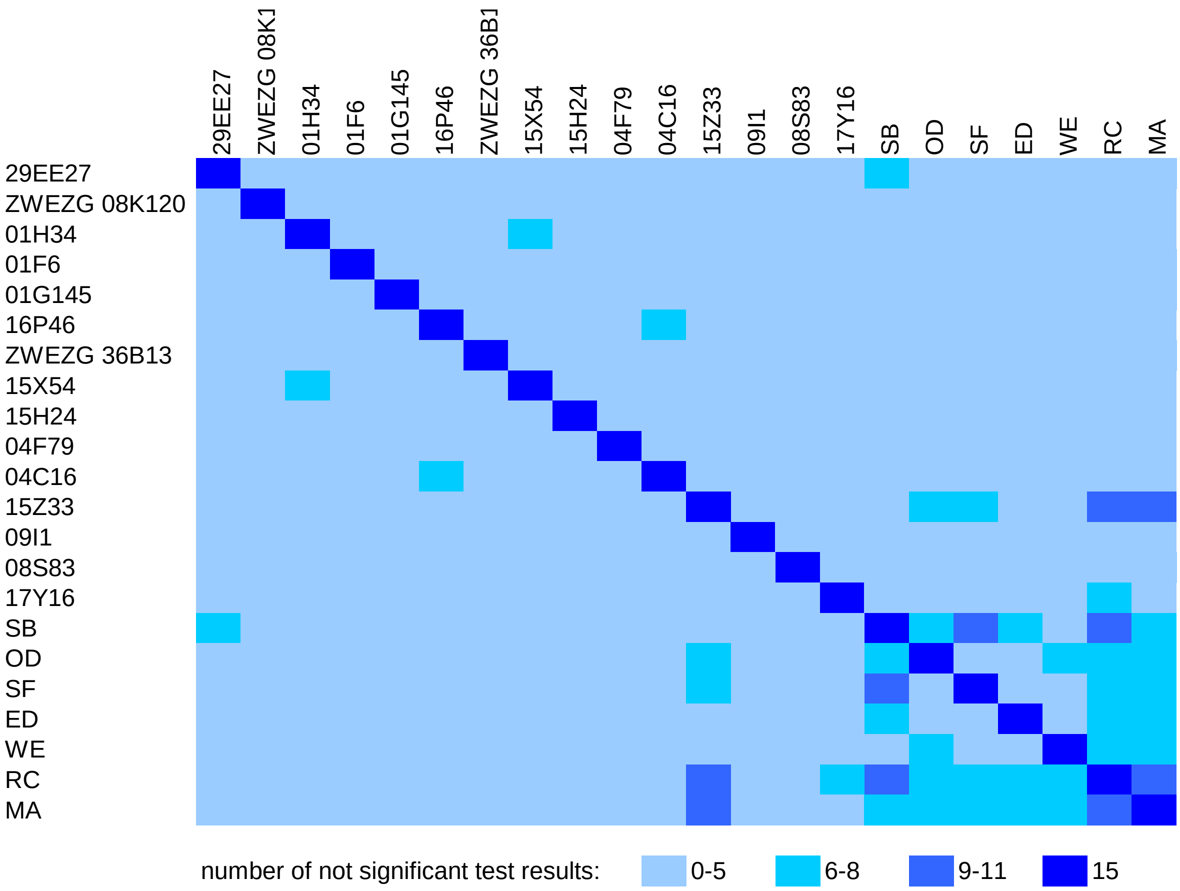


Figure 3-6. Pairwise frequency of not significant test results between all Dresden sub-catchments (least significance difference test and multiple comparisons of mean ranks)

Table 3-4. Comparison of measured I/I rates for similar sub-catchment pairs

Similar Pair	Situation and shape	Probable gw situation	Ratio of $q_{I/I}$
01H34 / 15X54	at valley bottom and leaning, both orthogonal to Elbe river	not similar	1 ÷ 8.5
16P46 / 04C16	both at valley bottom, both orthogonal to Elbe river	not similar	1 ÷ 2.4
29EE27 / SB	both northern upland, no influence of the Elbe river	similar	1 ÷ 1.0
Remaining pairs except with 15Z33 and WE	all eastern upland, no influence of the Elbe river	similar	1 ÷ 1.8

3.3.3 Relationships between attributes and I/I rates

3.3.3.1 Regression

A typical and easy to use method to determine statistically based relationships and functions between several independent attributes x_i and a dependent variable y is the multiple linear regression analysis. It determines a function

$$\hat{y} = c + b_1 \cdot x_1 + b_2 \cdot x_2 + \ldots + b_n \cdot x_n \qquad \text{Equation 3-2}$$

with $\hat{y}$ predicted dependent variable y
c constant
b_i regression coefficient for x_i

so that the squared deviations of the observed dependent variables from the predicted values $\hat{y}$ are minimised. The coefficients can be estimated by means of several methods, e.g. by least squares estimation. For one independent attribute, i.e. a function $\hat{y} = c + b \cdot x$, the estimation results to:

$$b = \frac{\sum_{j=1}^{n} x_j \cdot y_j - n \cdot \bar{x} \cdot \bar{y}}{\sum_{j=1}^{n} x_j^2 - n \cdot \bar{y}^2}$$ Equation 3-3

with n number of items

The method usually requires continuous metrical data and a normal distribution of the residuals, i.e. the differences between predicted and observed values (Hill and Lewicki, 2006).

The direct application of the regression analysis for determining a statistically based relationship between independent attributes and dependent I/I rates is not possible. The I/I rate as mean value stands against not one but a multitude of items. Furthermore, the relevant attributes have different statistical scales. Thus, a multiple regression analysis was perfomed with the group means of metrical attributes neglecting their variance. It yields p values of 0.18. Therefore, the regression is not significant.

Simple visual investigations of box-whisker-plots showed some weak relations. In these plots the variations of reach-related attributes within an individual sub-catchment are displayed. The sub-catchments are sorted by the specific I/I rate. The rates increase with a higher population density (Figure 3-7) and a higher profile circumference (Figure 3-8). A high population density stands for a high impact on reaches due to traffic and building activities as well as – at least at the extensive building structure of Dresden – for more house connections. Sewers with larger dimensions are located deeper and closer to the Elbe river due to the network topology. Thus, the probability of infiltration occurrence is higher (Karpf and Krebs, 2004b). Further correlations of the remaining attributes were not recognisable.

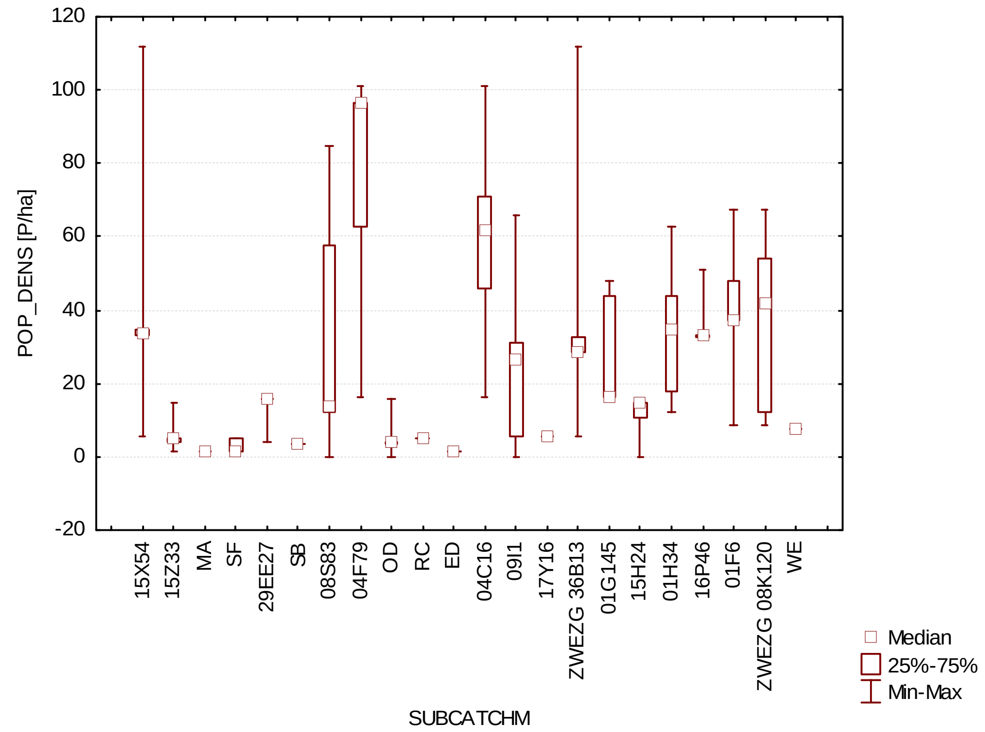


Figure 3-7. Population density of the Dresden sub-catchments, sub-catchments sorted upwardly by $q_{I/I}$

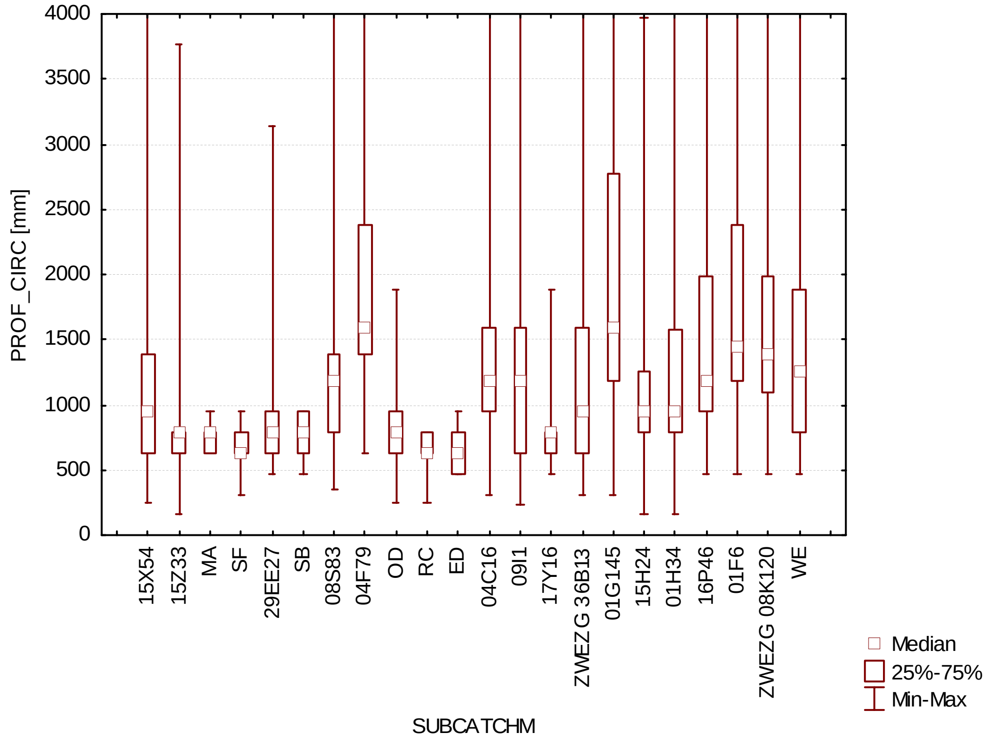


Figure 3-8. Profile circumference of the Dresden sub-catchments, sub-catchments sorted upwardly by $q_{I/I}$

3.3.3.2 Multidimensional scaling

To evade the restrictions of regression analysis, the data were analysed with multidimensional scaling (MDS). By using this method it is possible to reduce data efficiently and to include as much attributes as possible in the investigation of relations between attributes and I/I rates. Multidimensional scaling belongs to the exploratory data analysis approaches.

Exploratory data analysis (EDA) is part of applied statistics and stands methodically between descriptive and inferential statistics. Basically, EDA methods detect and verify structures and patterns in data sets when there is a low level of a priori knowledge and expectations. They generate hypotheses about systematic relationships between variables and items (Jambu, 1992). Thus, EDA methods can among others

- identify redundant attributes
- reduce the dimensionality of data sets
- identify homogeneous item groups
- investigate differences between groups
- classify items.

The used techniques comprehend a multitude of methods both of simple basic statistics and more advanced multivariate approaches (Table 3-5). An overview of multivariate exploratory methods can be found in Jambu (1992), Backhaus et al. (1994) or Fahrmeir et al. (1996).

A basic concept of the EDA is the equivalence of distance and dissimilarity (Handl, 2002). Assuming that n attributes span an orthogonal n-dimensional space where every dimension stands for one attribute, the investigated items are represented by objects in this space according to their attribute values. The distance between two objects is a measure for their dissimilarity: the closer the objects the more similar they are. This measure can be calculated and used for several problems. An example is given in Figure 3-9. In a two-dimensional space characterised by the attributes x_1 and x_2 a number of objects and items, respectively, are arranged according to their attribute values. Object o_1 is closer to o_2 than to o_3. Therefore, o_1 and o_2 are more similar than o_1 and o_3.

Table 3-5. Important EDA methods (Hill and Lewicki, 2006)

Computational methods	**Graphical methods**
Basic statistical methods – variables distributions – correlation matrices – multi-way frequency tables	Brushing – interactive removing or adding of specific subsets of data to examine their effects on relations between relevant variables
Multivariate exploratory techniques – cluster analysis – factor analysis – discriminant analysis – multidimensional scaling – time series analysis	Other methods – function fitting and plotting – data smoothing – splitting and merging subsets of data in graphs – plotting confidence intervals and areas – interactive rotation with animated stratification – data image reduction
Neural networks	

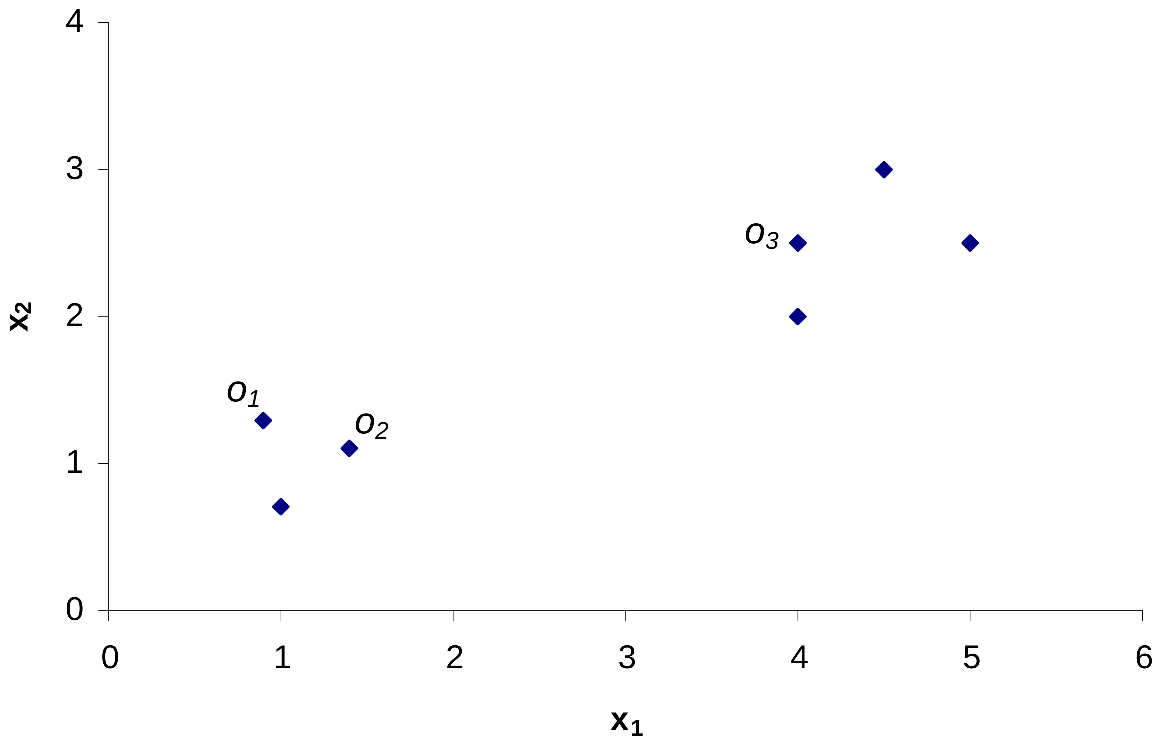


Figure 3-9. Principle of equivalence of distance and dissimilarity

MDS approach

MDS comprehends a collection of methods which detect the underlying structure of relations between items by providing a geometrical representation of these relations (Van Deun and Delbeke, 2006). Thus, MDS can display high dimensional data in low dimensional spaces, i.e. it reduces data and makes them accessible to several types of investigations.

Every kind of relation between a pair of items is a possible input for MDS methods if it is or if it can be translated into a similarity or a dissimilarity measure. This applies for parametric distances derived from metrical attributes as shown in Figure 3-9 and non-parametric ranks or correlations derived e.g. from comparisons. Compared with other multivariate methods MDS has the following advantages (Hill and Lewicki, 2006):

- Attributes with different statistical scales can be handled together.
- There are no requirements for normal distribution and linearity of relationships.
- Dissimilarity or similarity measures do not have to be assessed by the characteristics of the investigated items. Their values can be identified by subjective appraisals.

Based on a dissimilarity or similarity matrix, i.e. pairwise comparisons of items, the MDS transfers iteratively the high dimensional arrangement of items to a low-dimensional end configuration with an optimum approximation of the observed distance pattern. Although there are several methods to define an optimal dimensionality (Gigerenzer, 1981) typically one or two dimensions are used in order to allow for a visual investigation. The interpretation of the result is focused on the definition of the obtained dimensions. Scatter or cluster patterns of the items signify their relative similarity. Disadvantageously, the MDS results are difficult to interpret with regard to a concrete meaning because there might be no direct or obvious relations between the dimensions of the end configuration and the acquired attributes of the items.

A comprehensive explanation and consideration of MDS is given in Kruskal and Wish (1978) or in Borg and Groenen (1997).

MDS procedure

The MDS algorithm consists of four stages (adapted from Backhaus et al., 1994):

1. Acquisition and pre-processing: Acquired attribute values are transformed into dissimilarity and similarity measures, respectively. This can be done e.g. by using the distance/dissimilarity concept described above, by ranking or by calculating Pearson's product-moment or Spearman's rank correlation coefficients. Metrical attributes have to be standardised because distance measures for such attributes are often not scale invariant (chapter 4.2.2.1). Alternatively, dissimilarity or similarity values can be assessed directly by subjective comparisons.
2. Selection of the distance model: In the end configuration, dissimilarity and similarity values are represented by distances. Euclidean (shortest distance) and city-block (sum of absolute values) distances are recommended. An overview about distance measures is given in chapter 4.2.2.2.
3. Determination of the end configuration: The determination of the end configuration is an iterative process (Figure 3-10). The number of dimensions of the end configuration has to be defined beforehand. The start configuration of the investigated items in these dimensions is set arbitrarily. Then, two values are calculated: the distances $d(o_i,o_j)$ between the items o_i and o_j in the configuration and the corresponding disparities $\hat{d}(o_i,o_j)$. Disparities are the monotonously transformed dissimilarity and similarity values, respectively. This transformation or rescaling is necessary, because the raw measures as ranks or comparative values cannot directly compared with the metrical distances $d(o_i,o_j)$ in the configuration. The aim of the iteration is to minimise a fit measure, the stress value *STRESS*. There are several statistical error approaches to calculate this value. A very common example is

$$STRESS = \sqrt{\frac{\sum_{o_i}\sum_{o_j}\left(d(o_i,o_j)-\hat{d}(o_i,o_j)\right)^2}{\sum_{o_i}\sum_{o_j} d(o_i,o_j)^2}} \qquad \text{Equation 3-4}$$

   If the stop criterion – STRESS threshold or number of cycles – is not reached, then the item configuration is rearranged. The mathematical back-ground of this iteration is described e.g. in Gifi (1990) or Backhaus et al. (1994).

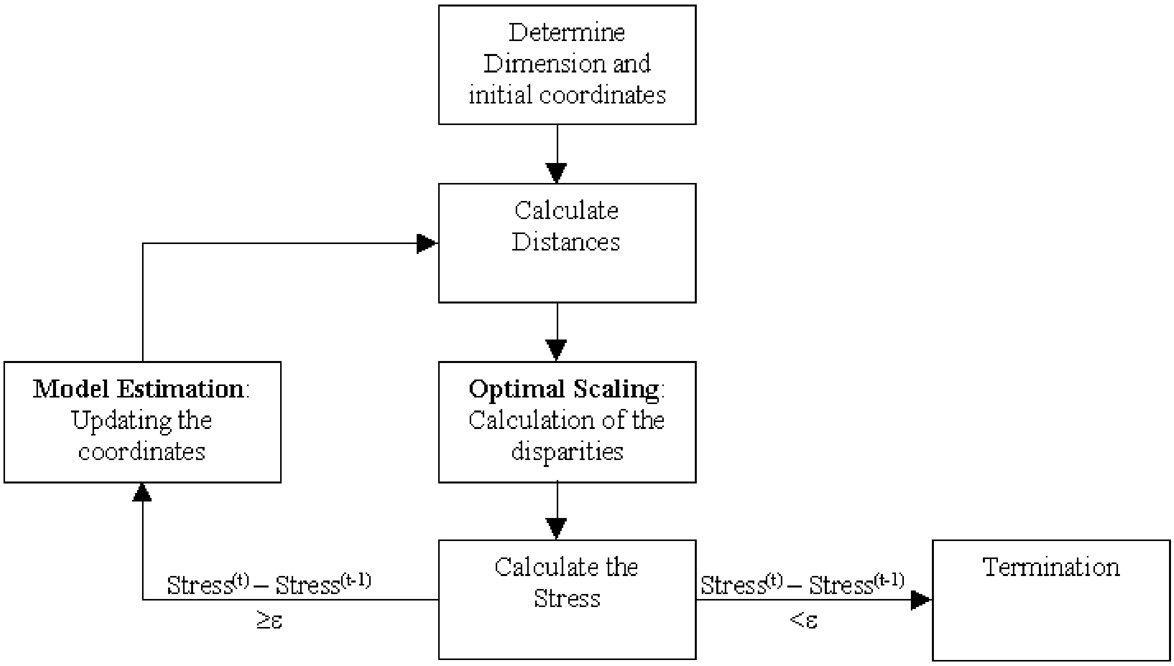


Figure 3-10. Iterative MDS-algorithm (Van Deun and Delbeke, 2006)

Due to its iterative nature the results of MDS might be not unique. Further problems are the occurence of local minima and degenerated configurations which leads to wrong results (Gigerenzer, 1981). With MDS a level progression is performed, i.e. data are condensed. A key number describing this condensation is the data reduction coefficient Q:

$$Q = \frac{n_{item} \cdot (n_{item} - 1)/2}{n_{item} \cdot n_{dimension}} \qquad \text{Equation 3-5}$$

$Q \geq 2$ applies for a stable solution. The quality of the end configuration can be described by the *STRESS* value. Commonly suggested benchmarks are given in Table 3-6. However, a very small *STRESS* indicates a degenerated configuration, a very high *STRESS* can be the consequence of high error in the data. Thus, this value must not be overestimated. A graphical representation of the result quality is the Shepard diagram (example in Figure 3-12). It compares the observed input dissimilarity or similarity measures with the reproduced distances of the end configuration. Furthermore, the diagram includes the cascaded disparities transfer function. A deviation of the reproduced distances from this function shows a lack of fit.

Table 3-6. Benchmarks for *STRESS* values calculated according to Equation 3-4

STRESS [-]	Benchmark
0.000	perfect
0.025	excellent
0.050	good
0.100	fair
0.200	poor

4. Interpretation of dimensions and patterns: The orientation of the axes of the end configuration is arbitrary. For a better interpretation they can be rotated around their point of origin. The arrangement of items can be mirrored. Beside a pure subjective definition of dimension based on specialised knowledge, regression methods can be used to interprete dimensions analytically. Item clusters and particular patterns like circles and manifolds are of interest. Their occurrence supports the interpretation of dimensions and the understanding of relationships between items.

MDS application

In a first step, MDS was applied separately for the catchments of Dresden and Bottrop without considering groundwater information. For the Dresden data, only sub-catchments connected to the main WWTP were considered (chapter 3.3.2). The mean attribute values of the single reach populations, i.e sub-catchments, were ranked and combined in a distance matrix. Therefore, the variances of the attributes are neglected. This seems feasible due to the ANOVA results. The iteration was repeatedly conducted with randomly generated start configurations. Therefore, the detection of the global minimum can be assumed. This procedure was used for further analyses, too.

The MDS of the Bottrop data had no stable solution ($Q = 1$, $STRESS < 10^{-5}$). The end configuration for the Dresden data with two dimensions combined with the observed specific I/I rates is shown in Figure 3-11. The *STRESS* value of 0.117 and the Shepard diagram (Figure 3-12) indicate a reasonable quality of the result. The obtained dimensions *dim. 1* and *dim. 2* represent sewer and sub-catchment characteristics. However, a proper definition of the single dimensions in terms of a physical property was not found. Furthermore, a relation between the I/I rates and the point pattern could not be identified. Like for the ANOVA post hoc tests (Figure 3-6), the main reason for that is the absence of groundwater information as essential factor for infiltration.

By rotating the dimensions and marking the quarter type and general building structure, respectively, the dimensions become interpretable (Figure 3-13). All sub-catchments with *dim. 1* < -0.5 are situated within a distance of less than 2 km to the Elbe river; all sub-catchments with *dim. 1* > 1 are situated at the leanings of the Elbe valley, i.e. in most cases at a distance of more than 4 km to the Elbe river. Thus, this dimension might stand for a geographical location. The interpretation of *dim. 2* is more distinct: the smaller the value of *dim. 2*, the more urban is the sub-catchment. However, both interpretations – localisation and degree of urbanisation – are not independent from each other as shown below. Other interpretations might be possible.

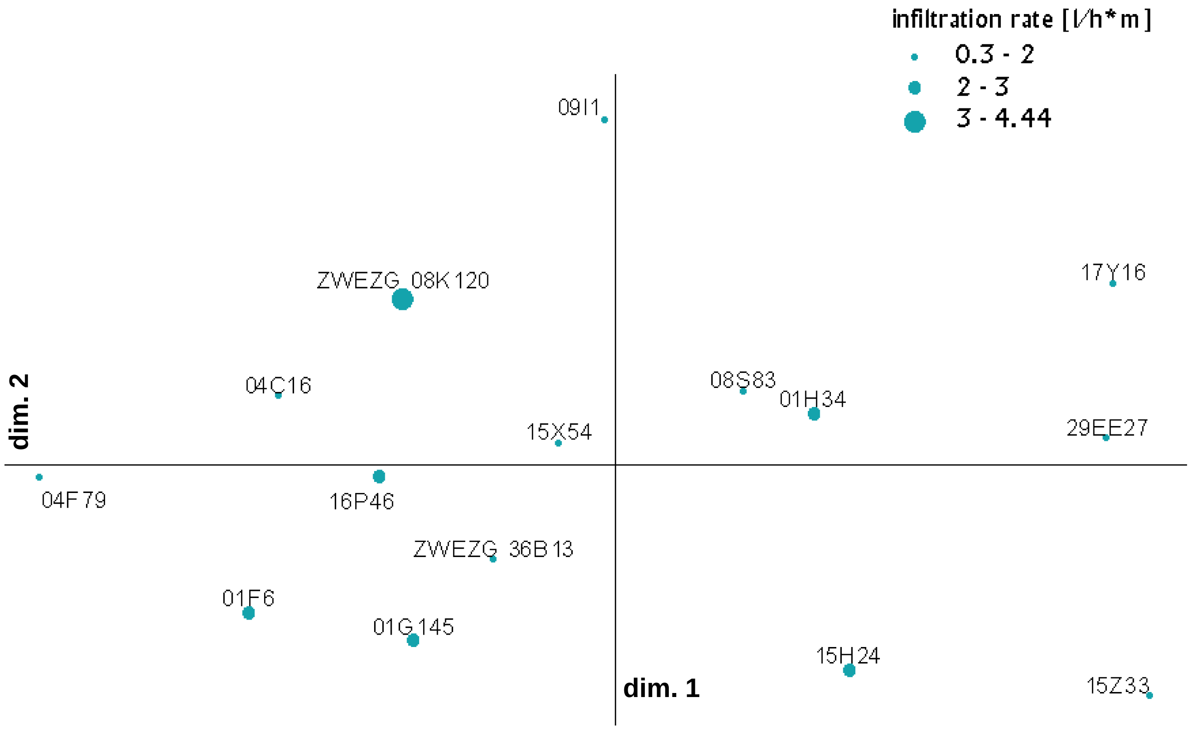


Figure 3-11. End configuration: Dresden data without gw, *STRESS* = 0.117, with $q_{I/I}$

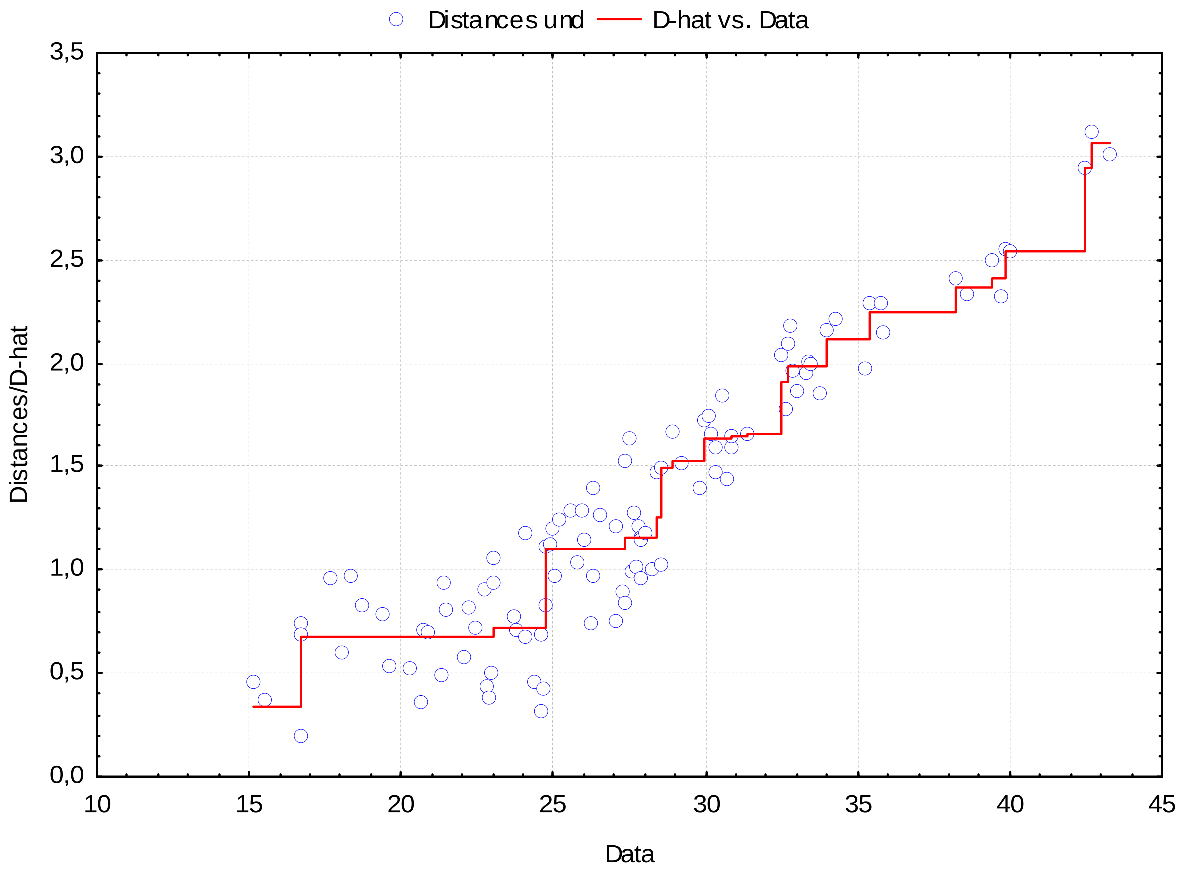


Figure 3-12. Shepard diagram: Dresden data without gw

In a next step, the data set was reduced to only one dimension. The *STRESS* amounted to 0.195. The dimension values are displayed in Figure 3-14. Furthermore, significant correlations between the obtained dimension values and metrical attributes are listed in Table 3-7. From these results it can be clearly concluded, that *dim. 1* of the 1D configuration stands for the degree of urbanisation and urban development, respectively.

A deeper investigation of the correlation coefficients shows that the mainly topographically and geologically influenced attributes *THICK_COHSV*, *DIST_WATER*, *SLOPE* and with restrictions *COVERAGE* have the smallest absolute coefficient values. Obviously, they are not or only weakly coupled to the urban development. The positive or negative orientations of the technical attribute *PROF_CIRC*, the population density related *POP_DENS* and *POP_LENGTH* as well as the historically influenced *DATE_CONSTR* and *DIST_STORM* indicate a more or less concentrical development of the city of Dresden and its sewer system.

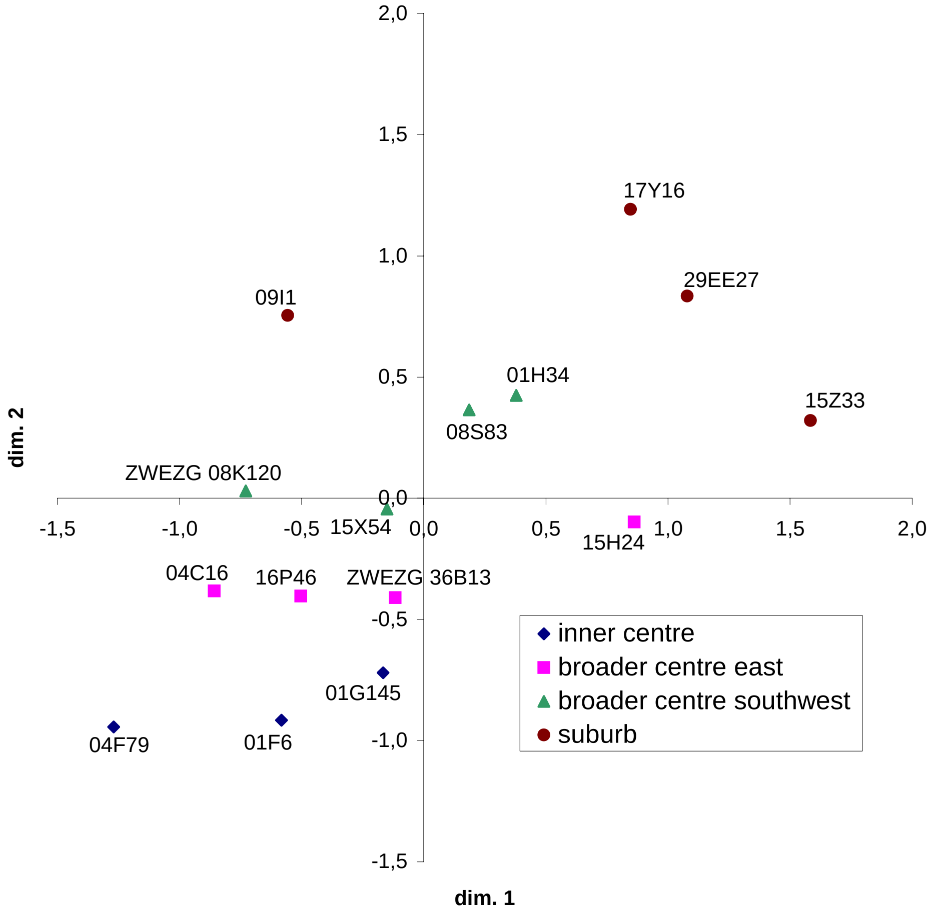


Figure 3-13: End configuration: Dresden data without gw, *STRESS* = 0.117, rotated, with quarter type

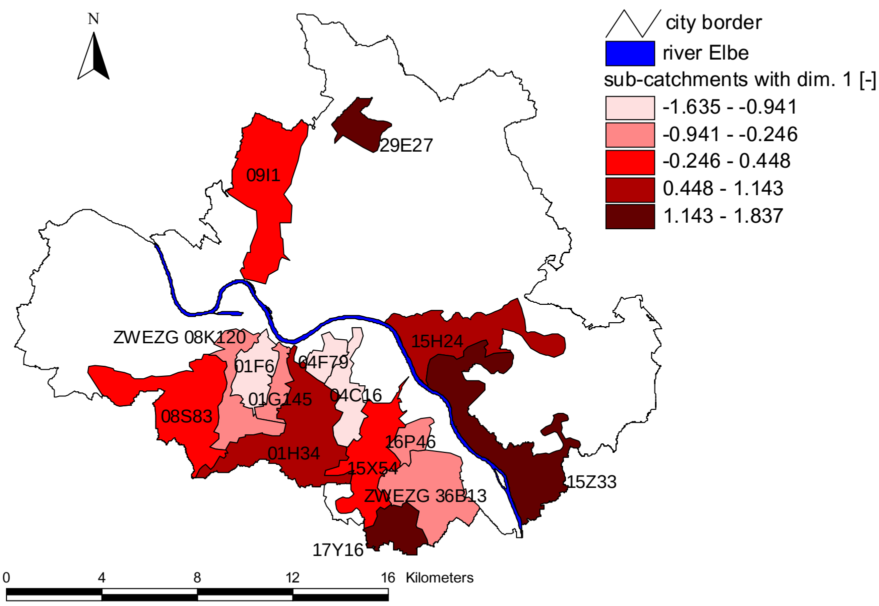


Figure 3-14. Values of *dim. 1*, Dresden data without gw, *STRESS* = 0.195

Table 3-7: Significant correlations between *dim. 1* and single attributes

Attribute	Correlation coefficient *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(city centre) < *dim. 1*(suburb)	

In order to include groundwater information into the MDS the data sets with available groundwater information were modified (Figure 3-4, Table 3-8). Reaches not influenced by groundwater were eliminated. For the remaining ones the reach-related water head was calculated as difference between the time-weighted groundwater level and the pipe invert. Additionally, mean heads for the single sub-catchments were determined. The attributes *SEW_SYSTEM*, *DIST_DRAIN* and *DIST_STORM* were excluded. The sewer system in the relevant subcatchments is combined, only. A Kruskal-Wallis-ANOVA showed no significant differences between the reach populations for the other two attributes. The I/I rates were recalculated as specific values related to the total sewer surface influenced by groundwater.

The water head cannot be implemented as simple additional attribute. This becomes apparent by examining the infiltration model given in Equation 2-8. Altered for a specific infiltration rate the equation is:

$$q_{infiltration} = k_L \cdot \Delta h \qquad \text{Equation 3-6}$$

In principle, the factor k_L encompasses all attributes of sewers and sub-catchments. The water head Δh influences exclusively all of those attributes. Thus, the attribute values of the reaches were weighted due to the relevant groundwater level.

Table 3-8. Characteristics of the investigated sub-catchments with gw information

Sub-catchment	Fraction of gw influenced sewers [%]	Total gw influenced sewer surface [m²]	I/I rate [L/m²·h]
Dresden catchment			
01F6	14.9	29,627	5.00
01G145[1]	0.6	923	81.26
04C16	2.7	10,660	4.50
04F79	2.7	6,615	2.87
16P46	19.2	4,354	7.35
ZWEZG 36B13	4.1	10,323	8.52
Bottrop catchment			
F42	14.2	611	7.66
F99	67.4	9,688	3.67
F90	55.6	6,440	3.33
F50	18.6	5,299	2.96
F46	75.1	10,015	2.34

[1]outlier, was not considered further

The Dresden data set was reduced to one dimension in order to achieve an easy comparability of the results and other variables. The *STRESS* value amounted to 0.236. This value is acceptable due to the data reduction done beforehand. The results of the MDS are shown in Figure 3-15 compared to the specific I/I rates. A good correlation with $R^2 = 0.87$ was found between the rates and *dim. 1* which represents sewer, sub-catchment and groundwater data, i.e. factors determining infiltration processes. The comparison between the specific I/I rate and the mean water head shows, that this correlation and with it the specific infiltration rate is not dominated by the water head (Figure 3-16).

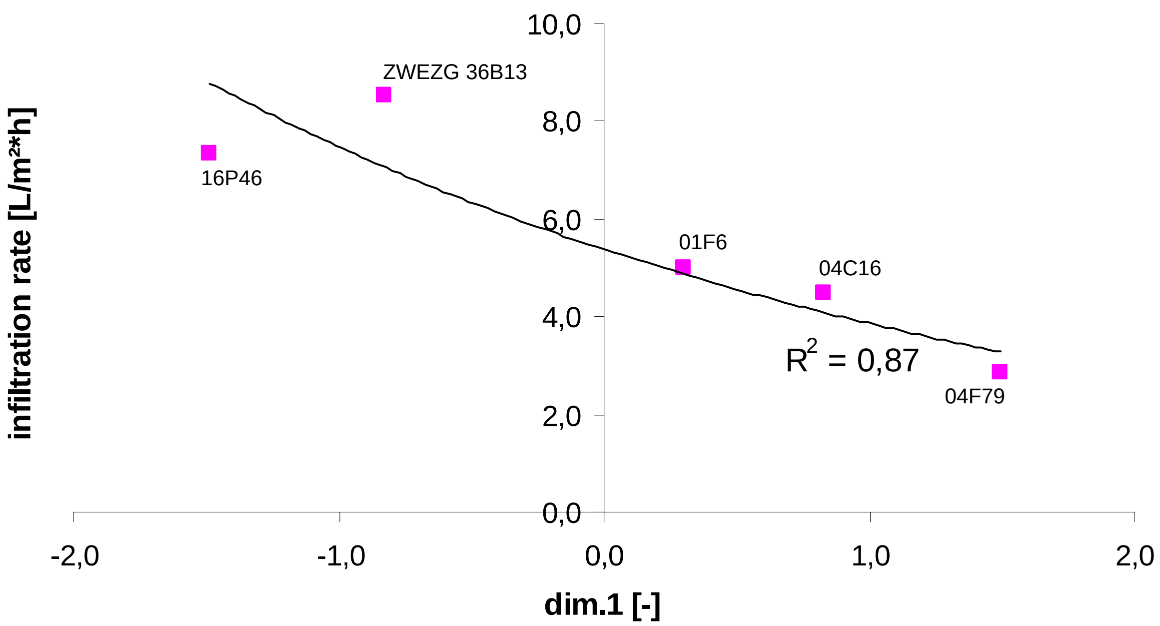


Figure 3-15: *Dim. 1* vs. specific infiltration rate, Dresden data with gw, *STRESS* = 0.236

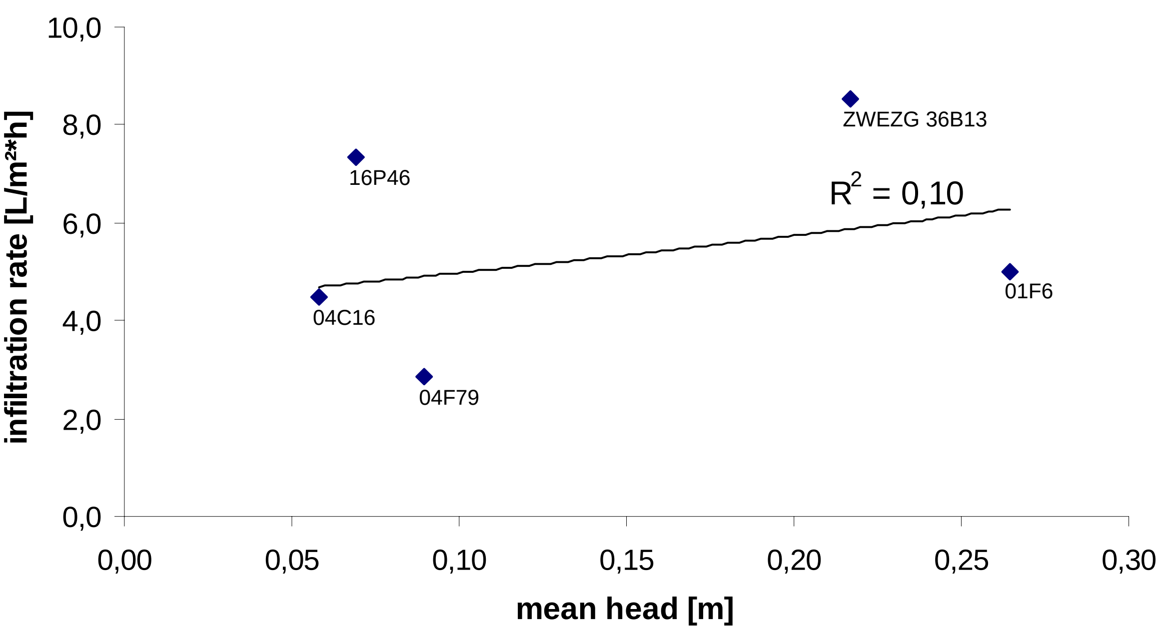


Figure 3-16: Mean water head vs. specific infiltration rate, Dresden data with gw

In a further step, the data sets with groundwater information of both catchments were combined. The intersection of different data sets and the regard of several missing data yield a reduced data base: the attributes *PROF_CIRC*, *LENGTH*, *POP_DENS*, *DIST_WATER*, *DIST_BUILD* and *SLOPE* were analysed, only.

The combined data were reduced to one dimension. The *STRESS* value amounted to 0.026. The reason for this improvement compared to the cases above is not clear. The result of the MDS confronted with specific I/I rates is shown in Figure 3-17. The affiliation to the Dresden or Bottrop catchment is marked. Since the data bases differ, the changed input pattern yields different values of *dim. 1* for the Dresden sub-catchments compared to Figure 3-15.

The correlation between *dim. 1* and $q_{I/I}$ is good and similar to the one above. But, significant differences of the I/I amount between the catchments and cities, respectively, could be observed. The interpolated specific I/I rate of the Dresden sub-catchments is higher with a difference $\Delta q_{I/I} \approx 2$ L/(m²·h). It is not clear whether this difference is based on natural/regional factors like the hydro-geological situation or on artificial/local factors like the building history (chapter 2.4.2). Anyway, a transfer of results of I/I investigations between different catchments does not seem to be reasonable.

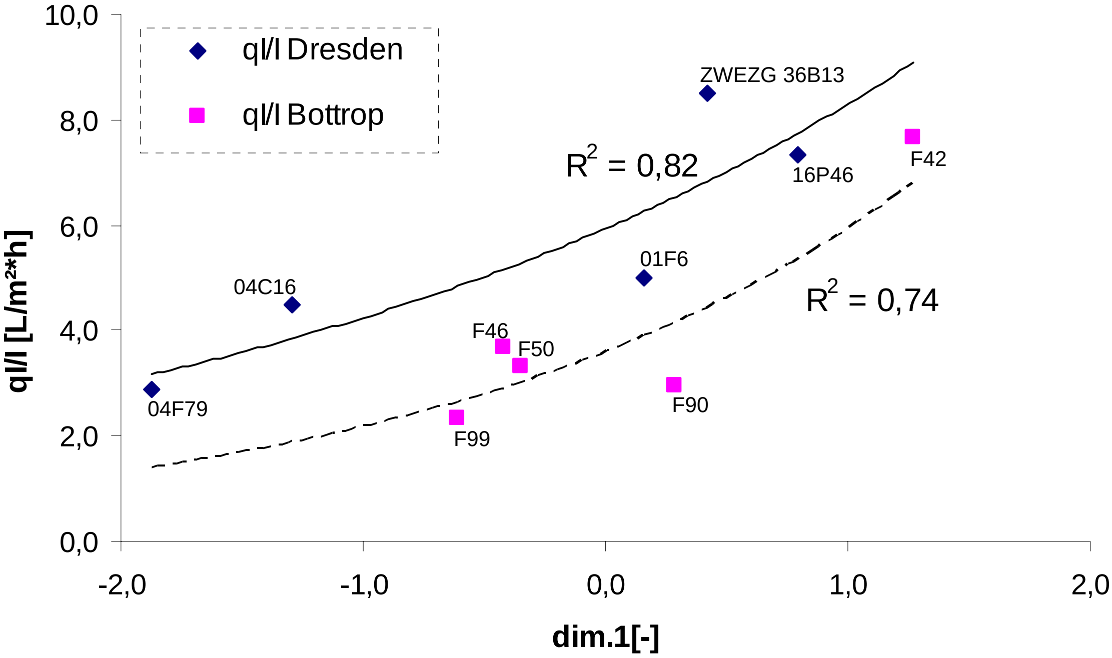


Figure 3-17: *Dim. 1* vs. specific infiltration rate, Dresden and Bottrop data with gw, *STRESS* = 0.026

3.3.4 Conclusion

By means of limited data sets of two catchments similarities and differences between sub-catchments with different I/I rates were investigated. Furthermore, relationships between sewer and sub-catchment characteristics and the corresponding I/I rates were analysed.

With ANOVA techniques it could be shown, that reach populations and sub-catchments, respectively, differ significantly. Even group-to-group comparisons indicate a high significance of attribute differences (Figure 3-6). But, the explanatory power of these results for I/I purposes has to be attenuated as the mostly used parametric tests are very selective.

Statistically based relationships between independent reach-related attributes and dependent I/I rates could not be investigated by means of commonly used multiple regression analysis, because the I/I rate is a mean value for a multitude of reaches. Thus, the data were analysed by means of multidimensional scaling which belongs to multivariate methods of the exploratory data analysis. The analysis of data without groundwater information showed no relation between attributes and I/I rates, but a clear linkage between the development of cities and the development of their sewer systems (Figure 3-13, Figure 3-14).

The analysis of data with groundwater information yields a good correlation between *dim. 1* representing sewer, sub-catchment and groundwater data and the specific I/I rate. This correlation is not dominated by the water head between the groundwater level outside and the waste water level inside the pipe (Figure 3-15). It can be concluded that on the one hand there is a recognisable relationship between reach attributes and I/I rates and on the other hand the attributes or a part of them are suitable to describe infiltration, whereas groundwater information is essential. Therefore, the assumption of the similarity approach "Similar sewer conditions lead to similar infiltration/inflow rates" can be the fundament for methods and applications which look for and work with similar entities within a sewer system.

3.4 Relevance of attributes

In order to determine the importance of attributes for sub-catchment discrimination and to identify redundant attributes further statistical investigations were performed.

For every metrical and ordinal attribute, the number of significant post-hoc tests, i.e. the number of significant differences between all sub-catchment pairs (chapter 3.3.2), were summarised and standardised to the maximum possible value (Table 3-9). These fractions represent a ranking of the attributes regarding their responsibility for dissimilarities between sub-catchments. A high fraction and frequency, respectively, equals a high importance for differences between sub-catchments.

The rankings for both catchments are very similar. Attributes related to the distance to surface waters and population density are of outstanding interest. This might be the result of a differentiated urban development of different quarters. The attributes most unimportant for the observed dissimilarities – but not necessarily for infiltration/inflow – are *DIST_BUILD*, *DIST_STREET*, *LENGTH*, *STREET_TYP* and *SLOPE*. This finding is comprehensible, because these attributes have to be relatively similar due to technical reasons and the purpose of sewer systems.

Most attributes have a high frequency due to the selective power of the used tests. The generally lower values for the Bottrop catchment result from a lower number of relevant sub-catchments and a higher similarity between those sub-catchments (Table 3-1).

For nominal attributes the contingency measure between the attribute and the sub-catchment affiliation was determined. This measure describes the relation strength between two variables in a frequency table and is based on the Pearson χ^2 test. The measure ranges between 0 (complete independence) and 1 (Hill and Lewicki, 2006). Theoretically, a large measure stands for a high importance for differences between sub-catchments. But, an attribute ranking as such is not definite, because the contingency measure correlates with the number of possible attribute values and the value frequencies. Comparing contingency measures, number of attribute values and largest fraction of a single attribute value, the ranking shown in Table 3-10 seems to be strongly influenced by the data situation and thus not meaningful.

Table 3-9. Summarised frequency of significant pairwise differences for metrical and ordinal attributes

Dresden catchment		Bottrop catchment	
Attribute	**Frequency [%]**	**Attribute**	**Frequency [%]**
DIST_ELBE	95	*DIST_WATER*	100
POP_DENS	95	*POP_DENS*	90
DIST_DRAIN	94	*POP_LENGTH*	90
POP_LENGTH	94	*K*	90
THICK_COHSV	94	*COVERAGE*	80
DIST_STORM	91	*LENGTH*	80
DIST_WATER	91	*SLOPE*	80
COVERAGE	85	*PROF_CIRC*	70
DATE_CONSTR	85	*DIST_STREET*	60
PROF_CIRC	84	*A_IAREA*	40
DIST_BUILD	70	*DIST_BUILD*	20
DIST_STREET	68		
LENGTH	61		
STREET_TYP	31		
SLOPE	15		

Table 3-10. Contigency measures nominal attributes vs. sub-catchment affiliation

Dresden catchment				Bottrop catchment[1]	
Attribute	**Contingency measure [-]**	**Number of attribute values [-]**	**Largest fraction [%]**	**Attribute**	**Contingency measure [-]**
MATERIAL	0.72	9	79.5	*MATERIAL*	0.50
SEW_SYSTEM	0.55	2	63.8		
PROF_TYP	0.49	3	59.4		
FUNCTION	0.29	3	89.2		

[1]other variables were not available or had identical values for all reaches

The multidimensional scaling was also used to investigate the inter-attribute relations. The input distance matrix was calculated based on a transposed ranked data matrix. The results are shown in Figure 3-18 for the Dresden catchment (*STRESS* = 0.179) and in Figure 3-19 for the Bottrop catchment (*STRESS* = 0.141). The interpretation of the pattern is comparable to that mentioned above: the proximity of attributes stands for a similarity, i.e. a kind of correlation.

The ellipsoid pattern (dashed lines) indicates that in principle a merging for reduction purposes is not reasonable (Gifi, 1990). The observed cluster effects (full lines) on structural data do not stand inevitably for a possible simplification. *PROF_TYP* and *PROF_CIRC* are correlated because the discrete circumference values depends on the shape. But, the attributes *MATERIAL*, *SEW_SYSTEM, DATE_CONSTR* and in case of Bottrop *NO_JOINTS* can be certainly simplified to a factor construction period or standard of construction as discussed in chapter 2.3.1.4. The distinct separation of these attributes in Figure 3-19 is ambiguous and may stand for a particular importance. An interpretation of the obtained dimensions in terms of physical properties was not possible.

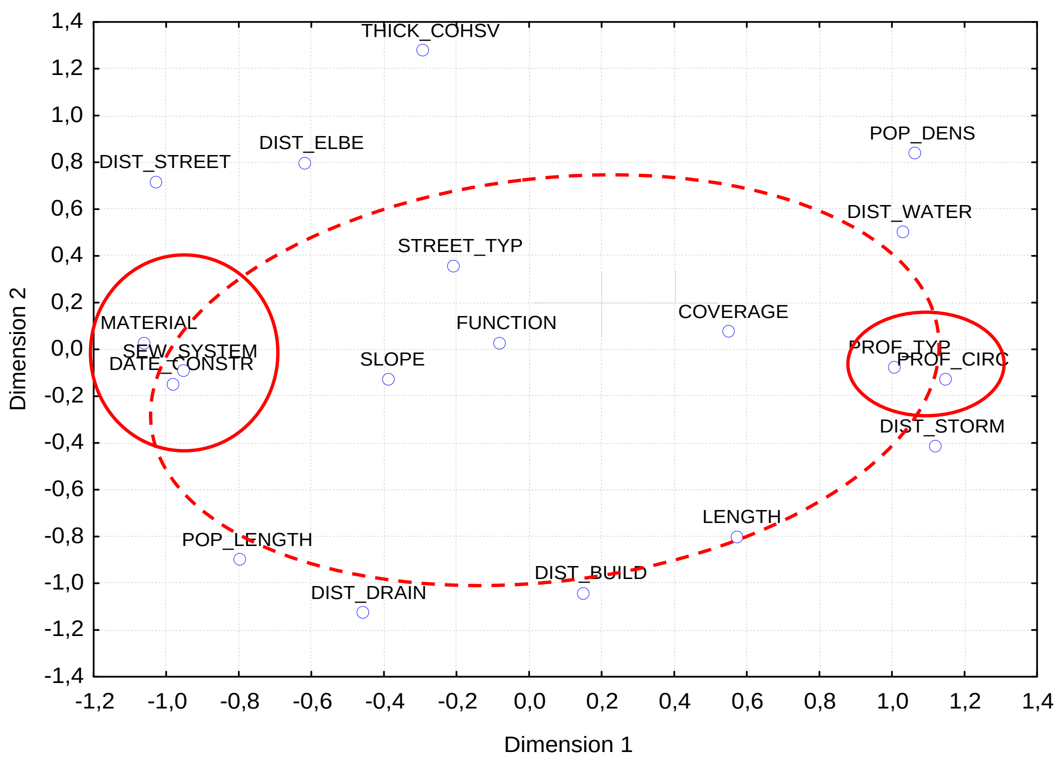


Figure 3-18. End configuration: attributes of the Dresden data, *STRESS* = 0.179

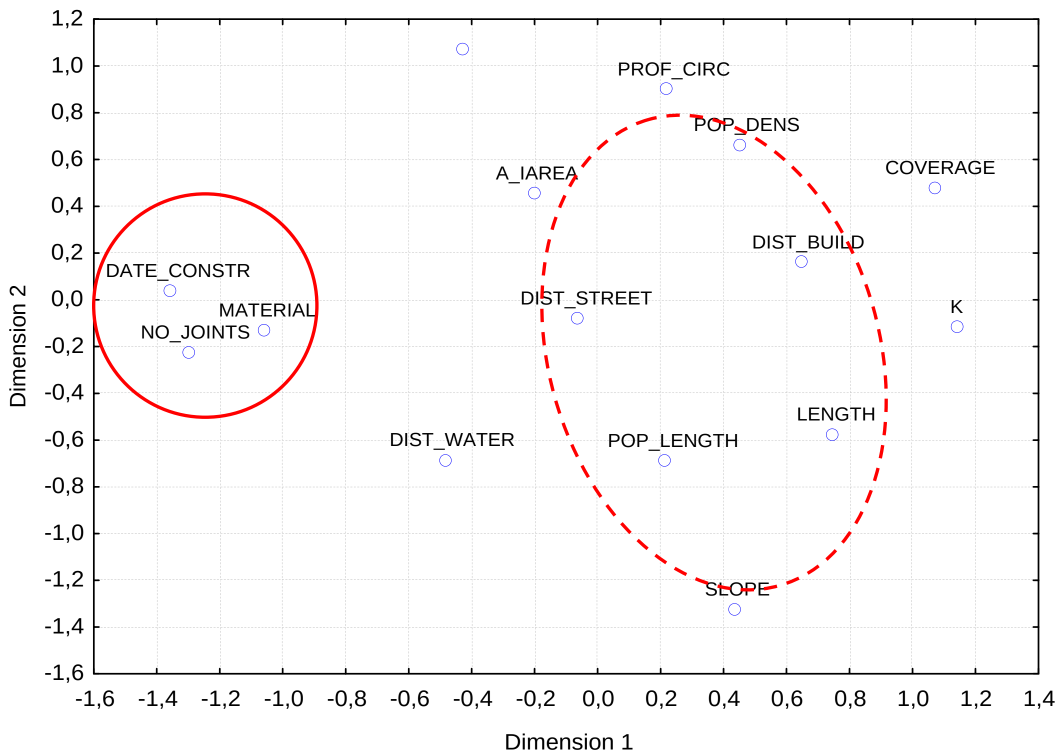


Figure 3-19. End configuration: attributes of the Bottrop data, STRESS = 0.141

Although some unconventional methods were used to investigate relations between independent attributes and I/I rates (chapter 3.3.3) and inter-attribute relations (chapter 3.4) the results confirm the literature review. It was not possible to pinpoint one attribute or a small group of attributes as being of overriding importance for discriminating sub-catchments and describing the I/I situation of a sewer system. Some corresponding results are given in chapter 5.3.1.3.

Some qualitative assessments could be made, though. The attribute groups pipe location (e.g. distance to streets, buildings) and dimensions (e.g. profile type, circumference, length) are less important. Building circumstances (e.g. date of construction) and external loads (e.g. coverage, population density) are of higher importance. Groundwater information connected with surface water information is essential.

Generally, the determination of construction periods would be very valuable. But, for the available data sets this was not possible. For the Bottrop sub-catchments, the range and coverage of the age data were unsufficient. For the

Dresden data, it was not possible to find a definition with a reasonable resolution. Distinct construction periods were not detectable especially for the period between World War II and the German reunification (Schmeißer, 2003).

3.5 Blind alleys

While applying the similarity approach several methods and techniques were investigated which did not yield results or were not applicable.

Classification

Common classification methods as well as artificial neural networks (Haykin, 1994) and pattern recognition (Kiers et al., 2000) were not applicable, because reaches could not be considered as independent from each other.

Geostatistics

Typical applications of geostatistical methods are the investigation of mining or contaminated sites. Under the conditions of natural investigation objects with continuous characteristics geostatistics yields better results than classical statistics, e.g. the use of semi-variograms and kriging compared to calculating the mean. An overview can be found in Wackernagel (1998) or Walford (1995).

Geostatistics is conditionally suitable for quasi one-dimensional investigations objects like sewer networks. Only one example for a more or less comparable object could be found: an investigation of river sediments (Stoyan et al., 1997). In technical networks the discontinuities of properties are too extreme to be handled by geostatistical methods. Thus, these methods were not applicable.

Grids

The breakdown of very large investigation areas into grids is very common, e.g. for investigating water mains (Kleiner and Rajani, 2001) or for balancing river basins compounds (Biegel et al., 2004). For the investigated catchments such a breakdown with information loss was not necessary.

4 Optimal measuring points

4.1 Basic concept

Theoretically provided that the infiltration/inflow measurement for a sub-catchment is error free, the difference between the actual and the measured I/I rate for a single reach $reach_i$, i.e. the remaining error, evolves from averaging:

$$e_{reach_i} = \left| Q_{I/I,real,reach_i} - LENGTH_{reach_i} \cdot \frac{Q_{I/I,measured}}{\sum_{j=1}^{n_{reach}} LENGTH_{reach_j}} \right| \qquad \text{Equation 4-1}$$

with e error
$Q_{I/I,real}$ real I/I discharge
$Q_{I/I,measured}$ measured I/I discharge, supposed to be true

Due to the discrepancy between the sewer lengths covered by single I/I measurements (*LENGTH* » 10 km) and those covered by detailed rehabilitation planning (*LENGTH* < 2 km) misdirected investments are likely. Thus, the mentioned error has to be minimised by determining an optimal positioning of measurement points (MPs) within a catchment.

With the use of the similarity approach such optimal positionings are associated with homogeneous reach populations, i.e. optimal positionings can be determined by finding MPs which maximise – to the greatest possible extent – the similarity and homogeneity, respectively, of the upstream sub-catchments. This is schematically shown in Figure 4-1. In this figure the real specific I/I rate of a linear sewer consisting of three sections with different reach types and different resulting I/I rates is displayed and compared with the measured and averaged I/I rates of an equal, arbitrary and an optimised distribution of MPs. The respective measurement error is the sum of differences between the curves. The optimised positioning yields much better results, i.e. a minimised error.

The aim of the optimisation is the determination of the number and the distribution of I/I measurement points within a catchment. Thus, the method development consists of two tasks:

- Development of a similarity measure: For every potential sub-catchment a similarity measure and homogeneity degree, respectively, has to be defined. This measure has to have an interval or ratio scale. Based on it, MPs can be compared, approved and disapproved. Additionally, the measure should represent a potential uncertainty or information yield.
- Development of an optimisation algorithm: The MP distribution has to be optimised based on the relevance of single MPs and the network structure. The limited number of MPs is either given or determined by suitable criteria.

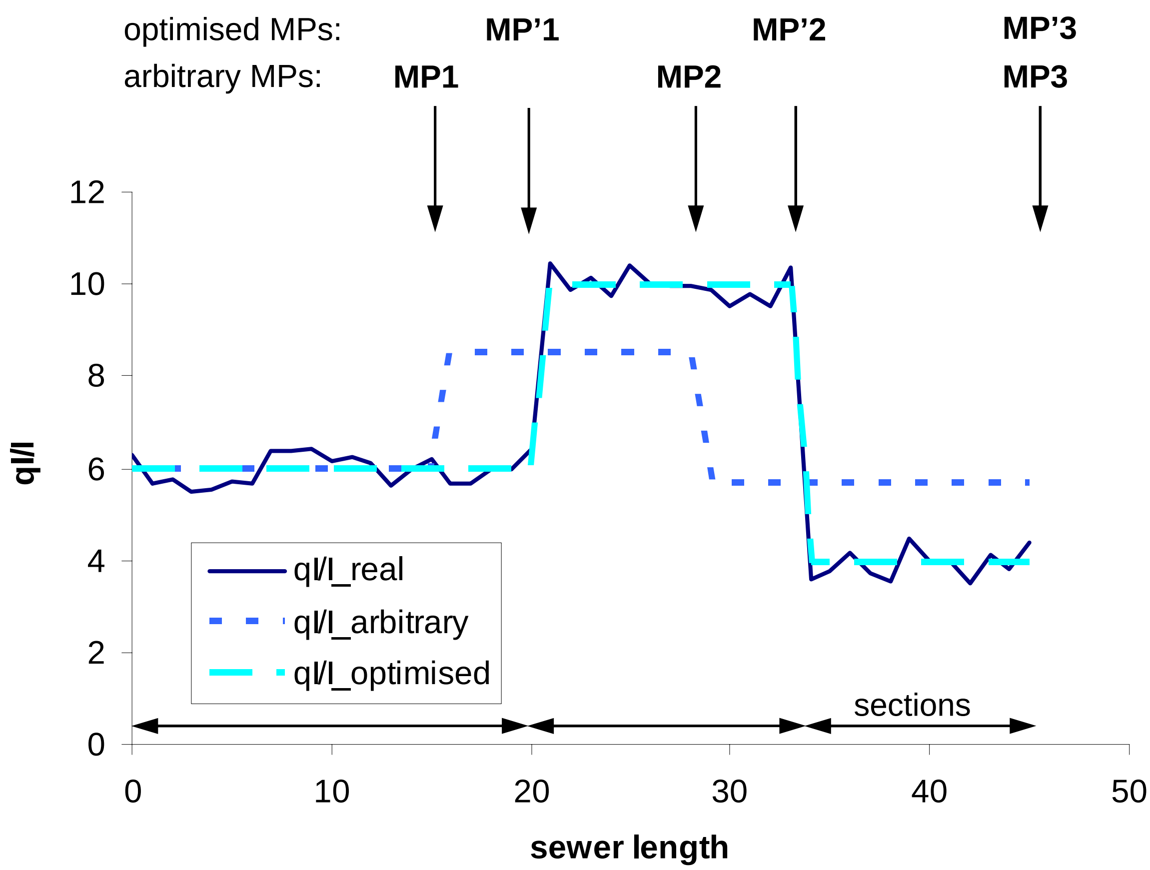


Figure 4-1. Basic concept of the optimal positioning of MPs

4.2 Cluster analysis

4.2.1 Approach

The task of the identification of homogeneous reach populations within a basic population is comparable to cluster analysis. Cluster analysis or clustering comprehends a group of methods which belong to the exploratory data analysis and detect structures in data sets. They follow the concept of the equivalence between distance and dissimilarity (chapter 3.3.3.2).

The aim of clustering is the grouping of items based on their attributes into classes and the partitioning of a data set into sub-sets (clusters), respectively. The items in a class are to be similar, items from different classes should distinctly differ. Typically, the number and the characteristics of the classes are unknown at the beginning of the analysis.

The commonly used deterministic cluster methods are either partitional or hierarchical. Partitional algorithms determine all clusters at once, whereas hierarchical ones find clusters successively. Hierarchical algorithms can be agglomerative or divisive. Agglomerative algorithms begin with each item as a separate cluster and merge them stepwise to larger clusters. Divisive algorithms begin with the whole data set and proceed to divide it into smaller clusters (Bacher, 1996).

Hierarchical agglomerative clustering is relevant for developing a MP positioning method. It is independent from the number of classes and is more meaningful regarding the structure of data. But, the single steps of hierarchical methods are irreversible.

A simplified clustering algorithm is shown in Figure 4-2. It consists of three stages (adapted from Backhaus et al., 1994; Kurth, 2004):

1. Acquisition and pre-processing: Acquired attribute values have to be standardised because distance measures for metrical attributes are often not scale invariant. Thus, the attributes become comparable.
2. Selection of the distance or proximity model: The selection depends on the problem which is to be solved. Distance measures can be a metric, i.e. the triangle inequality applies, or a pseudometric.

3. Clustering: The items and clusters are successively merged. The merging is based on fusion algorithms. The selection of the algorithm depends on the problem which is to be solved. The clustering result is assessed by a homogeneity measure.

A comprehensive explanation and consideration of cluster analysis is given in Kaufman and Rousseeuw (1990) or Bacher (1996).

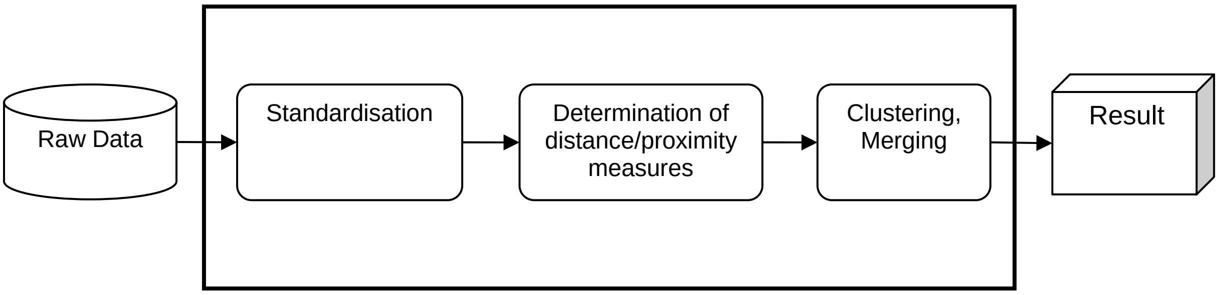


Figure 4-2: Algorithm of cluster analysis (Kurth, 2004)

4.2.2 Procedure

4.2.2.1 Standardisation

Distance measures for metrical attributes are mostly not scale invariant, i.e. they are sensitive to different attribute magnitudes. Therefore, all attributes have to have a similar range. Otherwise they would have an unintentional weighting, i.e. attributes with a much larger range than other ones would dominate the distance measure. The problem of different attribute ranges is solved with standardisation (e.g. Stoyan et al., 1997). The following options are common:

– Standardisation to characteristic values like mean, median, maximum

$$z_{ij} = \frac{x_{ij}}{\bar{x}_i} \qquad \text{Equation 4-2}$$

with z_{ij} standardised value j of attribute x_i
x_{ij} value j of attribute x_i
$\bar{x}_i$ mean value of attribute x_i

– Standardisation to extreme values (interval-0-1-standardisation)

$$z_{ij} = \frac{x_{ij} - x_{i,min}}{x_{i,max} - x_{i,min}} \qquad \text{Equation 4-3}$$

with $x_{i,min}$ minimum value of attribute x_i
$x_{i,max}$ maximum value of attribute x_i

– Standardisation to variances (z-transformation)

$$z_{ij} = \frac{x_{ij} - \bar{x}_i}{s_i} \qquad \text{Equation 4-4}$$

with s_i empirical standard deviation

– Standardisation to relevance (weighting)

$$z_{ij} = w_i \cdot z_{ij} \qquad \text{Equation 4-5}$$

with w_i weighting factor

The first two options standardise the range only, the z-transformation standardises range and distribution. The weighting is only used in combination with other options. All options can be done with theoretical or empirical values, i.e. physical possible or measured values.

4.2.2.2 Distance and proximity measures

Similarities and dissimilarities of items are determined indirectly by calculating distance measures d and proximity measures s, respectively. Given three items o_1, o_2 and o_3, for these measures the following applies:

$$d(o_1, o_1) = 0 \qquad \text{Equation 4-6}$$

$$d(o_1, o_2) \geq 0 \qquad \text{Equation 4-7}$$

$$d(o_1, o_2) = d(o_2, o_1) \qquad \text{Equation 4-8}$$

$$s(o_1, o_2) \le s(o_1, o_1) \qquad \text{Equation 4-9}$$

$$s(o_1, o_2) = s(o_2, o_1) \qquad \text{Equation 4-10}$$

For metrical distance measures the triangle inequality applies:

$$d(o_1, o_2) \le d(o_1, o_3) + d(o_2, o_3) \qquad \text{Equation 4-11}$$

Distance measures can be transformed in proximity measures and vice versa (Fahrmeir et al., 1996). The approach for the measures differs depending on the statistical scale.

In general, distance measures are appropriate when the absolute distance of items is relevant, i.e. the dissimilarity between the items. Proximity measures are appropriate, when the shape of attribute profile is of interest rather than the level, i.e. the correlation between the items (Backhaus et al., 1994). Therefore, only distance measures are relevant for developing a MP positioning method and described in the following. A comprehensive overview is given in Bacher (1996).

Nominal attributes

If the nominal attribute has just two possible values (e.g. binary: 0, 1) there are four possible situations for two items as given in Table 4-1 (Backhaus et al., 1994).

Table 4-1. Contingency table for two items with nominal binary attributes

	$x_{i,o1} = 1$	$x_{i,o1} = 0$
$x_{i,o2} = 1$	$n_{1,1}$	$n_{0,1}$
$x_{i,o2} = 0$	$n_{1,0}$	$n_{0,0}$

The distance is then calculated with

$$d(o_1, o_2) = 1 - \frac{n_{1,1} + \delta \cdot n_{0,0}}{n_{1,1} + \delta \cdot n_{0,0} + \lambda \cdot (n_{1,0} + n_{0,1})} \qquad \text{Equation 4-12}$$

with n matching frequency
δ weighting factor
λ weighting factor

The weighting factors characterise a multitude of distance measures, e.g. simple matching for $\delta = \lambda = 1$. A comprehensive list is given in Steinhausen and Langer (1977).

Nominal attributes x_i with more than two values become binary coded. Thereby, the attribute is replaced by the possible attribute values, e.g. stoneware, concrete and brickwork instead of material. Then, the binary values existent or not existent are allocated to these new attributes (Table 4-2).

Another possibility to treat nominal attributes with more than two values is the generalised M-coefficient (Backhaus et al., 1994):

$$d(o_1, o_2) = 1 - \frac{n}{\sum x_i} \qquad \text{Equation 4-13}$$

Ordinal attributes

Ordinal attributes can be binary coded (Table 4-2) and treated as nominal binary attributes, or they can be treated as metrical attributes. In that case they are additionally standardised on an interval [0, 1]:

$$d(o_1, o_2) = \frac{\left| x_{i,o_1} - x_{i,o_2} \right|}{x_{i,max} - x_{i,min}} \qquad \text{Equation 4-14}$$

Table 4-2. Binary coding of nominal and ordinal attributes

Statistical scale	Values	Coding / new attributes
Nominal	$x_{i,1} \neq x_{i,2} \neq x_{i,3}$	$x_{i,1} = (1,0,0)$
		$x_{i,2} = (0,1,0)$
		$x_{i,3} = (0,0,1)$
Ordinal	$x_{i,1} < x_{i,2} < x_{i,3}$	$x_{i,1} = (1,0,0)$
		$x_{i,2} = (1,1,0)$
		$x_{i,3} = (1,1,1)$

Metrical attributes

Distance measures for metrical attributes are mainly deduced from the generalised Minkowki-metrics (Fahrmeir et al., 1996):

$$d(o_1, o_2) = \left(\sum_{i=1}^{n} \left| x_{i,o_1} - x_{i,o_2} \right|^r \right)^{\frac{1}{q}}$$ Equation 4-15

with r factor, $r \geq 1$
q factor, $q \geq 1$

With $r > 1$ larger differences in a few attributes are stronger weighted than smaller differences in many attributes. The factor q is to normalise back to the original unit. The use of city-block-metrics ($r = 1$, $q = 1$), Euclidean distance ($r = 2$, $q = 2$) and squared Euclidean distance ($r = 2$, $q = 1$) is common (Bacher, 1996).

In comparison to Minkowki-metrics and in particular to the Euclidean distance, an advantageous measure is the Mahalanobis distance (Fahrmeir et al., 1996):

$$d(o_1, o_2) = \sqrt{(\vec{o}_1 - \vec{o}_2)^T \cdot S^{-1} \cdot (\vec{o}_1 - \vec{o}_2)}$$ Equation 4-16

with $\vec{o}_i$ attribute vector of item o_i
S empirical covariance matrix

This distance is scale invariant, i.e. the attributes do not need to be standardised. The transformed vectors $S^{-1} \cdot (\vec{o}_1 - \vec{o}_2)$ are empirically uncorrelated. Thus, the

Mahalanobis distance is calculated with uncorrelated attributes, even if the original attributes are correlated. The significance enhancement of attributes due to correlation effects is prevented (Steinhausen and Langer, 1977). If the standard deviation amounts to zero, the Mahalanobis distance cannot be calculated. Due to the inversion of *S* a division by zero occurs.

A graphical comparison of the Euclidean and the Mahalanobis distance is given in Figure 4-3 which shows isolines around the centre or the centroid, respectively, of a points cloud. The Mahalanobis isolines form turned and distorted ellipses, i.e. they reproduce the shape of the point cloud. If the covariance matrix is equal to the identity matrix then the ellipses become circles, i.e. the distances are identical.

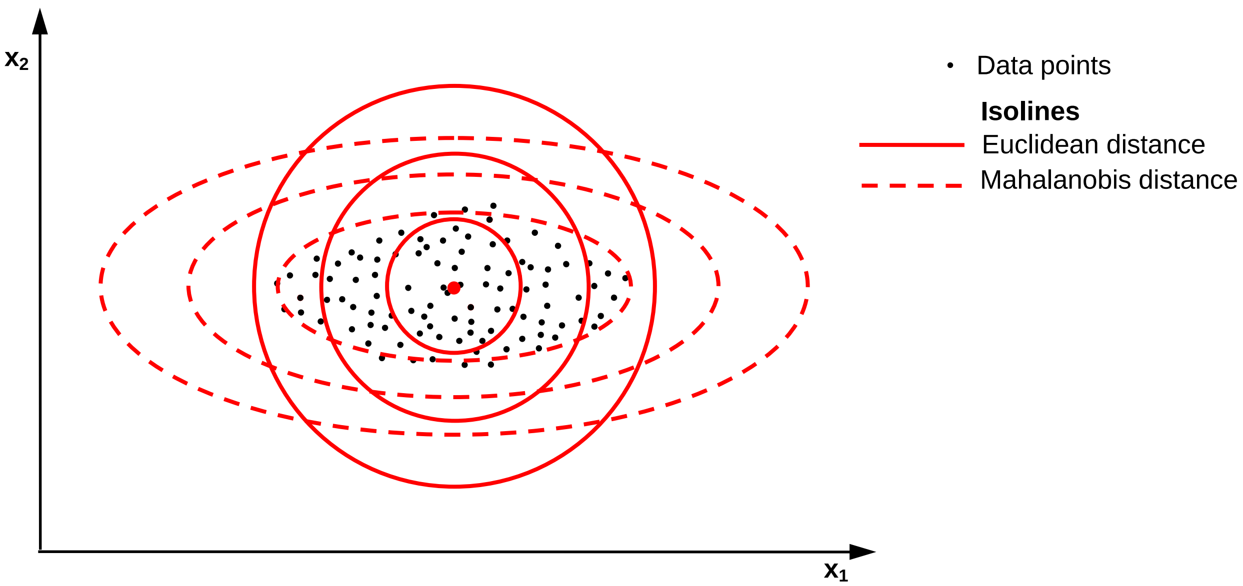


Figure 4-3. Isolines of Euclidean and Mahalanobis distance in a two-dimensional space

Attributes with different statistical scales

Beside level regression and level progression (chapter 3.2.2) attributes with quantitative and qualitative scales can be combined by the calculation of a weighted mean of all distances (Backhaus et al., 1994):

- Ordinary mean

$$d(o_1,o_2)=\frac{1}{n_{attribute}}\cdot\left(n_{nominal\_attr}\cdot d_{nominal}(o_1,o_2)+n_{ordinal\_attr}\cdot d_{ordinal}(o_1,o_2)+n_{metrical\_attr}\cdot d_{metrical}(o_1,o_2)\right)$$ Equation 4-17

- Gower coefficient (Gower, 1971)

$$d(o_1,o_2)=\frac{\sum_{i=1}^{n_{attributes}}\delta_i(o_1,o_2)\cdot d_i(o_1,o_2)}{\sum_{i=1}^{n_{attributes}}\delta_i(o_1,o_2)}$$ Equation 4-18

with δ weighting factor

4.2.2.3 Clustering and fusion algorithms

The clusters are successively merged. Each merging occurs at a greater distance between clusters than the previous one. The clustering is stopped either when the clusters are too far apart to be merged (distance criterion) or when a sufficiently small number of clusters is reached (number criterion). The obtained clusters should be completely interpretable.

The merging is based on fusion algorithms. The most common fusion methods are assessed and compared in Bacher (1996). The multitude of algorithms as listed e.g. in Bijnen (1973) are derived from four basic principles as described in Bacher (1996):

- Linkage clustering: Clusters are composed in a way that every item has a certain number of next neighbours in the cluster to which it is linked. Common examples are complete linkage or single linkage. For example, the cluster distance for the latter is calculated with

  $$d(G_1,G_2)=\min_{\substack{o_i\in G_1\\ o_j\in G_2}}\left(d(o_i,o_j)\right)$$ Equation 4-19

  with G group or cluster

– Average clustering: The clusters are characterised by the mean pairwise similarities or dissimilarities. An example is the average linkage:

$$d(G_1, G_2) = \frac{1}{|G_1| \cdot |G_2|} \sum_{\substack{o_i \in G_1 \\ o_j \in G_2}} d(o_i, o_j) \qquad \text{Equation 4-20}$$

– Items as representatives: Every cluster is represented by a typical item. New items are linked to the most similar, i.e. nearest representative.
– Cluster centroids as representatives: Clusters are defined by their centroids, i.e. their attribute means. Clusters are composed in a way that the distances between the centroids are maximised, e.g. centroid method, or that the variances of the clusters are minimised, e.g. Ward's method:

$$d(G_1, G_2) \underset{\substack{o_i \in G_1 \\ o_j \in G_2}}{=} \frac{d(\overline{o}_i, \overline{o}_j)}{\frac{1}{|G_1|} + \frac{1}{|G_2|}} \qquad \text{Equation 4-21}$$

with $\overline{o}$ mean item, cluster centroid

The kind of fusion algorithm influences strongly the formation of clusters. A schematical example is given in Figure 4-4. It displays two clusters G1 and G2 in a two-dimensional space, each with two items. Both have the same shape, i.e. the same homogeneity. Depending on the selected fusion algorithm, a new item o_{new} is assigned to the clusters due to the relevant minimum distance d_{min}:

– simple linkage: to G_2, $d_{min} = d(o_{new}, o_3)$
– complete linkage: to G_1, $d_{min} = d(o_{new}, o_1)$
– average linkage: to G_1, $d_{min} = d(o_{new}, \overline{o}_{G_1})$
– centroid: to G_1 or G_2, $d_{min} = d(o_{new}, \overline{o}_{G_1}) = d(o_{new}, \overline{o}_{G_1})$

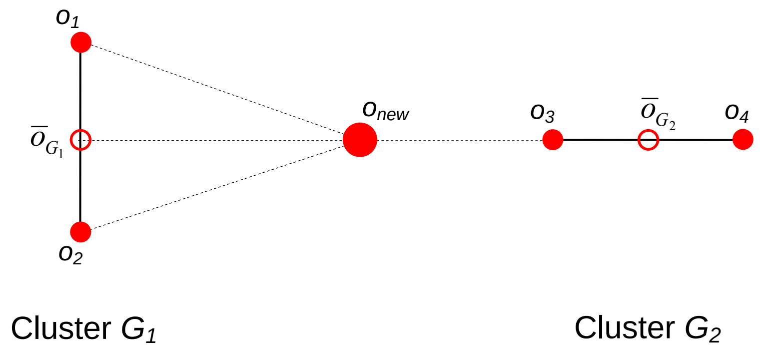


Figure 4-4. Assignment of a new item to different clusters

4.2.2.4 Homogeneity measures

A good clustering result is characterised by a maximum homogeneity of the single clusters and a maximum dissimilarity between the clusters. For the result assessment, the respective homogeneity and dissimilarity have to be described.

The existence of group homogeneity and the significance of a clustering result, respectively, can be proved by testing expected probability distributions (Bacher, 1996). Several approaches for the mean dissimilarity of all obtained clusters are given in Klastorin (1983). For comparing different clusters G_i a homogeneity measure h_i has to be defined. For a cluster containing only two items o_1 and o_2 this measure should have the properties:

$$h = 0 \qquad \text{if } \vec{o}_1 = \vec{o}_2 \qquad \text{Equation 4-22}$$

$$h > 0 \qquad \text{if } \vec{o}_1 \neq \vec{o}_2 \qquad \text{Equation 4-23}$$

For four items $o_1, o_2 \in G_1$ and $o_3, o_4 \in G_2$ it should apply

$$h_1 < h_2 \qquad \text{if } d(o_1, o_2) < d(o_3, o_4) \qquad \text{Equation 4-24}$$

For such a measure Hartung and Elpelt (1995) propose the options:

- mean distance between all items

$$h_i = \frac{1}{c} \cdot \sum_{\substack{j<k \\ o_j, o_k \in G_i}} d(o_j, o_k) \text{ with } c = |G_i| \text{ or } c = |G_i| \cdot (|G_i| - 1)$$ Equation 4-25

with c constant

- mean distance to the centroid
- maximal distance between two items within the cluster
- minimal distance between two items within the cluster
- sum of attribute variances

$$h_i = \sum_{j=1}^{n_{attribute}} s_j^2$$ Equation 4-26

Comparable to fusion algorithms, the kind of calculation influences strongly the result, i.e. the assessment of single clusters. A schematical example is given in Figure 4-5. It displays three clusters G_1 to G_3 in a two-dimensional space, each with four items. Depending on the selected measure the rankings of the cluster homogeneities h_i differ:

- mean distance between all items: $h_1 < h_2 < h_3$
- mean distance to the centroid: $h_1 < h_3 < h_2$
- maximal distance between two items: $h_1 < h_2 < h_3$
- minimal distance between two items: $h_1 = h_3 < h_2$

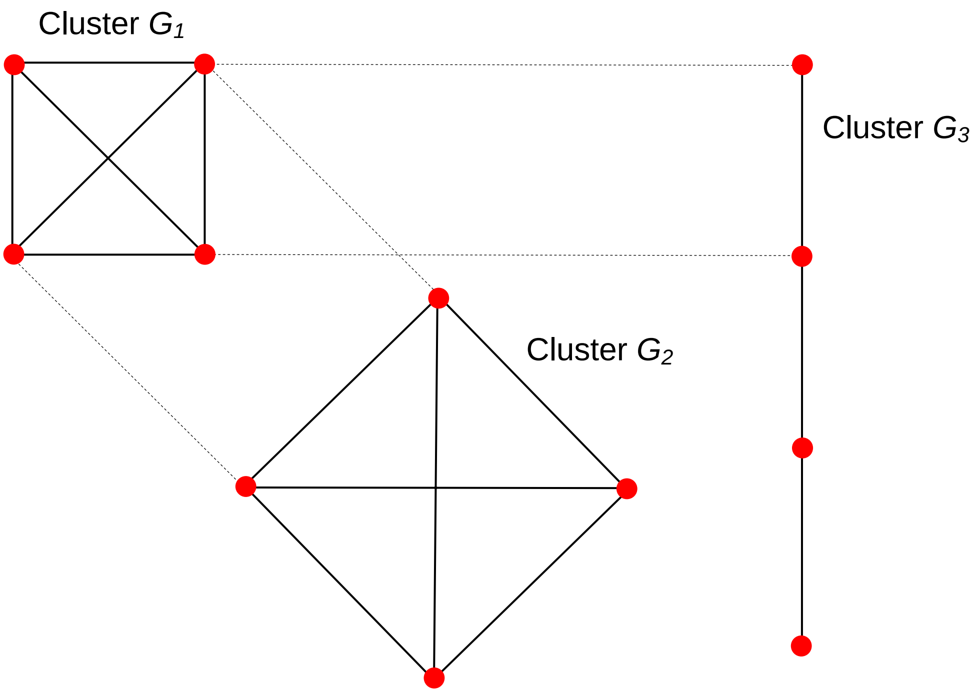


Figure 4-5. Homogeneity of different clusters

4.2.3 Example

Several cluster analyses were performed with the Dresden data. The data were reduced to the sub-catchments connected to the main WWTP (chapter 3.3.2) and the attributes *DATE_CONSTR*, *SEW_SYSTEM*, *PROF_CIRC*, *POP_DENS*, *DIST_ELBE*, *DIST_BUILD*, *DIST_STREET*, *DIST_STORM*, *SLOPE* and *COVERAGE*. The attribute *SEW_SYSTEM* is nominal and therefore not includable in a cluster analysis. Hence, the attribute was binary coded according to its possible characteristic values.

A first cluster analysis aimed at a result with two clusters in order to show general properties of sewers. The standardised cluster means are given in Figure 4-6. These values indicate several relationsships between the attributes which are mainly caused by constructive features and their historical development (compare chapter 3.4). Older sewers (cluster 2) are situated in quarters with a higher population density and closer to the Elbe river, i.e. within the city centre. They can be found mostly in combined sewer systems. Therefore, they are far away from storm water sewers and have larger dimensions. Their coverage is higher due to their location in the downstream part of the catchment at the valley bottom. Newer sewers (cluster 1) can be found mostly in outer areas within a separate sewer system.

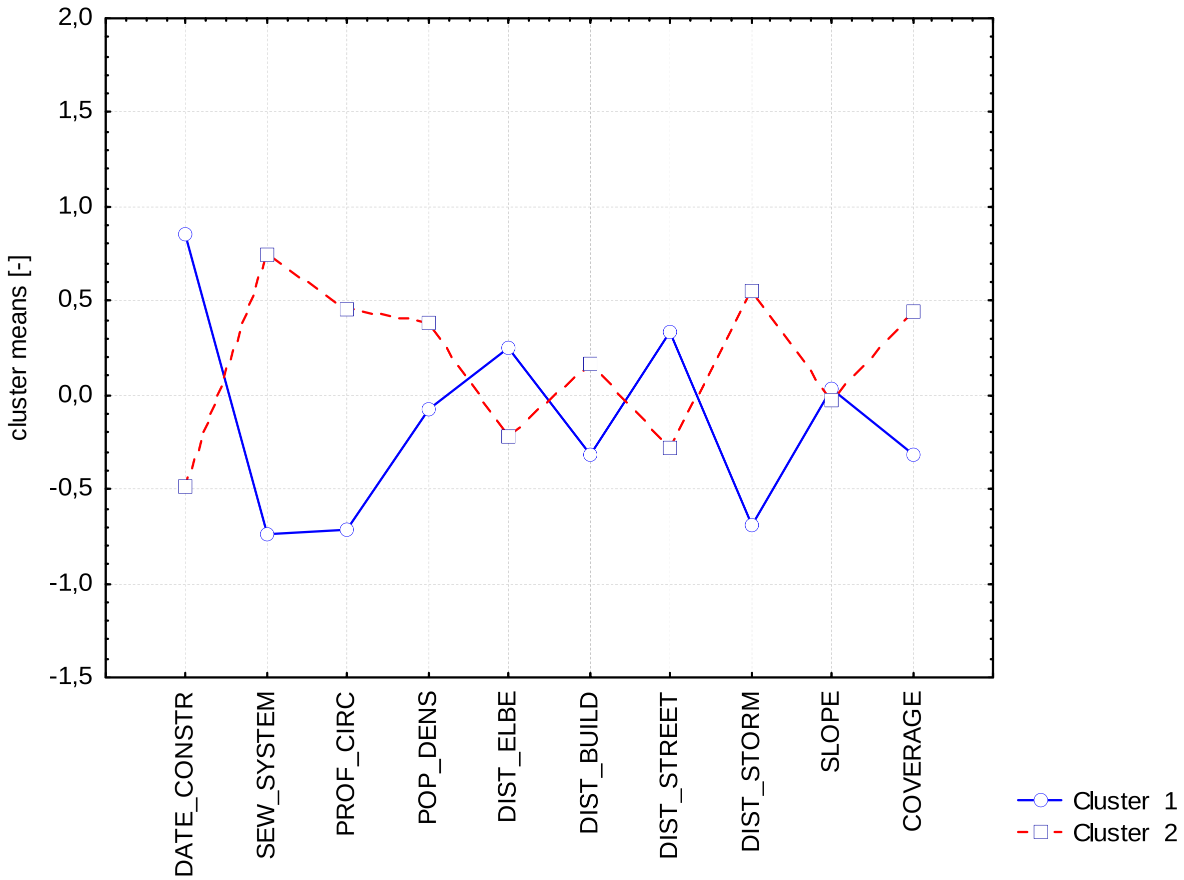


Figure 4-6. Standardised cluster means, Dresden data without gw

Figure 4-7 shows the frequencies of cluster affiliations per sub-catchment for a cluster analysis with 10 clusters. With some exceptions – the sub-catchments 29EE27, 15H24, 15Z33 and 09I1 – a multitude of different cluster affiliations, i.e. distinctly different reach types, occur within the individual sub-catchments. It can be concluded, that these real sub-catchments are not optimally defined concerning their homogeneity. A high potential of optimisation to that effect is expected.

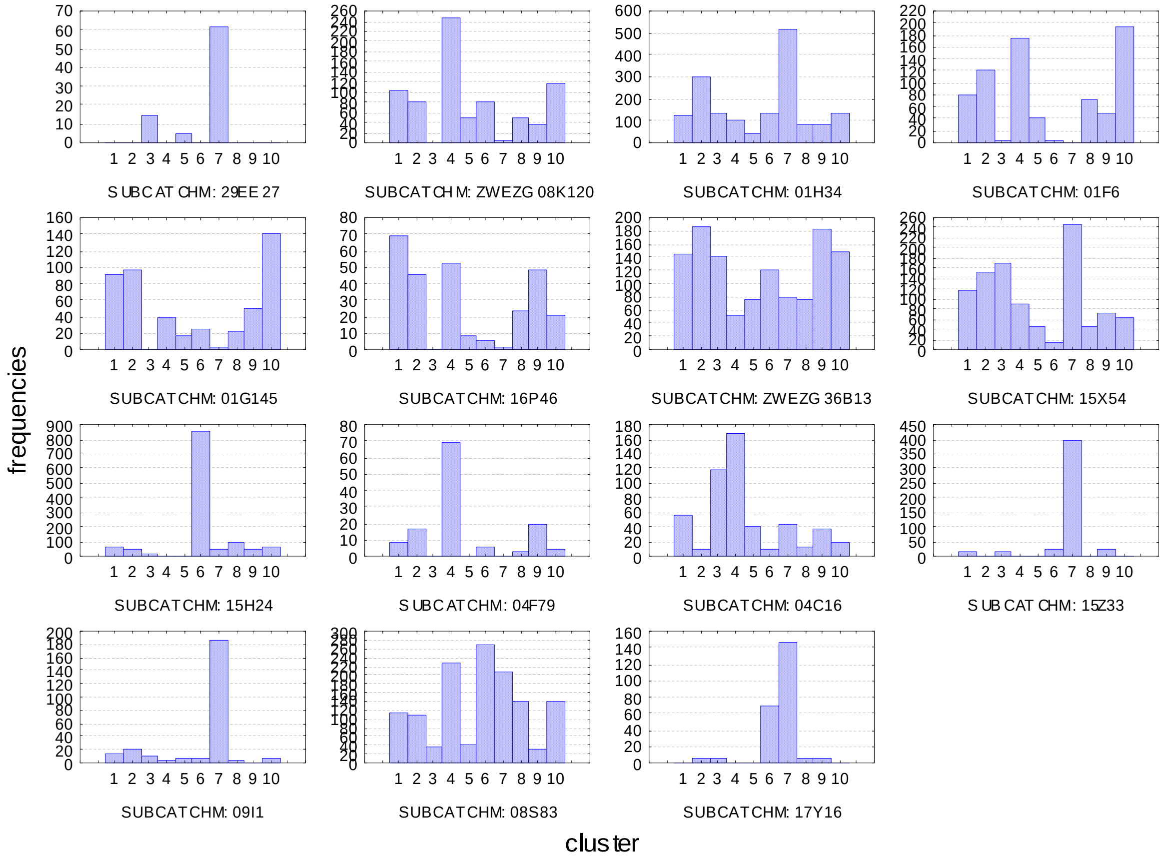


Figure 4-7. Frequencies of cluster affiliations per sub-catchment, Dresden data without gw

4.3 Similarity figure

4.3.1 Approach

A one-to-one application of cluster analysis is not feasible for the determination of a similarity measure and in the broader sense for the number and the distribution of MPs. Clustering methods classify a number of independent items. However, sub-catchments represent spatial units and their reach populations represent linked elements of a network. Therefore, reaches are not independent from each other. It is necessary to classify them with regard to spatial information in terms of network topologies but not georeferencing. This is feasible by defining a reach population, i.e. all reaches upstream of a potential MP, as a cluster.

With this definition the measures and procedures provided by cluster analysis can be used and adapted to determine the homogeneity of sub-catchments.

Based on the homogeneity measures and their calculation methods (chapter 4.2.2.4, chapter 4.2.2.2) a similarity figure φ can be defined. This measure describes the homogeneity of a sub-catchment, but not its typical characteristics. The developed algorithm for calculating the similarity figure φ consists of three steps (Figure 4-8):

1. Standardisation of the attributes
2. Determination of distance measure
3. Group aggregation to one characteristic value.

For every step several options are proposed. Thus, the calculation can be adapted to any individual data set.

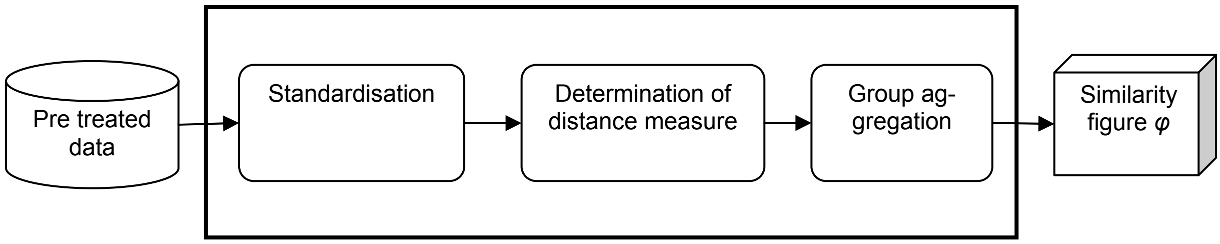


Figure 4-8. Algorithm for calculating the similarity figure for one sub-catchment

4.3.2 Procedure

Standardisation

The input is a data set containing all reaches of a catchment with their attributes. The data set should be pre-treated (outlier identification, attributes relevance etc.). The proposed standardisation methods are shown in Table 4-3. Two options were selected, which standardise the range on the one hand and the range and the spread on the other. Ordinal attributes are treated as metrical ones, i.e. ordinal attributes with n classes are coded in values 1, 2, … n due to their ranking. It is estimated, that the influence of this arbitrary information increase is not so profoundly compared with the information loss of level regression.

It is possible to weight attributes and reaches. Attributes can be weighted due to their relevance for infiltration. But, such weighting is not recommended because of the limited knowledge (chapter 2.3.1.4, chapter 3.4). Rather the reaches should be weigthed with the water head Δh due to the relationship $q_{inf\,iltration} \sim \Delta h$ (adapted from Equation 3-6) Weights like damage numbers or condition classes are conceivable but were not considered further.

Table 4-3. Pre-processing

Standardisation	**Attributes**		
	nominal	**ordinal**	**metrical**
none	X		
standardisation to extreme values		X	X
standardisation to variances		(X)	X
weighting	X	X	X

Determination of distance measure

The generalised M-coefficient is proposed for nominal attributes. For metrical and level progressed ordinal attributes the Euclidean distance as typical Minkowski-metric and the Mahalanobis distance as scale invariant and uncorrelated measure are used. While using the latter it has to be proved whether the constraint $s \neq 0$ is fulfilled for all attributes.

Group aggregation

The following group aggregations and calculations of a characteristic value, respectively, are proposed:

- mean distance to the centroid
- mean distance to the centroid of the 5 % most distant reaches.

The first option emanates from the assumption of an equal distribution of infiltration/inflow rates depending on the reach characteristics. With the calculation of a mean the influence of outliers are limited. The second option implies in contrary, that a few reaches, e.g. the most damaged, have an outstanding importance for I/I rates. The percentage of 5 % is arbitrary.

Similarity figure

The similarity figure φ is calculated for a connected reach population. The separating element between two reaches is a manhole, therefore φ is linked to the manhole downstream of the population. The uppermost manhole of a network containing no reach and the second uppermost manhole containing one reach have a value $\varphi = 0$. Negative values are not possible. For manholes inside a network mesh the similarity figure is not defined, because an infiltration rate measured in a mesh cannot be allocated definitely to reaches due to the flow separation which occurs upstream.

Using a standardisation to extreme values and the mean Euclidean distance between all reaches the maximum possible value φ_{max} amounts to

$$\phi_{max} = \sqrt{n_{attribute}}$$ Equation 4-27

Further options

Further options to deal with the similarity figure φ were tested: the standardisation to characteristic values and for group aggregation the sum of attribute variances and the mean distance between all reaches. In several preliminary tests, the results did not significantly differ from the selected ones. Thus, these φ-options were discarded.

4.4 Optimisation algorithms

4.4.1 General remarks

Two optimisation algorithms – a simple and an advanced one – were developed and applied. They were kept relatively simple due to clarity and traceability reasons. Regarding the calculation time and the result quality the algorithms are satisfying. But, improvements might be possible.

Optimally positioned measuring points are associated with homogeneous sub-catchments. Therefore, the main target function of the optimisation is a configuration of minimum similarity figures. With both the simple and the advanced optimisation algorithm this configuration is determined by an iterative procedure which divides stepwise the catchment at the manhole with the minimum φ-value. Some basic and more theoretical boundary conditions like a minimum flow or the regularity of the MP distribution were considered. Restrictions of MP positioning which are relevant for the practical implementation – accessibility of manholes, proximity to pumping stations, etc. – were neglected.

4.4.2 Simple optimisation

The simple algorithm is shown in Figure 4-9. It iteratively divides the catchment until a certain number of sub-catchments, i.e. measuring points is reached. The most downstream manhole standing for a WWTP is automatically a MP. For every separation step one manhole is identified, which divides the considered (sub-)catchment into two sub-catchments. The conditions for the separating manhole are:

- The similarity figure φ is minimal: A minimum φ stands for a maximum possible homogeneity of the upstream reaches.
- Sum of the size measures of upstream reaches is larger than a critical value: The size measure can be the sewer length, the reach surface, the connected area, connected inhabitants etc. This constraint results from measurement requirements like minimum flow or sewer length.
- The manhole is not within a mesh: An infiltration rate measured in a mesh cannot be definitely allocated to reaches.

The critical value of the size measure, i.e. the minimum sub-catchment size, is the only variable option of the optimisation algorithm. It influences the spatial regularity of the MP distribution: the larger the value the higher the obtained regularity. The reason for this effect is the typical sequence of separations. Along a sewer section the homogeneity decreases with the sewer length. Assuming a catchment without large breaks this decrease is steady and the minimum φ-values are found in the upstream areas. Thus, the separation and the determination of MPs, respectively, occur from the up- to the downstream parts of the network.

With a small critical value applied for a relatively uniform sewer system the optimisation result is a configuration with a number of smaller sub-catchments with a high homogeneity and one large, downstream situated sub-catchment with a low homogeneity, i.e. a spatially unequal distribution of MPs. To obtain an even MP distribution, the critical value has to be specified depending on the catchment size.

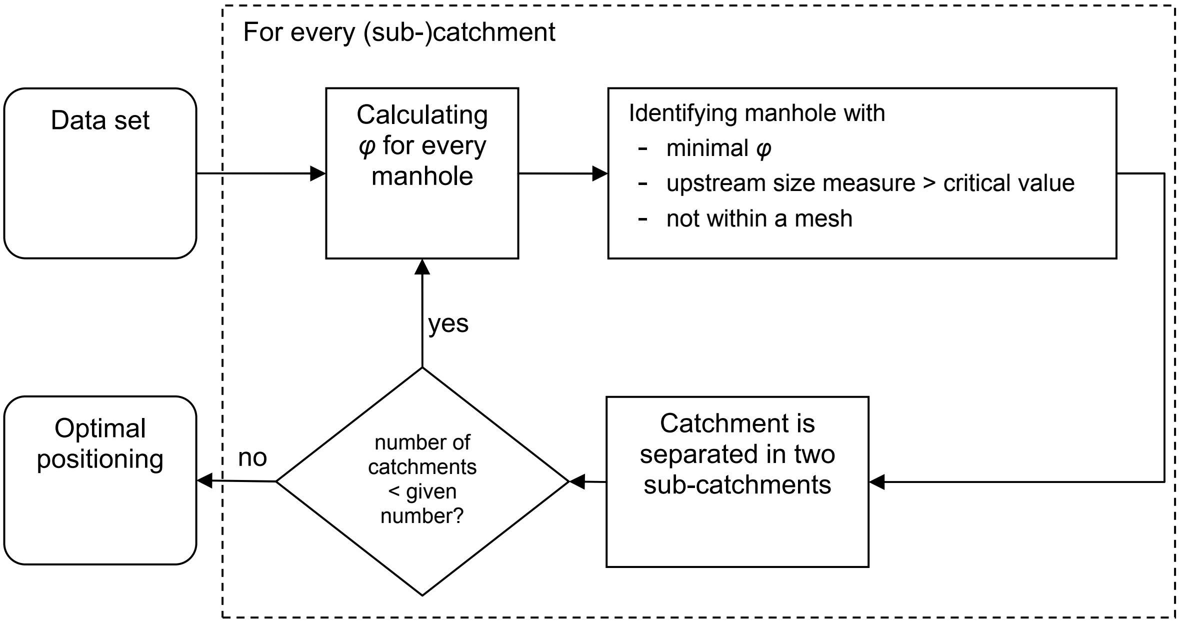


Figure 4-9. Algorithm of the simple optimisation

The number of MPs is either defined beforehand or determined by suitable criteria. Such criteria optimise the MP number between the competitive trends minimising the number due to financial restrictions and maximising the number to yield more information. The criteria can be derived from quality measures and procedures used for determining the optimal number of a cluster solution.

Fahrmeir et al. (1996) propose the variance criterion to find the clustering solution which efficiently explains the observed variances:

$$v_G = \sum_{i=1}^{G} \sum_{j=1}^{n} d\left(o_{ij}, \bar{o}_i\right)^2 \rightarrow min \qquad \text{Equation 4-28}$$

with v variance measure

Among a multitude of cluster solutions the natural or optimal number of clusters G is obtained if $v_{G-1} - v_G$ is significantly larger than $v_G - v_{G+1}$. A large value $v_{G-1} - v_G$ stands for a remaining heterogeneous class. A small value $v_G - v_{G+1}$ indicates, that a homogeneous class was divided. This is explained graphically by the elbow criterion (Figure 4-10).

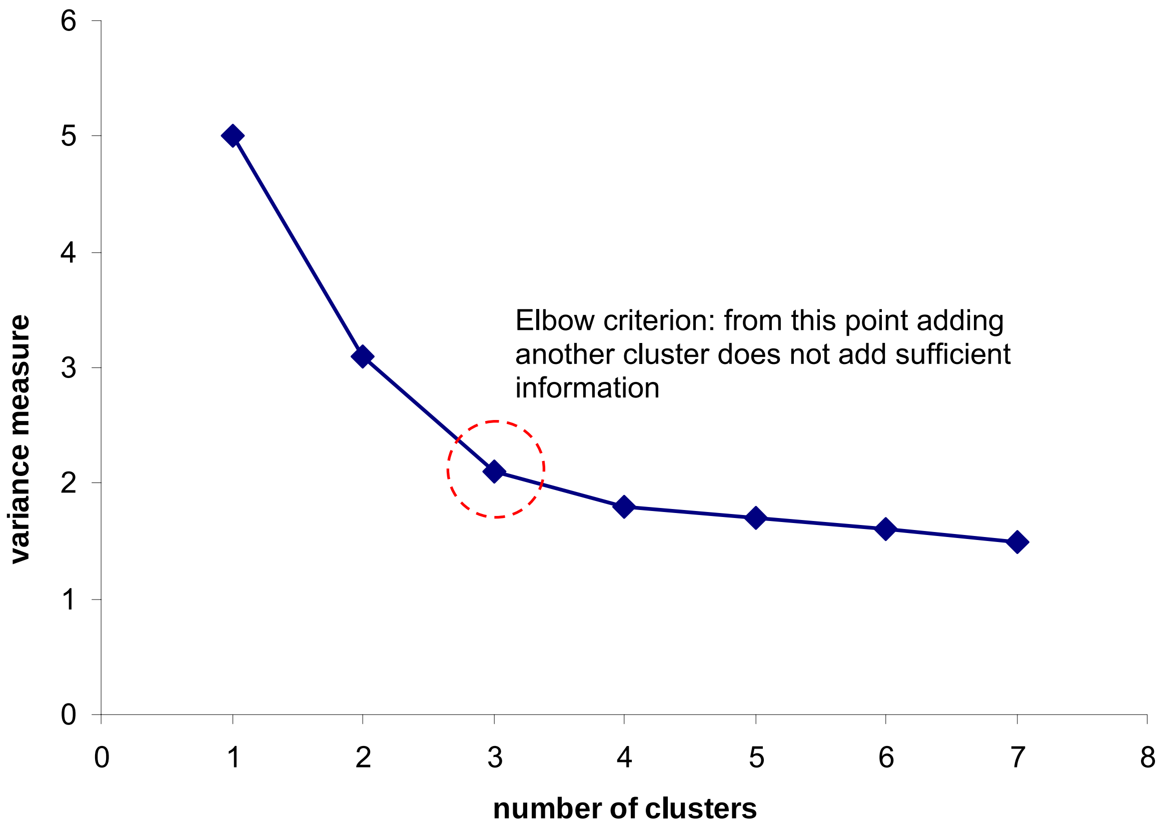


Figure 4-10. Elbow criterion

Assuming a strictly functional relationship between the reach characteristics and the I/I rate, this variance measure does not only determine the quality of the cluster solution but is correlated to the potential error reduction and the information yield, respectively, of the MP configuration. Thus, it could be used to determine the optimal MP number. For comparison purposes the variance measure v_{nMP} is normalised to the unclustered state, i.e. the optimised configuration is compared with a single MP at the end of the catchment:

$$v_{n_{MP}} = \frac{\sum_{i=1}^{n_{MP}} \sum_{j=1}^{n_{reaches}} d\left(o_{ij}, \overline{o}_i\right)^2}{\sum_{j=1}^{n_{reaches}} d\left(o_j, \overline{o}\right)^2} \qquad \text{Equation 4-29}$$

4.4.3 Advanced optimisation

Preliminary tests of the simple optimisation algorithm applied to real sewer systems showed a weak, inversely proportional relationship between the number of reaches of a sub-catchment and its homogeneity. This is comprehensible because sewer systems cannot be completely homogeneous. Even at equal boundary conditions the variability of the attributes increases due to the tree structure of a sewer network. Thus, the simple algorithm, i.e. use of φ as an absolute single value tends towards a preferential separation of outer sub-catchments. Under the practically ubiquitary conditions of a limited MP number and a critical value which is small compared to the total size measure an obtained positioning does not cover efficiently the whole catchment, because the downstream areas are not considered.

The alternative is the use of the difference $\Delta\varphi$ between the similarity figures of adjacent, i.e. up- and downstream sub-catchments as a measure for discriminatory power between those sub-catchments. Thus, the separation between sub-catchments with different φ-values is assumed to be stronger than those with similar ones.

The similarity figure describes the homogeneity, but not the type of a sub-catchment. Nevertheless, neighbouring sub-catchments with a similar φ could be merged with a moderate information loss. Adjacent sub-catchments with low φ-values might have different group centroids, but, the distribution of their attributes is narrow. Therefore, a relatively high homogeneity remains while merging them. Sub-catchments with a high φ have a wide range of attribute values. Their low homogeneity remains also after merging.

The advanced algorithm is shown in Figure 4-11. It is based on a simple optimisation with relatively small critical values. Therewith, much more MPs than necessary are determined. Among the so obtained pre-choice of separating manholes the manholes with maximum $\Delta\varphi$ between up- and downstream are identified and used as measuring points.

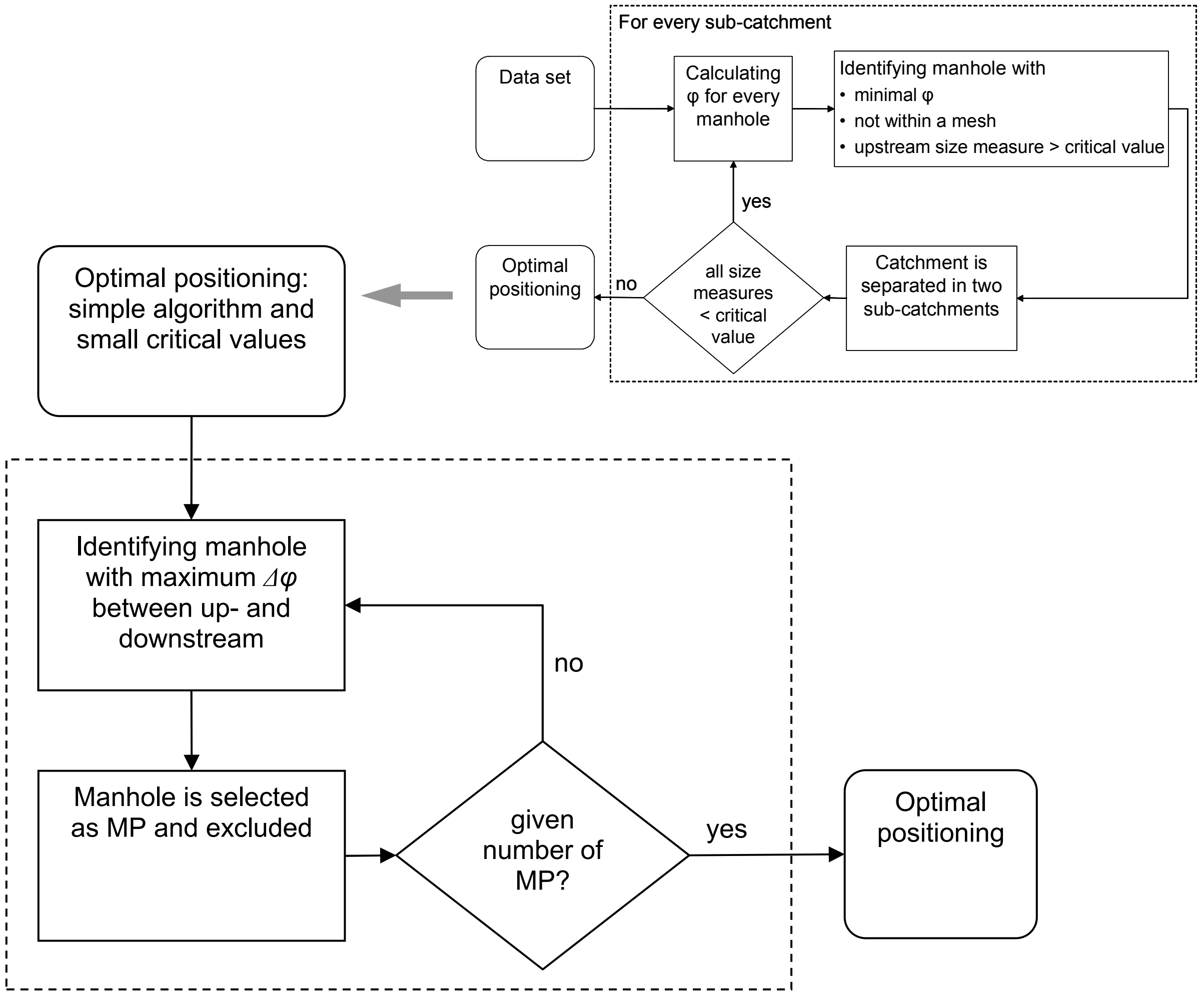


Figure 4-11. Algorithm of the advanced optimisation

4.5 Verification

4.5.1 Framework

Investigated cases

The following cases were investigated:

- Theoretical cases: Theoretical cases have either randomised or uniform infiltration rates. They were used to investigate some theoretical aspects of the methods.
- Cases with artificial infiltration rates: Infiltration/inflow data with a high spatial resolution were not available. By using arbitrary infiltration models it was possible to verify the optimisation procedure on reach scale. Furthermore, sub-catchments originating from different cities could be investigated together compared to the separated investigations of chapter 3.3. The question remains how far away these models are from reality.
- Cases with measured infiltration rates: Relatively detailed measured infiltration rates were available for a few catchments.

Only infiltration was considered for the verification. Inflow was not included due to the better definition of inflow sources (chapter 2.2) and the common practice of measuring I/I during dry weather flow periods (chapter 2.6.1). This has no consequences for the validity of the verification. Therefore, the terms infiltration and I/I are used synonymously in the following.

The consideration of inflow – especially multipoint event-based inflow like inflow over manhole covers – within the optimisation is possible by including suitable attributes which are linked to the respective processes, e.g. the geodetic difference between manhole cover and street top edges or the number of wrong connections.

Used data

Six real data sets (chapter 3.2.3) were used for verification. They were limited to the attributes *DATE_CONSTR*, *PROF_CIRC*, *LENGTH*, *POP_DENS* and *SLOPE* and contained one arbitrarily defined, plain groundwater level. In order to obtain reach-related I/I rates three arbitrary infiltration models were implemented:

– model "random":

$$Q_{infiltration} = random\_number \qquad \text{Equation 4-30}$$

– model "simple":

$$Q_{infiltration} = \prod attributes \qquad \text{Equation 4-31}$$

– model "not so simple":

$$Q_{infiltration} = \frac{A_{surface}}{\sqrt{2005 - DATE\_CONSTR} * (100 * e^{2*POP\_DENS}) * (10 * SLOPE)^2} \qquad \text{Equation 4-32}$$

with $A_{surface}$ groundwater influenced reach surface

For building theoretical cases the model "random" was applied to three of the six sewer networks. Furthermore, the model "simple" was applied to these networks which were filled with artificial attributes, i.e. only the network topology remains real. Data sets with a very uniform distribution of infiltration rates result out of it.

For detailed investigation of the behaviour and the potential of the optimisation methods the models "not so simple" and "simple" were applied to all sub-catchments. Three additional sub-catchments could be investigated, for which measured infiltration rates with a relatively high spatial resolution were available. The data sets and their use are listed in Table 4-4.

Table 4-4. Data sets for verification

Sub-catchment	Origin	Total sewer length [km]	Theoretical cases	Artificial $Q_{I/I}$	Measured $Q_{I/I}$
01G145	Dresden	22.9		X	
04F79	Dresden	22.6	X	X	
16P46	Dresden	10.9	X	X	
F42	Bottrop	2.7		X	
F46	Bottrop	7.7	X	X	
F50	Bottrop	9.8		X	
ED	Dresden	9.3			X
OD	Dresden	37.4			X
SF	Dresden	6.9			X

Options

Both the simple and the advanced optimisation algorithm were used for determing the optimised MP configuration. The number of optimised MPs was set to five. The configuration was compared either with one measuring point at the end of the sub-catchment or with random distributions of five MPs.

For every sub-catchment the best combination of options for calculating the similarity figure was applied. In the following, the chosen combination is marked with a four letter code:

- standardisation of attributes: e – to extreme values, v – to variances
- weighting with Δh: n – no weigthing, f – as factor
- distance measure: e – Euclidean, m – Mahalanobis
- aggregation of groups: m – mean distance to centroid, x – mean distance to centroid of most distant reaches.

The water head and groundwater information, respectively, were either supposed to be unknown or used as weighting factor. The sewer length was chosen as size measure. The optimisation was done for equally und unequally sized sub-catchments, i.e. either the critical value was set as a constant to 2 % of the total length or it was variable due to the ratio of the total length of the respective sub-catchment and the set number of MPs.

Measure of optimisation quality

The ratio of the summarised measurement errors according to Equation 4-1 before and after the optimisation was chosen as an indicator for the optimisation quality. A graphical impression of these errors occurring due to averaging measurement results is given in Figure 4-1. In order to reflect an improvement the ratio was inverted. Thus, a value of 0 % stands for no outcome of the optimisation, a value of 100 % for a perfect, errorless result, which is obviously not possible. The optimisation quality indicator or error reduction r is calculated to

$$r = 1 - \frac{\sum_{i=1}^{n_{reach}} \left| Q_{infiltration,measured\_after\_optimisation,reach_i} - Q_{infiltration,modelled,reach_i} \right|}{\sum_{i=1}^{n_{reach}} \left| Q_{infiltration,measured\_before\_optimisation,reach_i} - Q_{infiltration,modelled,reach_i} \right|} \qquad \text{Equation 4-33}$$

with

$$Q_{infiltration,measured,reach_i} \underset{\substack{reach_i \in sb-ctm_k \\ reach_j \in sb-ctm_k}}{=} LENGTH_{reach_i} \cdot \frac{\sum_{j=1}^{n_{reaches}} Q_{infiltration,modelled,reach_j}}{\sum_{j=1}^{n_{reaches}} LENGTH_{reach_j}} \qquad \text{Equation 4-34}$$

with $Q_{infiltration,modelled}$ modelled I/I discharge
sb-ctm sub-catchment

4.5.2 Theoretical cases

Networks with a real topology but randomised infiltration rates or uniform attributes were used to investigate extreme states of networks. These states are very badly or very well suited for a successful optimisation procedure whose results should be accordingly. For all investigated combinations one measuring point at the end of the sub-catchment was compared with an optimised configuration of five MPs according to the simple algorithm introduced in chapter 4.4.2. The groundwater table was not relevant due to the selected I/I models.

The infiltration model "random" causes no relationship between independent attributes, i.e. the reach characteristics, and infiltration rates. Therefore, an optimal positioning of MPs based on similarities is not possible and the optimisation quality should be minimal. For the catchments 04F79, 16P46 and F46 with the infiltration model “random” the error reduction amounted as expected to $r < 1$ %.

The networks of the catchments 01G145, 16P46 and F46 were filled with two variables each with two to three values. The infiltration was calculated with model “simple”. The results were very structured catchments, i.e. the specific infiltration rates were distributed with low variations (Figure 4-12). The optimisation quality should be very good with these strong homogeneities. In fact, the results were widely spread (Table 4-5).

Regarding the uniform distributions of attribute values and infiltration rates, obviously the network topology is the reason for these varying results. Comparing the error reductions and the respective topologies, a relationship between the optimisation outcome and the complexity of the network is probable: the less complex, the better the result. Thus, the network topology, e.g. the ramification degree or the number of meshes, seems to be very important for the applicability of the optimisation method.

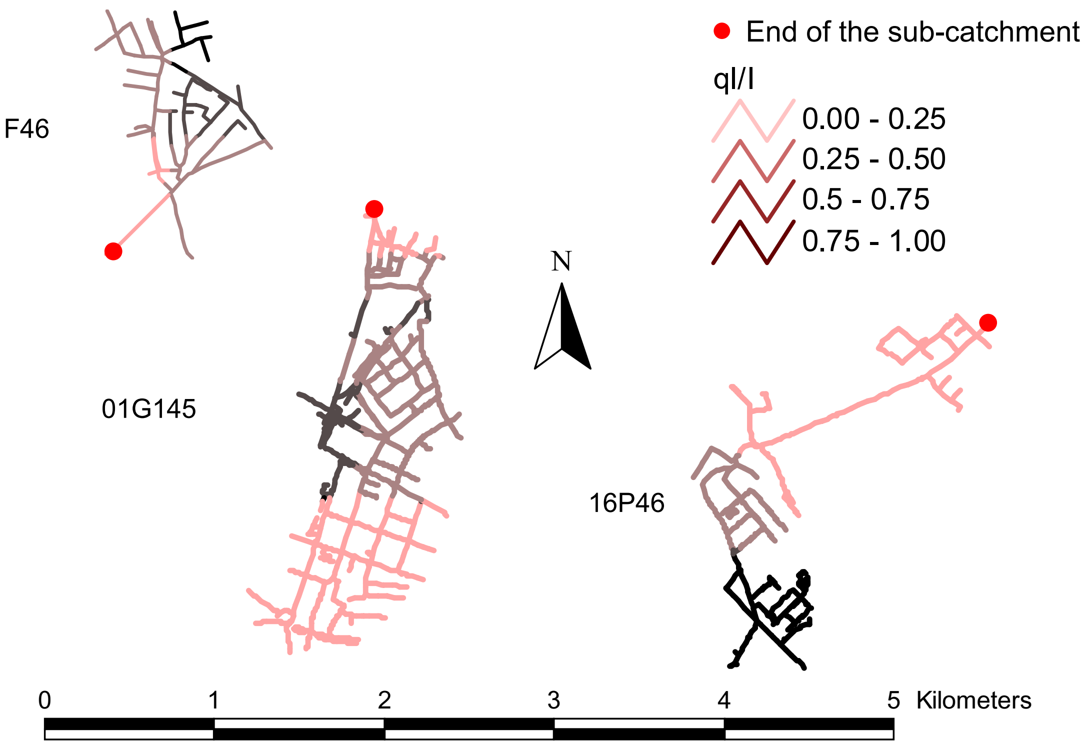


Figure 4-12. Network topologies and length-specific infiltration rates of the sub-catchments F46, 01G145 and 16P46 – uniform attributes, model “simple”

Table 4-5. Optimisation results – uniform attributes, model "simple"

Sub-catchment	Error reduction *r* [%]
01G145 (enem)	19.2
16P46 (enex)	95.1
F46 (enem)	45.3

4.5.3 Cases with artificial I/I rates

4.5.3.1 Optimal positioning

Table 4-6 shows the error reduction r for the cases with real attributes and network topologies to which the infiltration model "not so simple" was applied. The optimisation was conducted with the simple optimisation algorithm, equally sized sub-catchments and without groundwater information. The optimised configuration of five MPs was compared with one measuring point at the end of the sub-catchment. With a mean value of $r = 24$ % and a maximum value of $r = 51$ % the results of the optimisation are significant but not outstanding. The main reason for this is the fact, that the optimisation procedure is not a classification of independent items (chapter 4.3.1).

In Figure 4-13 the achieved error reduction is compared with the fraction of sewers within meshes. A clear linear relationship between the factors could be observed. The difference in magnitude of r between the sub-catchments of Dresden and Bottrop has its origin mainly in their size. The sub-catchments of Bottrop are smaller (Table 4-4) and their original homogeneity is more pronounced. A similar but non-linear relationship was obtained for the comparison with the number of meshes. In Figure 4-14 the network topologies of the catchment 01G145 with bad results and the catchment 04F79 with better results are compared. Catchment 01G145 has much more meshes spread in a wider area than catchment 04F79. From both figures and in addition to the discussion of chapter 4.5.2 it can be concluded, that the network topology, especially the kind and number of meshes, has a predominant influence on the optimisation potential.

Figure 4-15 indicates the existence of a relationship between the homogeneity of a catchment and the potential error reduction. In this figure the maximum observed φ-value within a catchment is compared with r. Neglecting the outlier 01G145, a clear non-linear relationship between the variables could be observed.

Table 4-6. Structural parameters; optimisation results – model “not so simple“, simple algorithm, 5 vs. 1 MP, no gw, equal size

Sub-catchment	Error reduction *r* [%]	Number of meshes [-]	Meshed sewer length [%]
01G145 (efem)	8.8	9	31.6
04F79 (efem)	31.2	2	4.4
16P46 (efem)	17.0	4	19.7
F42 (efem)	51.1	0	22.7
F46 (vfem)	25.3	1	37.3
F50 (efem)	11.3	2	43.9

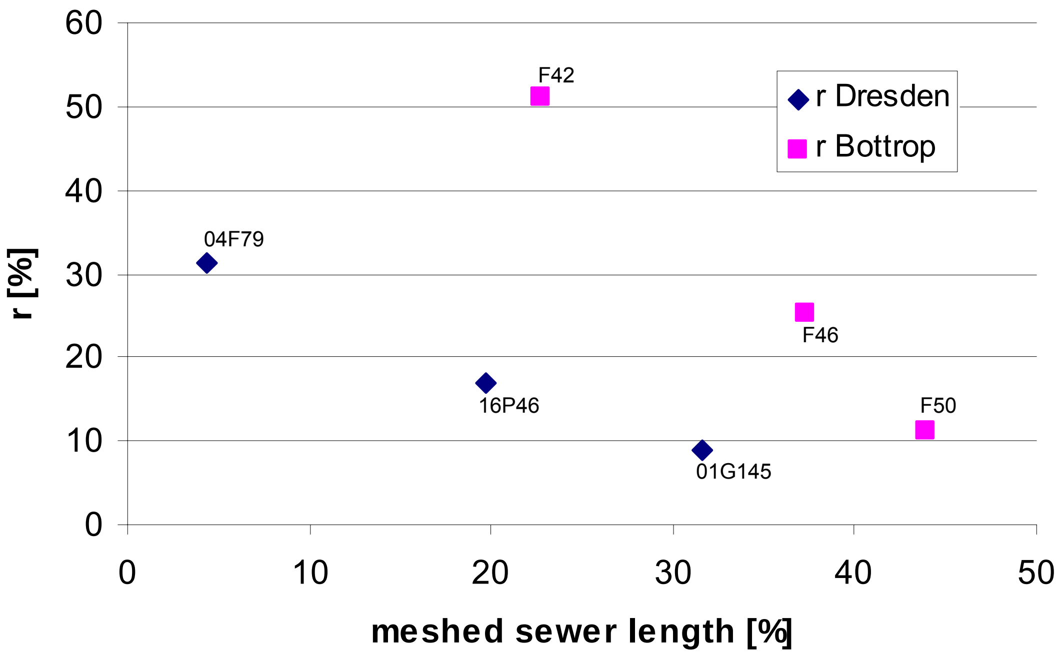


Figure 4-13. Error reduction and fraction of meshes

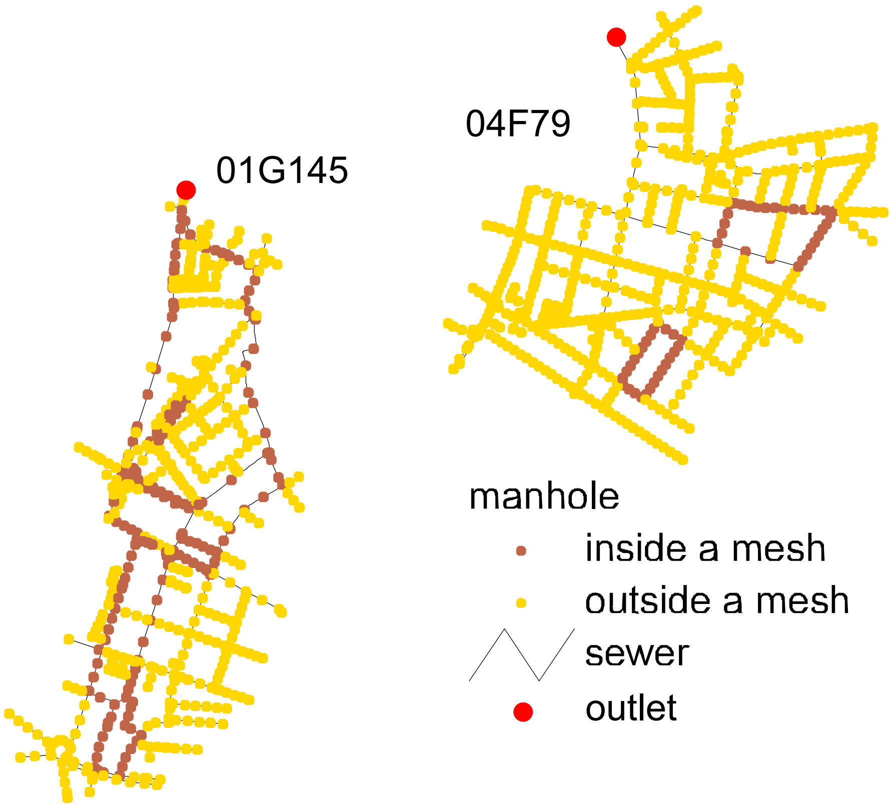


Figure 4-14. Network topologies with meshes of sub-catchments 01G145 and 04F79

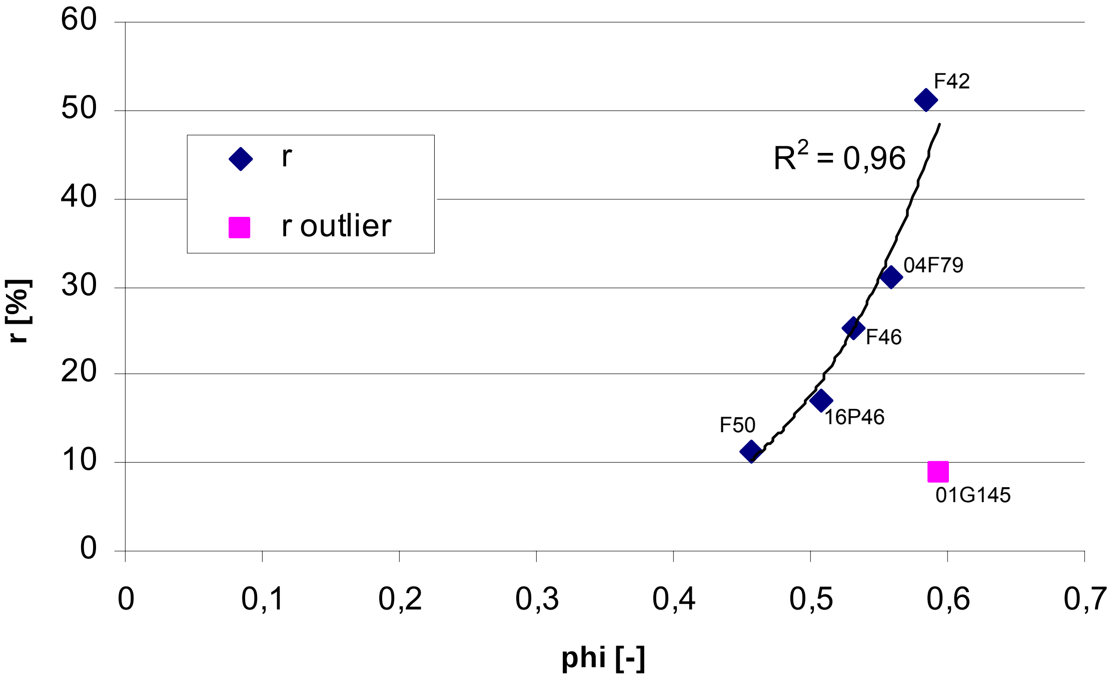


Figure 4-15. Error reduction and maximum observed φ-values

4.5.3.2 Comparison of optimisation options

Based on numerous calculations the following recommendations for calculating the similarity figure φ can be given:

- standardisation: to extreme values
- weighting: when the necessary information is available
- distance measure: Mahalanobis distance when possible
- aggregation: mean distance to centroid.

There are no vast differences between the φ-options except for the weighting. This observation supports the conclusion of a low correlation between the attributes given in chapter 3.4.

For all six sub-catchments the scenarios and options infiltration model, optimisation algorithm, groundwater information and regularity of MP distribution were compared pairwise due to their binary character. The optimisation results obtained by the comparison are given in Table 4-7. The reference procedure was the one named in chapter 4.5.3.1; its results can be found in the left columns.

The structure of the arbitrary infiltration models has a strong influence on the error reduction. Neglecting the outlier F42, the relative difference between the models is approximately 30 % in favour of the model "simple". It has for its attributes powers of one, only. In combination with the linear character of the optimisation procedure due to neglecting the different contributions of sewer characteristics to infiltration and an equal treatment of attributes, this yields to better results. Potentially, the results for the model "not so simple" could be improved by using appropriate weighting factors.

There are only small differences between the results obtained with the simple and the advanced optimisation algorithm. The reason for this finding is ambiguous; the sub-catchments might have a good a priori aptitude for clustering. However, for the cases with measured I/I rates a supervised application of the advanced algorithm yielded better results than the simple one (chapter 4.5.4).

The differences between the results obtained with different groundwater options have a wide range. Probably, there are complex dependencies upon the groundwater level, the network topology and the distribution of reach characteristics. A simple comparison as given is not sufficient to explain the observed optimisation results. Nevertheless, taking into account the general tendency of error reduction improvement by including groundwater information (Table 4-7, Table 4-8) as well as the theoretical consideration of infiltration processes given in chapter 2.3.1.2, groundwater information is considered to be essential.

The minimum sub-catchment size and critical value, respectively, have a distinct influence on the optimisation result. With regarding only the larger sub-catchments originating from the city of Dresden, the mean relative difference between the options amounts up to more than 30 %. The reason for these differences is the distribution of sub-catchment sizes and homogeneity values. Due to the separation sequence (Figure 4-9) an unequal sub-catchment size and MP distribution, respectively, leads to one or a few comparatively large sub-catchments with a low homogeneity and thus a low error reduction. These sub-catchments could dominate the optimisation result.

The comparison of a one MP and a five MPs configuration neglects the additional information gained by the pure number of MPs and does not reflect the practical situation that MPs already exist. Therefore, 50 random configurations of five MPs were generated for every sub-catchment and compared to the optimised one. Bacher (1996) recommends 20 classifications as minimum number for comparing purposes.

The characteristic values of the optimisation results are given in Table 4-8. The comparison shows an error reduction and information improvement, respectively, of in mean 14 % to maximum 35 %. Obviously these values are worse than those described above gained by a comparison of a one MP and a five MPs configuration. The influence of the network topology is indicated by the range of the results.

Due to the use of not weighted attributes, the optimisation procedure has a linear character; the infiltration model is nonlinear. This discrepancy as well as inconsistencies of boundary conditions between optimised and random MPs are the reasons for cases with $r < 0$, i.e. the respective random configuration of MPs yields better results than the optimised one. Since these cases are a clear minority, the optimisation procedure proves to be rather reliable.

Table 4-7. Optimisation results – pairwise comparison of scenarios and options, 5 vs. 1 MP; reference procedure: model "not so simple", simple algorithm, 5 vs. 5 MP, no gw, equal size

Sub-catchment	Error reduction *r* [%]			
	Infiltration model		Optimisation algorithm	
	"not so simple"	"simple"	simple	advanced
01G145 (efem)	8.8	10.1	8.8	8.0
04F79 (efem)	31.2	37.8	31.2	31.2
16P46 (efem)	17.0	31.2	17.0	22.8
F42 (efem)	51.1	11.4	51.1	34.1
F46 (vfem)	25.3	24.3	25.3	25.2
F50 (efmm)	11.3	15.9	11.3	11.2
	Error reduction *r* [%]			
	Groundwater information		**MP distribution**	
	not available	**available**	**equal**	**unequal**
01G145 (efem)	8.8	7.6	8.8	5.1
04F79 (efem)	31.2	28.1	31.2	27.1
16P46 (efem)	17.0	34.4	17.0	15.2
F42 (efem)	51.1	6.0	51.1	35.1
F46 (vfem)	25.3	35.2	25.3	2.9
F50 (efmm)	11.3	23.9	11.3	0.9

Table 4-8. Optimisation results – model "not so simple", simple algorithm, 5 vs. 5 MP (50 random distributions), equal size

Sub-catchment	Error reductions *r* [%]					
	minimum		mean		maximum	
	gw un-known	gw known	gw un-known	gw known	gw un-known	gw known
01G145 (efem)	-9.0	-4.8	-0.1	3.4	7.2	7.6
04F79 (efem)	0.3	-17.3	23.9	21.5	30.2	27.4
16P46 (efem)	-22.1	2.5	-6.1	15.2	7.8	32.9
F42 (efem)	-26.0	-23.4	22.0	1.2	44.9	10.7
F46 (vfem)	-1.4	2.2	19.9	26.6	25.7	34.8
F50 (efmm)	-27.8	-2.6	-4.8	13.4	10.8	23.2
mean	-14.3	-7.2	9.1	13.6	21.1	22.8

4.5.3.3 Robustness

The robustness of the optimisation method was tested in two ways:

- Adding a bias to the infiltration model: This simulates a kind of fuzzy relationship between sewer characteristics and the I/I rate.
- Using a reduced attribute set for optimisation: This simulates that not all attributes relevant for I/I are known.

For applying a fuzzy element to the infiltration model a random bias of +/- 10 % was added to the calculated I/I rates of every reach. After determining the optimal MP configuration the obtained error reductions were compared with those of the model without bias. The results presented in Table 4-9 show that the error reduction is decreased marginally only. Compared to the bias of 10 % the error reduction is reduced by about 0.5 % both for optimising with and without using groundwater information.

Table 4-9. Optimisation results – model "not so simple" with bias, simple algorithm, 5 vs. 1 MP, equal size

Sub-catchment	Error reduction *r* [%]			
	gw unknown		gw known	
	without bias	with bias	without bias	with bias
01G145 (efem)	8.8	8.8	7.6	7.6
04F79 (efem)	31.2	31.1	28.1	27.9
16P46 (efem)	17	16.9	34.4	34.2
F42 (efem)	51.1	51.0	6	5.9
F46 (vfem)	25.3	25.2	35.2	35.1
F50 (efmm)	11.3	11.3	23.9	23.8

In order to investigate the effect of limited process knowledge or an insufficient data situation three different attribute sets of the sub-catchment 04F79 were compiled with 40 to 60 % of the attributes which were used for calculating I/I rates (Table 4-10). The obtained error reductions for multiple configurations are compared in Figure 4-16. The differences between the attributes sets are unexpectedly marginal. The redundance of the attributes is low except the pair

PROF_CIRC and *LENGTH* which has a correlation coefficient of 0.71. Thus, the effect of an attribute reduction should be larger.

Although this observation is difficult to explain, the tests for robustness are satisfying. Despite several disturbances the optimisation procedure yields stable and reproducible results.

Table 4-10. Reduced attribute sets

Attribute	**Attribute set**			
	All	**Set 1**	**Set 2**	**Set 3**
DATE_CONST	X		X	
PROF_CIRC	X	X	X	X
LENGTH	X			X
POP_DENS	X	X	X	
SLOPE	X	X		

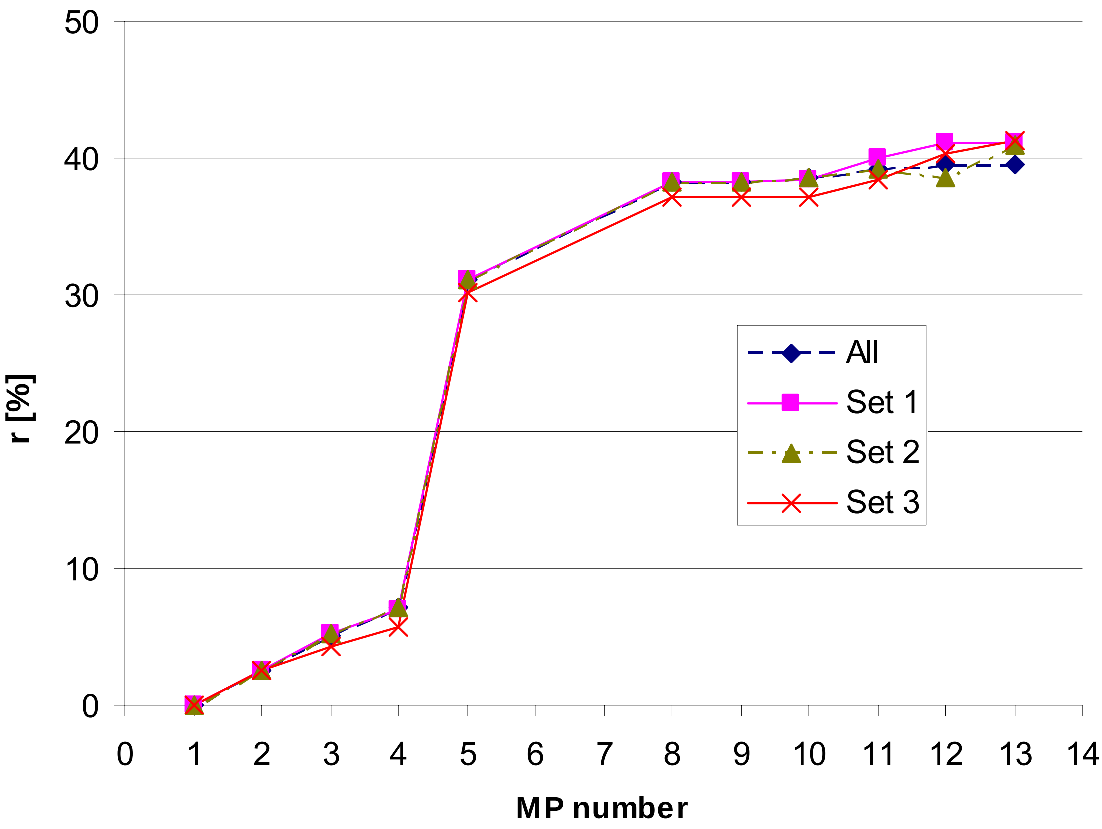


Figure 4-16. Optimisation results for sub-catchment 04F79 – model “not so simple“, simple algorithm, multiple vs. 1 MP, no gw, equal size, reduced attribute sets

4.5.3.4 Optimal number

Based on the configurations described in Table 4-6 modified configurations of four MPs were composed by removing the MPs one by one. Thereby, the error reduction declined about a factor with a range of 0.2 to 35.1 % and a mean of 10.1 %. A small decline means that the removal of the respective MP has nearly no influence on the information yield of the configuration. Thus, the observed low minimum values point at a non-optimal, i.e. too high number of MPs. The optimal number of MPs in terms of a maximised cost-benefit ratio is reached, if an additional MP does not cause a significant increase of the information yield. As a substitute for this yield the variance measure v_{nMP} is used (Equation 4-29).

For all investigated sub-catchments the variance measures and error reductions of multiple MP configurations are compared in Figure 4-17 and Figure 4-18. As expected, a clear correlation between v_{nMP} and r could be observed (Figure 4-19). The respective correlation coefficients of the individual sub-catchments lie in a range from -0.87 to -1.00. Due to this high correlation the variance measure seems to be a suitable substitute for the information yield of a MP configuration. Furthermore, there is a correlation between the number of MPs and vnMP with coefficients ranging from -0.80 to -0.99 (Figure 4-20). But, this is only valid for smaller MP numbers because both variance measure and error reduction seem to converge to a limit value. The maximum observed error reduction amounts to approximately 40 %.

By analysing the curves, elbow criteria (chapter 4.4.2) and with them the optimal numbers of MPs are identifiable by a flattening of the v_{nMP} curves. In most cases this identification is distinct because the change of the variance measure decreases abruptly. For the Dresden sub-catchments three to four MPs can be supposed to be optimal, for the Bottrop sub-catchments four to five MPs.

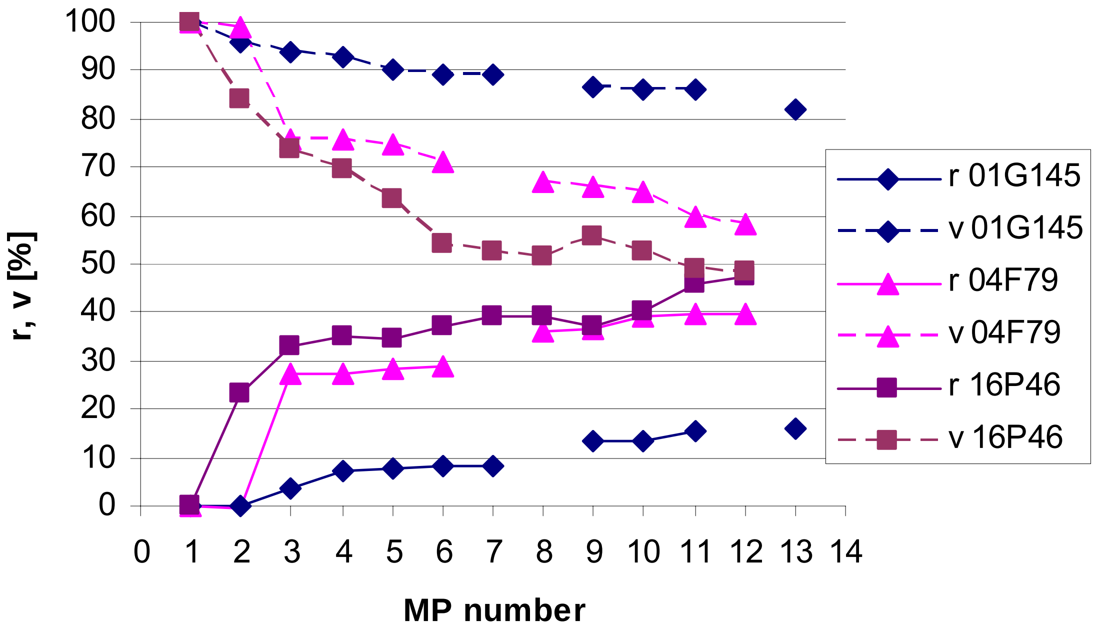


Figure 4-17. v_{nMP} and r vs. MP number for sub-catchments originating from Dresden – model "not so simple", simple algorithm, multiple vs. 1 MP, gw, equal size

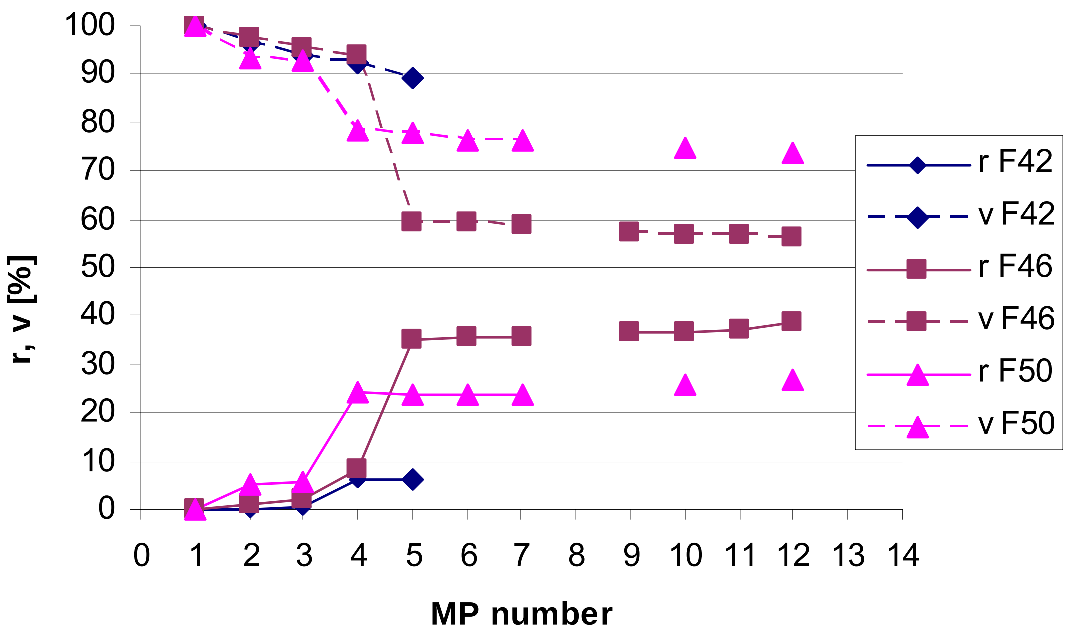


Figure 4-18. v_{nMP} and r vs. MP number for sub-catchments originating from Bottrop – model "not so simple", simple algorithm, multiple vs. 1 MP, gw, equal size

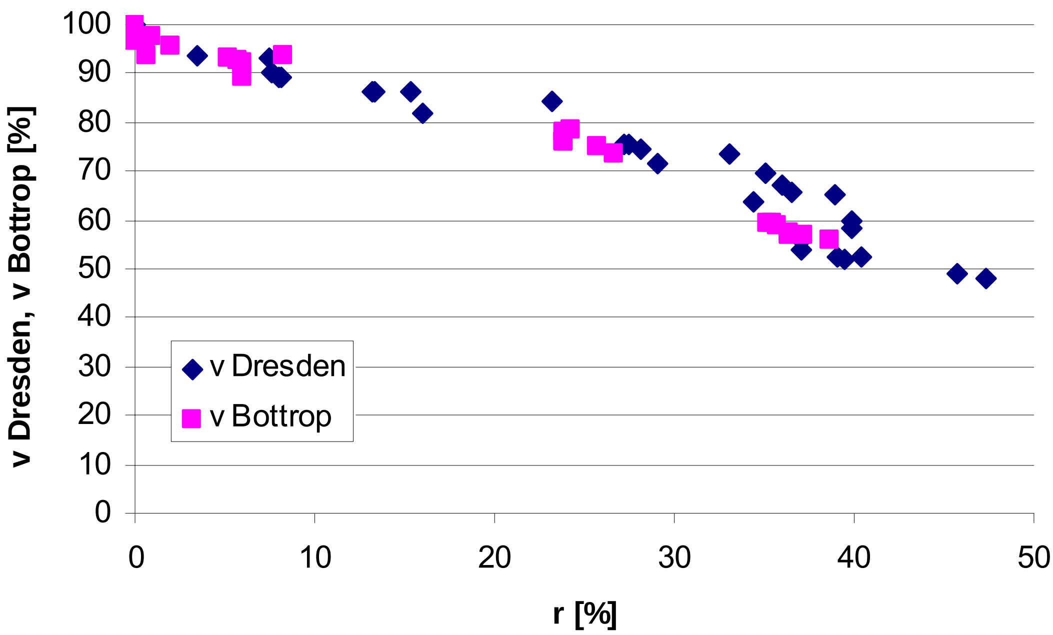


Figure 4-19. v_{nMP} vs. r for all sub-catchments – model “not so simple“, simple algorithm, multiple vs. 1 MP, gw, equal size

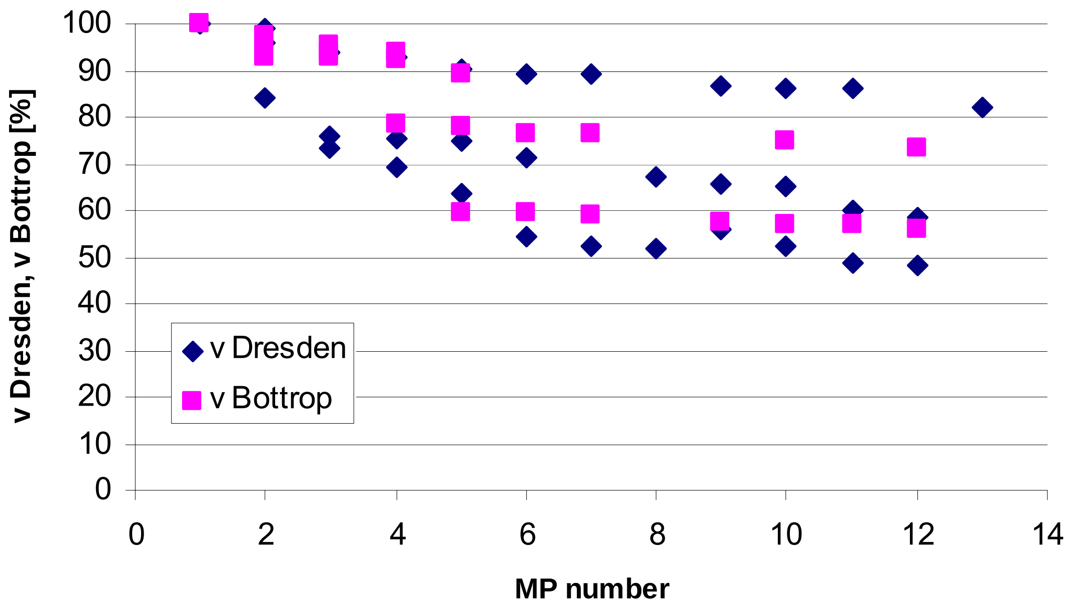


Figure 4-20. v_{nMP} vs. MP number for all sub-catchments – model “not so simple“, simple algorithm, multiple vs. 1 MP, gw, equal size

4.5.4 Cases with measured I/I rates

Based on temporary measurement campaigns data of several sub-catchments with a relatively high number of measuring points inside and a differentiated infiltration/inflow situation were available. They were investigated in order to evaluate the applicability of the optimisation method in reality. Three sub-catchments originating from the city of Dresden could be used for this purpose: ED, OD and SF (Table 3-1, Figure 3-3). All of them are self-contained with an own WWTP.

Compared to the cases with artificial I/I rates the data situation differed:

- I/I rates were available on sub-catchment level, but not on reach level.
- Information about the groundwater table was not available.
- The number of existent measuring points was given.

Thus, a modification of the advanced optimisation algorithm which was adapted for a supervised optimisation was used: the optimisation was performed generating approximately 50 % more virtual MPs than available ones. All ordinal and metrical attributes (Table 3-2) were considered. Then, the separating similarity figures φ were compared with the surface-specific infiltration rates and their variations. With this procedure it was possible not just to determine an optimal positioning, but also to compare the optimisation results with the measurements more detailed.

In the catchment ED eight MPs were operated beside the measurements at the WWTP. In Figure 4-21 the absolute change of the specific I/I rates $\Delta q_{I/I}$ at these MPs is compared with the calculated φ-value. Four of the MPs indicate no change of the specific I/I rate, i.e. the same I/I rate in adjacent sub-catchments. At all of these MPs the similarity figure does not change significantly. Therefore, an installation of additional MPs would not be recommended which is conform to the I/I measurements. For the three MPs in the western part of the catchment which indicate a change of the specific I/I rate, a change of the φ-value can be observed within a distance of 40 to 200 m. Furthermore, there seems to be a slight correlation between the magnitude of $\Delta q_{I/I}$ and $\Delta\varphi$.

The specific I/I rates and the similarity figures of the catchment ED are directly compared in Figure 4-22. Comparing the western and the eastern part of the catchment, a small or distinct change of $q_{I/I}$ seems to yield respective φ-values.

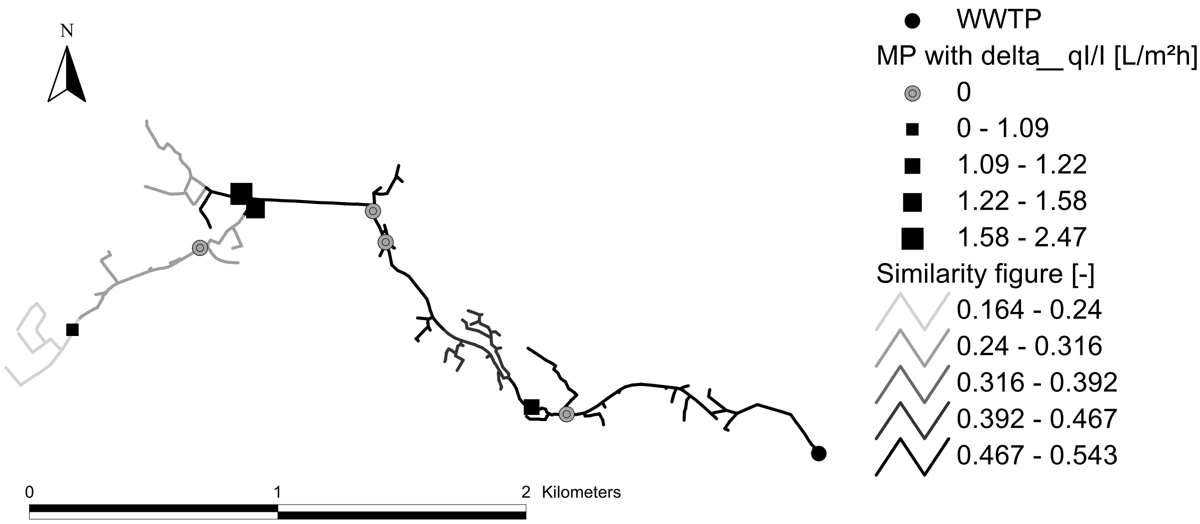


Figure 4-21. Similarity figures and changes of I/I rate: catchment ED

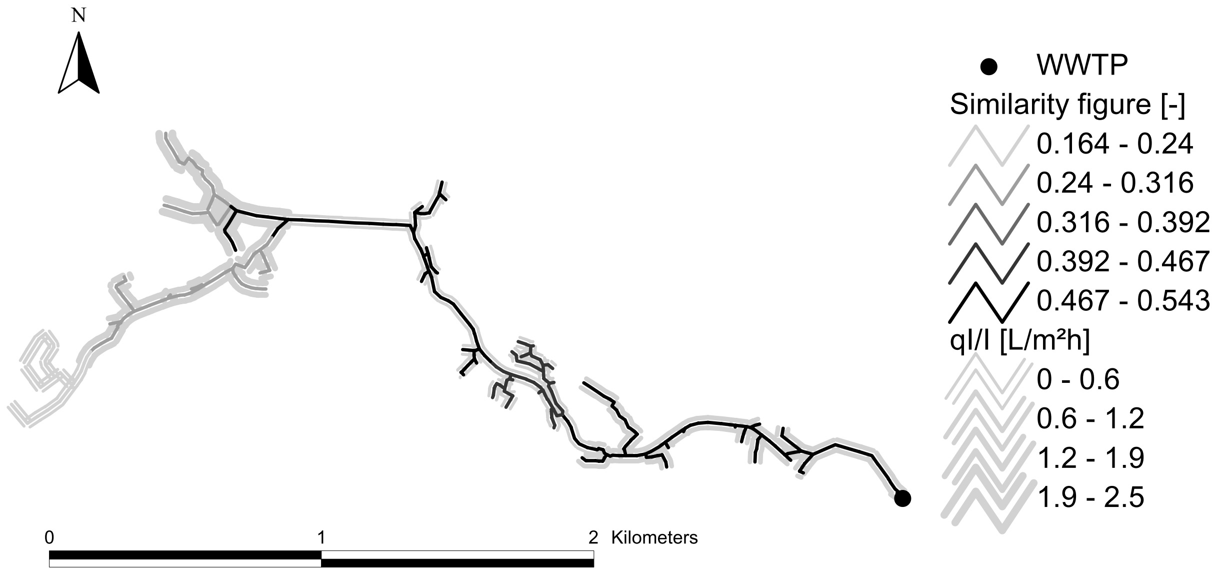


Figure 4-22. Similarity figures and I/I rates: catchment ED

The results for the catchments SF and OD are shown in Figure 4-23 and Figure 4-24. They are comparable with those of the catchment ED. Due to the lower number of available MPs the I/I situations can be displayed not so detailed, but a general relationship between changes of the specific I/I rate and the similarity figure can be observed.

The marked sub-catchments (dotted lines) are determined by an existent MP. They contain several optimised sub-catchments with low φ-values. That means, that the centroids of the optimised sub-catchments might be different, but their attributes distribution is low. Therefore, a relatively high homogeneity would remain while merging them to the measured sub-catchment.

The marked sub-catchments have an I/I rate which is significantly different from that of adjacent sub-catchments. It can be concluded, that there is concurrently a significant change of the similarity figure and the homogeneity of the reaches, respectively, with the change of the I/I rate. Thus, a joining of sub-catchments with low φ-values as described above is feasible with a moderate information loss and the approach of the advanced optimisation algorithm is proven to be reasonable.

By comparing the three catchments and the observed magnitudes of $q_{I/I}$ and φ two important conclusions can be drawn:

- In all cases the φ-values have a similar range whereas the ranges of $q_{I/I}$ differ. Therefore, catchments should always be analysed individually.
- A good quality of a single MP positioning seems to occur at φ–values lower than 0.4.

The optimised arrangements of MPs for the catchments OD and ED are shown in Figure 4-25. The application of the optimisation method results in good coherence between the MP arrangement and detected changes of measured I/I rates.

In the western part of both catchments the optimised MPs are nearly identical with observed changes of the I/I rate. For them either the similarity figures are relatively small or a significant change of the φ–value occurs. Thus, the identified MPs separate at least one homogeneous sub-catchment. For the eastern parts detailed conclusions about an optimal positioning cannot be drawn. This is affirmed by the calculated φ–values which are higher.

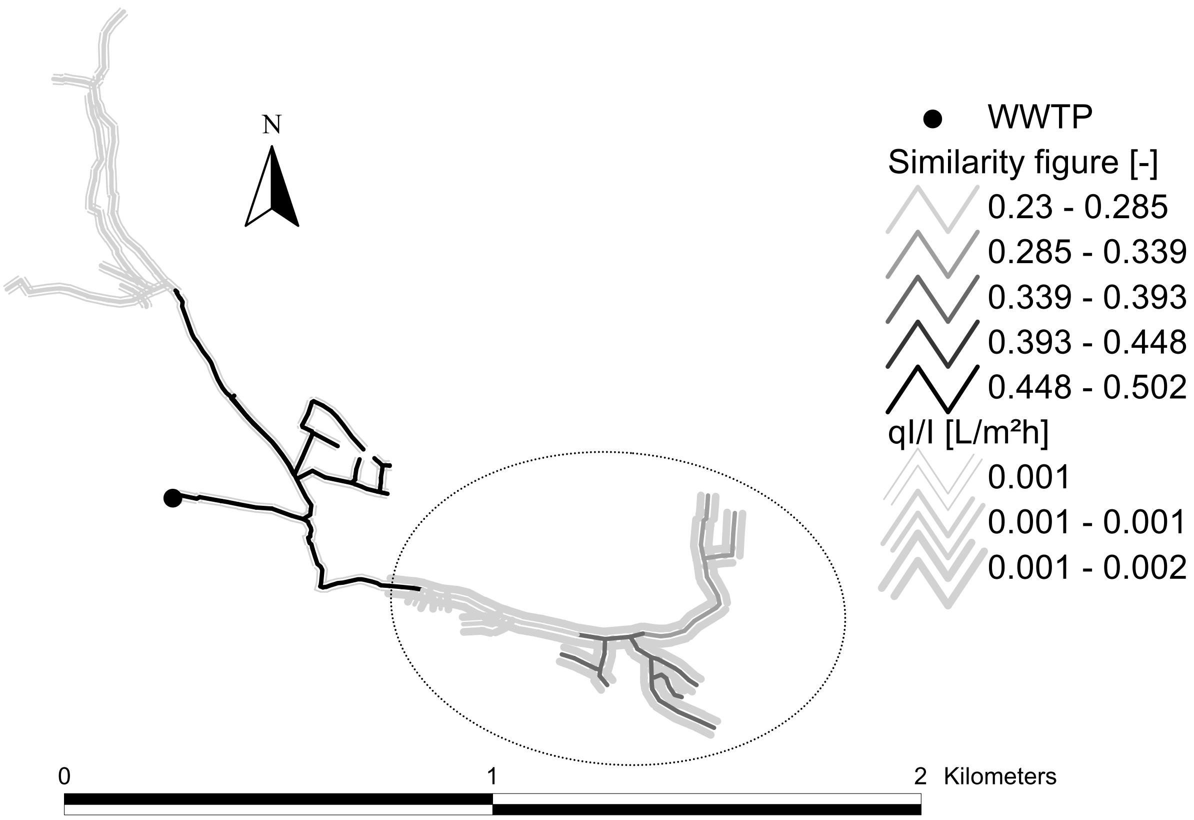


Figure 4-23. Similarity figures and I/I rates: catchment SF

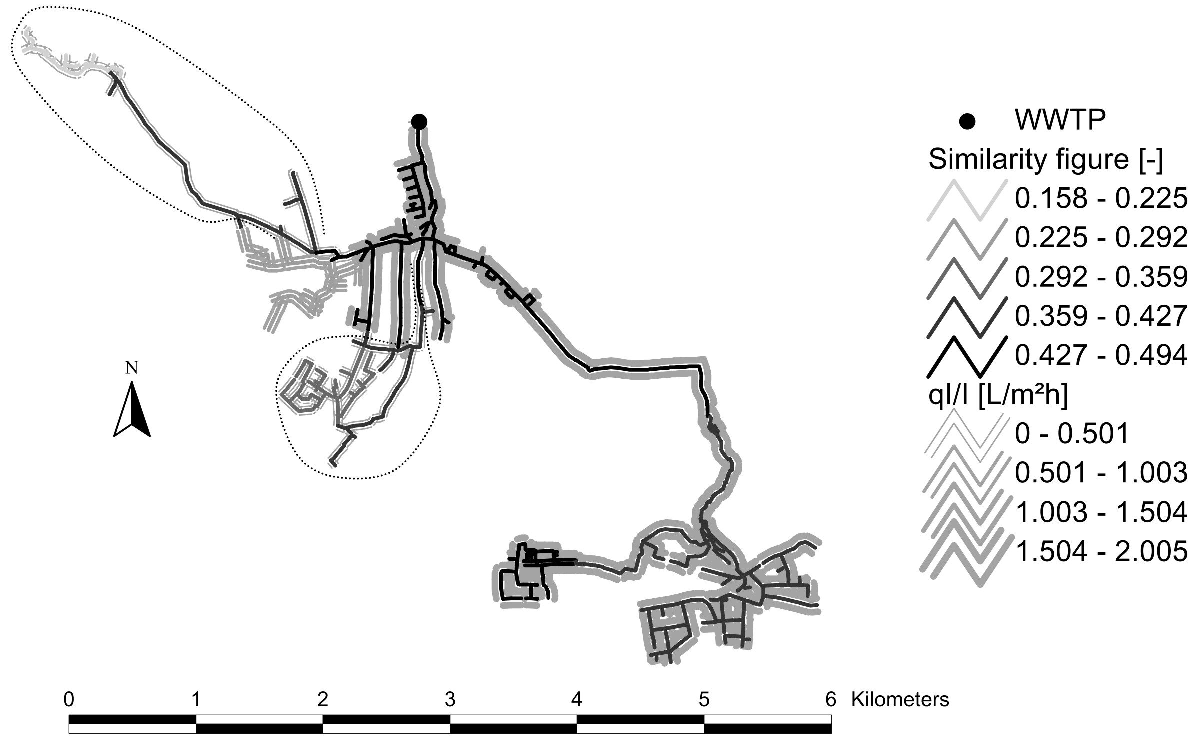


Figure 4-24. Similarity figures and I/I rates: catchment OD

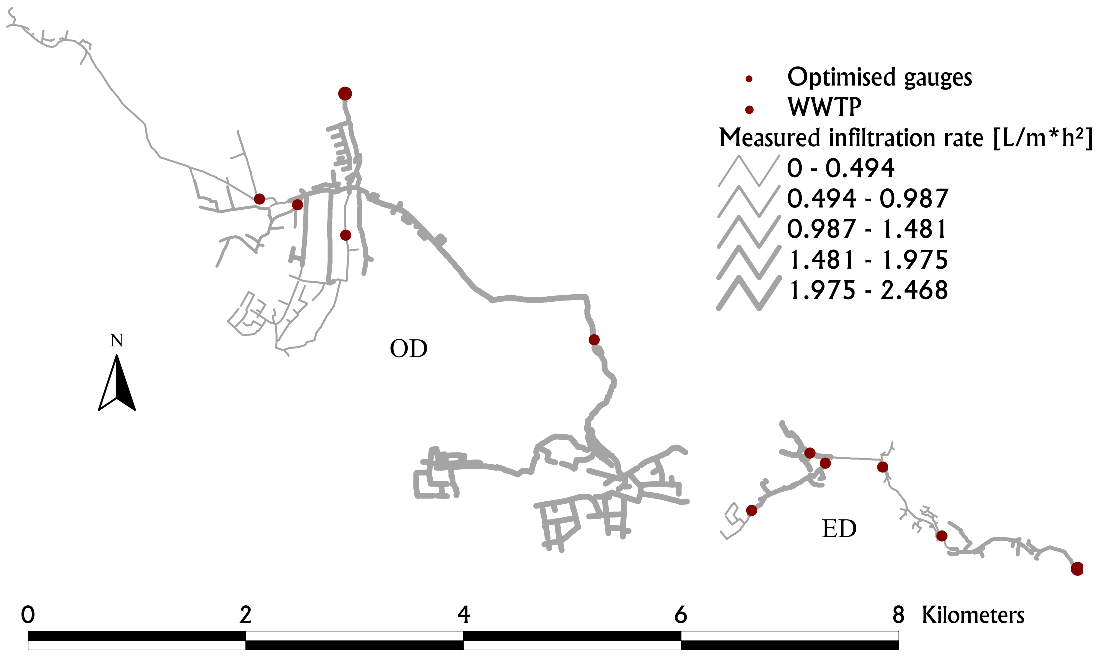


Figure 4-25. Optimised MP arrangement vs. measured I/I rates for the catchments OD and ED

4.6 Discussion

The proposed applications of the similarity approach – procedures to determine optimal positionings of measuring points as well as procedures to determine their relative usefulness – allow for an improvement of the information about the infiltration status of sewer systems and for a reduction of the measurement-related uncertainties and costs. The developed methods are based on cluster analysis and its characteristic values. This kind of classification had to be modified because reaches are not independent in terms of infiltration/inflow measurements. They have to be considered within their spatial and network relationships, respectively. Thus, the method to determine the optimal MP positioning is actually a classification procedure with regard to spatial information.

The developed methods are not based on functional relationships between reach characteristics and I/I rates. They compare and classify states of reaches and reach populations. Thus, their main advantage is a very high degree of freedom against data needs. A definite attribute set is not necessary; the methods can be adapted to nearly every data situation. The investigation scope can easily be extended by using suitable attributes, e.g. the number of wrong connections for inflow or by including additional sewer elements, e.g. house connections.

Due to the expression of I/I by reach attributes, the methods depend on the assumption of a functional relationship between reach attributes and I/I rates. Therefore, the methods are not suitable for I/I sources beyond common experience. The results gained with the developed procedures are to be considered within the boundary conditions of the given data set.

The basic behaviour of the optimisation methods was tested with theoretical verification cases that had randomised or uniform infiltration rates. The results corresponded very well with the expectations. But, the potential improvement had a wide range and depended strongly on the network topology. This dependency was found for the verification examples with artifical I/I rates, too.

Despite the unsatisfactory data situation concerning real I/I rates and the influence of the compensating arbitrary infiltration models the results of the verification cases with artifical I/I rates show a significant error reduction (e.g. Table 4-8). Thus, the verification of the optimisation methods is justified. Due to the specific character of sewer systems it is very difficult to give general conclusions about potential error reduction and optimisation quality. Mainly, the results depend on

- the fraction of meshed sewer length and the number of meshes (Table 4-6); it is not clear to what extent other structural parameters like degree of ramification are relevant
- the homogeneity of the investigated catchment (Figure 4-15); it might be expressed by the maximum φ-value
- the availability of groundwater information (Table 4-8).

The calculation options, i.e. the options for determining φ and the choice of the optimisation algorithm, have – with some exceptions – little influence on the optimisation result due to the structural properties of sewer systems, i.e. low redundance and weak correlations of reach attributes (chapter 3.4). In contrast, the options critical size measure and weighting based on water head are of great importance because they directly influence potential solutions and measuring points, respectively. At least for the cases with measured I/I rates the advanced optimisation algorithm achieves much better results.

The optimisation methods are very robust against disturbances like random bias or reduced data sets. They yield stable and reproducible results. For suitable catchments it is estimated, that the potential error reduction amounts up to 40 % compared to non-optimised MP configurations. It has to be kept in mind that the optimisation cannot reach the quality of common classification methods as spatial information is included. Suitable catchments with a high optimisation potential are relatively well structured (number and size of meshes, distribution of reach properties) and have infiltration that is dominated by diffuse sources.

The examples shown in Figure 4-17, Figure 4-18 and Figure 4-21 demonstrate that the relative usefulness and the information yield of MPs, respectively, differ significantly, even those of optimised MPs. Knowing the majority of relevant attributes, the information yield can be easily estimated by means of variance measures and similarity figures. Regarding the measurement costs as listed in chapter 2.6.5 there is a high potential for cost savings. Thus, investigations about the information yield are essential for measurement campaigns.

The three cases with measured I/I rates are extremely valuable for verification purposes. They provide evidence of usable relationships between sewer characteristics and optimised measuring points on the one hand and observed I/I rates on the other hand. By analysing these real sewer systems it can be concluded, that the proposed methods fully fulfil the tasks defined in chapter 2.9 under practical conditions. But, for an application aiming at a good cost-benefit ratio some additional constraints apply:

- In larger catchments (*LENGTH* » 500 km) MPs might be primarily determined due to other criteria, e.g. major confluence points. Here, the methods have a supportive character and should be used after a first identification of I/I sources.
- Numerous data should be available for the investigated catchment. The optimisation uncertainty increases with a decreasing number of attributes.
- Major changes of the sewer characteristics are likely in case of extreme changes of the quarter type or the age of buildings. Here, it is cheaper to determine the optimal MPs manually.

5 Transfer of measurement results

5.1 Basic concept

The mathematically justified transfer of infiltration/inflow measurement results to comparable sub-catchments would have a great potential for cost savings because the number of measurements could be reduced. With applying the similarity approach "Similar sewer conditions lead to similar infiltration/inflow rates", a result transfer from a sub-catchment to others is in fact a classification procedure assigning new items (sub-catchments or reaches without I/I measurements) to known and comparable groups (sub-catchments with I/I measurements). Thus, the strict restrictions of the measuring point optimisation concerning spatial information do not apply for the result transfer. The network topology, i.e. the location of the reaches to each other, is not relevant. The group and sub-catchment affiliation, respectively, has to be known, only.

Due to the multitude of reach attributes, multivariate classification procedures are a suitable basis for developing transfer methods. As observed in the optimal positioning procedure, the main problems while applying these techniques are the varying data availability and representation of sub-catchments and reaches. The smallest entities with definite I/I rates are sub-catchments. Their classification would be reasonable. However, regarding the results obtained in chapter 3.3.2, the attribute differences between sub-catchments are relatively high. This complicates a successful assignment of sub-catchments and I/I rates, respectively.

A classification of reaches is mathematically promising as the variability of the attributes is considered. But, the assignment of known I/I rates to reaches classified to the corresponding sub-catchments would be uncertain because such an assignment assumes that this I/I rate is equal for all reaches within a sub-catchment.

Two approaches were investigated in order to consider the advantages of both classifiable items:

– Transfer method based on analysis of variance: This approach uses ANOVA post hoc tests to compare sub-catchments directly.

- Transfer method based on discriminant analysis: This approach uses the discriminant analysis to assign reaches to sub-catchments with known I/I rates.

Compared to the determination of an optimal positioning of measuring points, the transfer of measurement results extends the potential application requirements of the similarity approach very much. The MP positioning just defines homogeneities; the transfer demands and uses homogeneities. The heterogeneity and the sub-optimal homogeneity, respectively, of real sub-catchments as shown in Figure 4-7 complicates the application. Thus, data requirements are more sophisticated and subject to some restrictions in order to overcome this suboptimal situation:

- Information about the groundwater situation in the catchment is essential. Required are the identification of groundwater influenced reaches or spatially uniform groundwater conditions in relation to the reaches.
- Due to the coarse resolution of I/I measurements the direct use of I/I rates is not reasonable. A definition of I/I classes $cl_{I/I}$ is necessary.
- Extrapolations are not feasable. Sub-catchments with unknown I/I rates have to match the characteristics of sub-catchments with known rates for a successful assignment of I/I classes. The coverage of all sub-catchments is therefore not always possible.

5.2 Transfer based on analysis of variance

5.2.1 Method

The ANOVA transfer method determines similarities of single attributes between sub-catchments with unknown I/I classes and sub-catchments with known I/I classes. In cases of high similarities the I/I class is transferred. The method uses the procedure of summarising ANOVA post hoc test results which was introduced in chapter 3.3.2.

Thereby, the reach attributes are analysed with the relevant post-hoc tests. A testing whether the sub-catchment characteristics match each other is not necessary since the post-hoc tests identify significant differences between the sub-catchments and reach populations, respectively, with regard to the variances. The number of non-significant test results is summarised. If a post hoc test result is not significant, then there is no significant difference between is not significant, then there is no significant difference between the reach populations and sub-catchments, respectively, for the respective attribute. Thus, those sums stand for a similarity degree to which all attributes contribute equally. Pairs of sub-catchments with a high sum can be assumed as similar and should have a similar I/I class. The threshold for a class transfer depends on the distribution of similarities. It is set due to a negative elbow criterion (Figure 5-1). If the cumulated frequency of similarities between all sub-catchments increases only weakly with adding a new attribute, the explanatory power of this similarity is weak and it can be neglected.

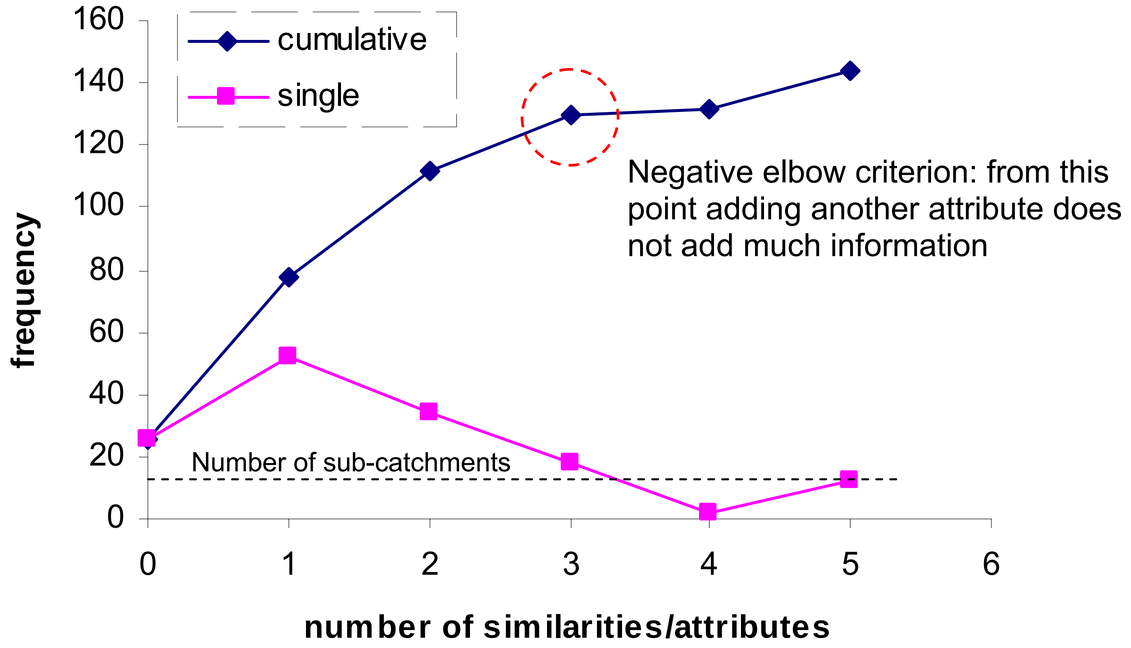


Figure 5-1. Negative elbow criterion (for the example shown in Figure 5-2)

5.2.2 Verification

5.2.2.1 Cases with artificial I/I rates

The first six sub-catchments of Table 4-4 were used for verification purposes. They were provided with artificial groundwater levels and I/I rates calculated with the model "not so simple" (Equation 4-32). Therefore, only groundwater influenced reaches were considered further. The reach populations were split randomly in order to increase their number. The splitting is possible because the network topology within a sub-catchment is not relevant for transfer purposes. Regarding the relatively low number of obtained sub-catchments the model-based I/I rates were classified equidistantly in three classes low, middle and high (Table 5-1).

Figure 5-2 shows a matrix of the sum of similarities between all paired sub-catchments based on parametric least significant difference tests. As five attributes were used for the infiltration model, five is the maximum number of similarities. Due to their distribution (Figure 5-1) the treshold of similarities was set to three or 60 %. From the 15 % of pairs identified to be similar only 50 % were correctly assigned, i.e. their I/I classes were identical (crosses in Figure 5-2).

Figure 5-3 shows a matrix based on multiple comparisons, i.e. the attributes were ranked beforehand. This non-parametric test has a lower discriminatory power. Thus, more pairs which are potentially similar were identified. Nevertheless, the results do not differ much to Figure 5-2. From the 38 % of pairs identified to be similar only 40 % were correctly assigned.

Several additional calculations showed that both a change of the significance level of the tests and a change of the threshold of similarities within a reasonable range have a low influence on the results, only. However, the applicability of the negative elbow criterion for determination thresholds for a class transfer is indicated.

The overall results of the ANOVA transfer method are not completely satisfying. The method suffers from a very low catchment coverage, i.e. only a few pairs are identified to be similar. The reason for this is the strong selectivity of the used post hoc tests. Therefore, an increase of the coverage due to a change of the methodical approach is unlikely. With the splitting of existent sub-catchments a number of sub-catchments with comparable I/I rates should be created. In contrary, the rate of correctly assigned sub-catchments is much lower than expected. Apparently, the attribute variances within a sub-catchment are too high.

Table 5-1. Sub-catchments with artificial I/I classes

Sub-catchment	Origin	Rate $q_{I/I}$ [L/m²·h]	Class $cl_{I/I}$ [-][1]
04F79_1	Dresden	0.00329	Low
04F79_2	Dresden	0.00086	Low
F50_1	Bottrop	0.01909	Low
F50_2	Bottrop	0.07001	High
16P46_1	Bottrop	0.01309	Low
16P46_2	Dresden	0.00368	Low
F42	Bottrop	0.00094	Low
F46_1	Bottrop	0.00815	Low
F46_2	Bottrop	0.03893	Middle
01G145_1	Dresden	0.05695	High
01G145_2	Dresden	0.03478	Middle
01G145_3	Dresden	0.02145	Low

[1]Classlimits: 0.00086, 0.02391, 0.04696, 0.07001 L/m²·h

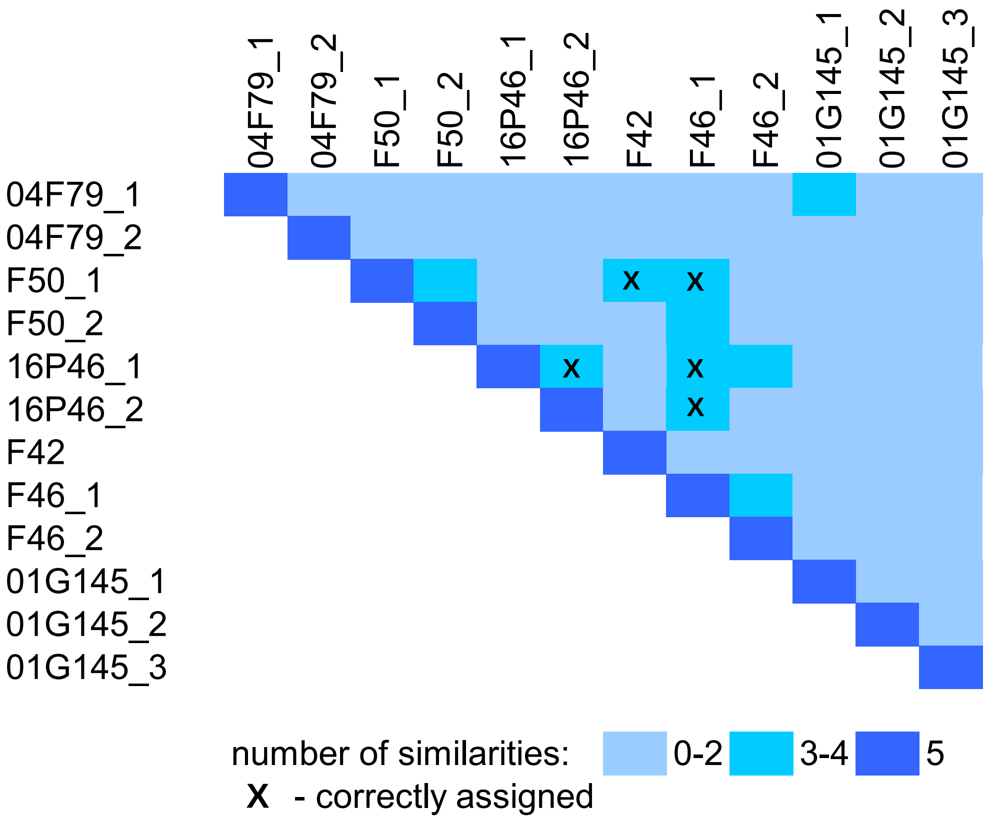


Figure 5-2. Frequency of similarities between sub-catchments – artificial I/I classes, parametric tests

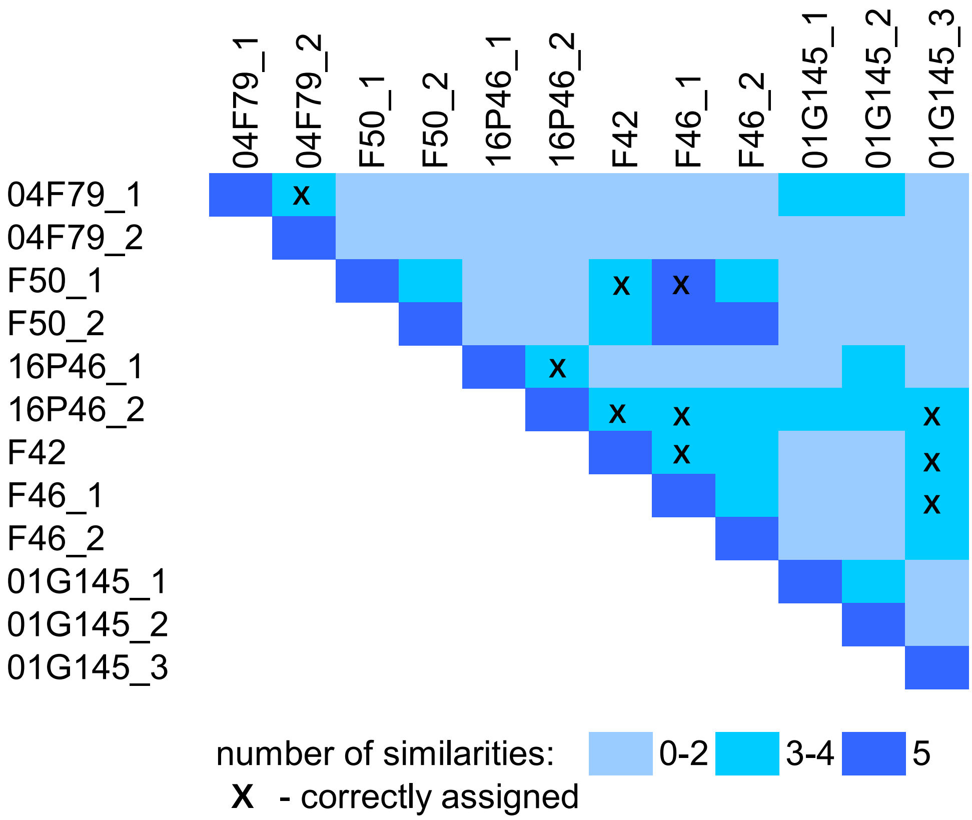


Figure 5-3. Frequency of similarities between sub-catchments – artificial I/I classes, non-parametric tests

5.2.2.2 Cases with measured I/I rates

The ANOVA transfer method was applied to the Dresden data set without groundwater information (Table 3-1). The following 15 attributes were selected for the analysis: *DATE_CONSTR*, *PROF_CIRC*, *LENGTH*, *POP_DENS*, *POP_LENGTH*, *DIST_WATER*, *DIST_BUILD*, *STREET_TYP*, *DIST_STREET*, *SLOPE*, *COVERAGE*, *DIST_ELBE*, *DIST_STORM*, *DIST_DRAIN* and *THICK_COHSV*. Regarding the relatively high number of sub-catchments the measured I/I rates were equidistantly classified in five classes from very low to very high (Table 5-2).

Table 5-2. Sub-catchments with measured I/I classes, without gw information

Sub-catchment	Rate $q_{I/I}$ [L/m²·h]	Class $cl_{I/I}$ [-][1]
01F6	1.20	Low
01G145	0.90	Low
01H34	1.73	Middle
04C16	0.52	Very Low
04F79	0.33	Very Low
08S83	0.52	Very Low
09I1	0.78	Low
15H24	2.07	High
15X54	0.18	Very Low
15Z33	0.73	Very Low
16P46	1.88	High
17Y16	1.67	Middle
29EE27	0.77	Low
ED	1.48	Middle
MA	0.80	Low
OD	1.14	Low
RC	1.56	Middle
SB	0.90	Low
SF	1.02	Low
WE	2.95	Very High
ZWEZG 08K120	2.22	High
ZWEZG 36B13	0.92	Low

[1]Classlimits: 0.18, 0.59, 1.00, 1.41, 1.81, 2.22 L/m²·h

The resulting matrix based on least significant difference tests is shown in Figure 5-4. The minimal number of similarities to be investigated was set to six. From the remaining 10 % of pairs identified to be similar only 43 % were correctly assigned, additional 30 % with a difference of just one class. Despite the violation of the restriction about groundwater information (chapter 5.1), these results are expected to be valid because uniform groundwater conditions can be assumed for the pairs identified to be similar (extracted from Landeshauptstadt Dresden, 2006). The use of non-parametric tests leads to comparable results.

The same effects of low catchment coverage and unsufficient assignment rate as at the cases with artifical I/I rates could be observed. The results are even worse due to the inclusion of reaches which are not influenced by groundwater. Mainly sub-catchments with a relatively high a priori similarity and with a groundwater situation assumed to be comparable (chapter 3.3.2) were detected as areas with similar I/I rates.

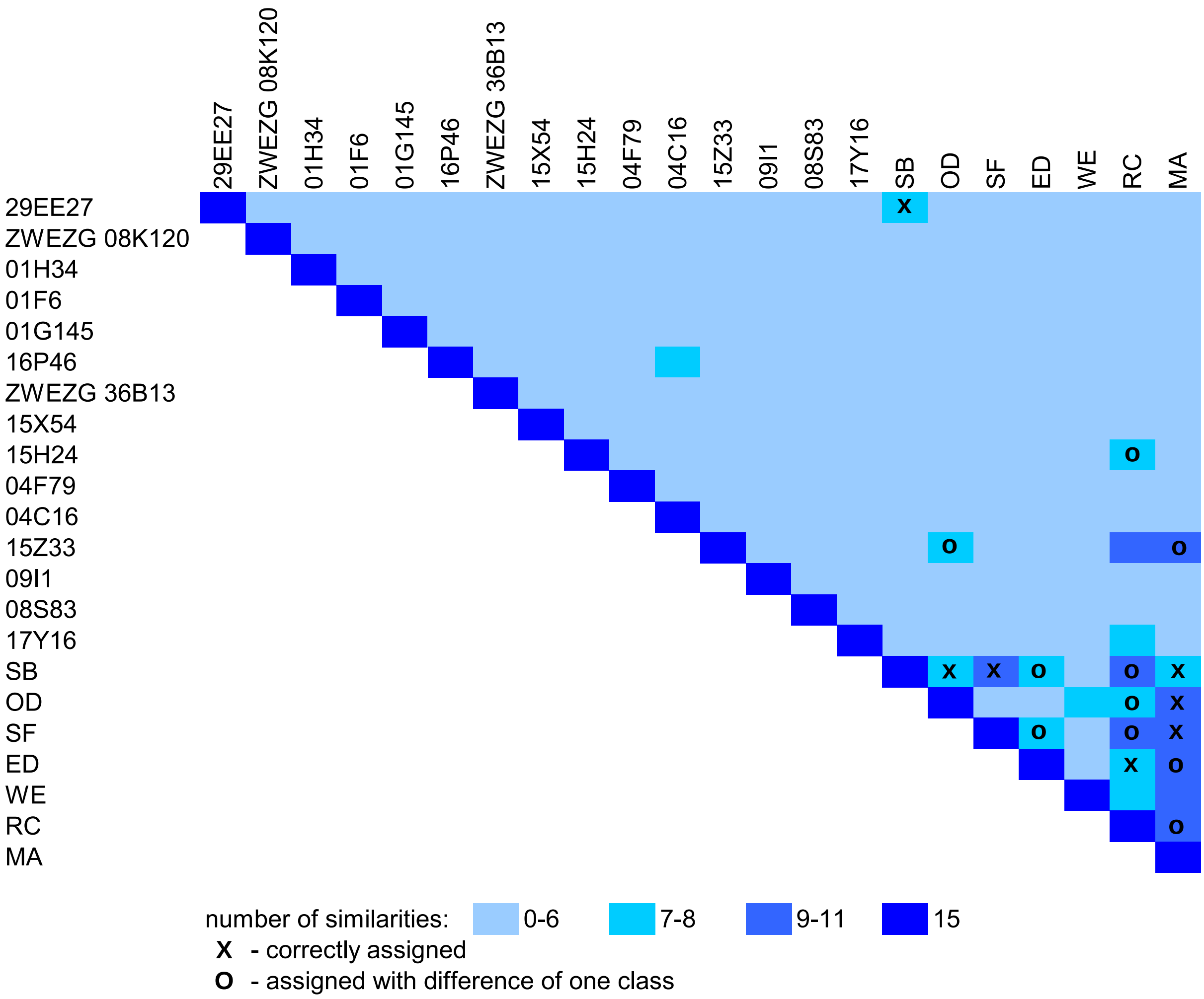


Figure 5-4. Frequency of similarities between sub-catchments – measured I/I classes, without gw, parametric tests

The application of the ANOVA transfer method to the Dresden data set with groundwater information (Figure 3-4, Table 3-8) yielded better results. The relevant sub-catchments are combined sewer systems and situated at the bottom of the Elbe valley. Therefore, the data set was reduced to the 11 attributes *DATE_CONSTR*, *PROF_CIRC*, *LENGTH*, *POP_DENS*, *POP_LENGTH*, *DIST_WATER*, *DIST_BUILD*, *DIST_STREET*, *COVERAGE*, *DIST_ELBE* and *THICK_COHSV*. The measured I/I rates were equidistantly classified in three classes (Table 5-3).

The resulting matrix based on least significant difference tests is shown in Figure 5-5. The minimal number of similarities to be investigated was set to six. From the remaining 20 % of 10 pairs identified to be similar 100 % were correctly assigned.

Keeping in mind the very low number of investigated sub-catchments, a consideration of groundwater information seems to lead to more reliable results as there is no adulterant influence of reaches not contributing to I/I. The exlusion of those reaches did not eliminate the differences between the sub-catchments. Thus, the catchment coverage is not improved.

Table 5-3. Dresden sub-catchments with real I/I classes, with gw information

Sub-catchment	Rate $q_{I/I}$ [L/m²·h]	Class $cl_{I/I}$ [-][1]
01F6	5.00	Middle
04C16	4.50	High
04F79	2.87	High
16P46	7.35	Low
ZWEZG 36B13	8.52	Low

[1]Classlimits: 2.87, 4.76, 6.64, 8.52 L/m²·h

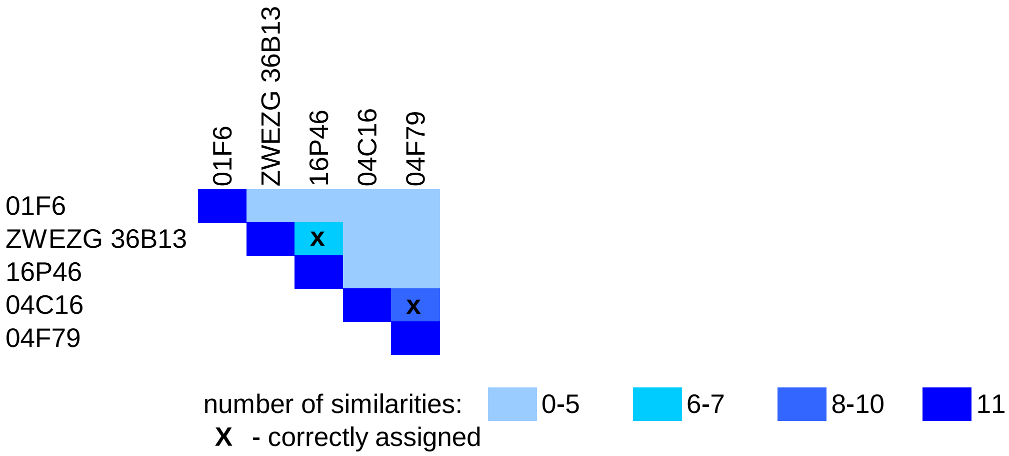


Figure 5-5. Frequency of similarities between sub-catchments – measured I/I classes, with gw, parametric tests

5.3 Transfer based on discriminant analysis

5.3.1 Discriminant analysis

5.3.1.1 Approach

The discriminant analysis belongs to the exploratory data analysis and verifies structures in data sets. It is used either as hypothesis testing or as exploratory method. For hypothesis testing, discriminant analysis determines which variables discriminate between several naturally occurring groups, i.e. it reduces data and ranks attributes. For data exploration it groups items based on their attributes into classes by using classification procedures. The main difference to cluster analysis whose task is similar is that the groups or clusters are known at the beginning of the analysis.

Computationally, discriminant analysis is similar to analysis of variance and multiple regression analysis (Hill and Lewicki, 2006). On the one hand, the method compares matrices of total and within-group variances and covariances by means of multivariate F-tests in order to determine significant differences between the groups. This procedure is identical to multivariate analysis of variance. On the other hand it determines analogous to multiple regression analysis linear discriminant functions or so-called canonical roots which discriminate the groups by means of a discriminant value $y_j = f(x_1, x_2, \ldots, x_n)$. The functions y_j are a (n-1)-dimensional representation of the n-dimensional attribute space. The iso-quant $y_j = 0$ is a separation plane between groups.

Graphically, this is shown in Figure 5-6. Two groups G_1 and G_2 are given whose items are characterised by the attributes x_1 and x_2. Distributions of attributes and overlaps of the groups are marked by bars. A discrimination of the groups based solely on the attribute x_1 – if $x_{1,o_1} \leq x_{crit}$ then $o_1 \in G_1$, if $x_{1,o_1} \geq x_{crit}$ then $o_1 \in G_2$ – yields suboptimal results due to the large overlap of both groups. The discrimination is much better while using the discriminant value y_1, because it minimises the overlapping (checkered bar).

New items can be classified to known groups by means of several concepts: the distance concept using calculated distances between items and group centroids, the probability concept as statistical decision problem and classification functions.

Due to the relationship between discriminant analysis and ANOVA, all assumptions for ANOVA apply: normal distribution of the data, homogeneity of variances and covariances, no correlations between means and variances. Beside this, the attributes which are used to discriminate between groups must not be completely redundant.

A comprehensive explanation and consideration of the discriminant analysis is given in Hartung and Elpelt (1995) or Backhaus et al. (1996).

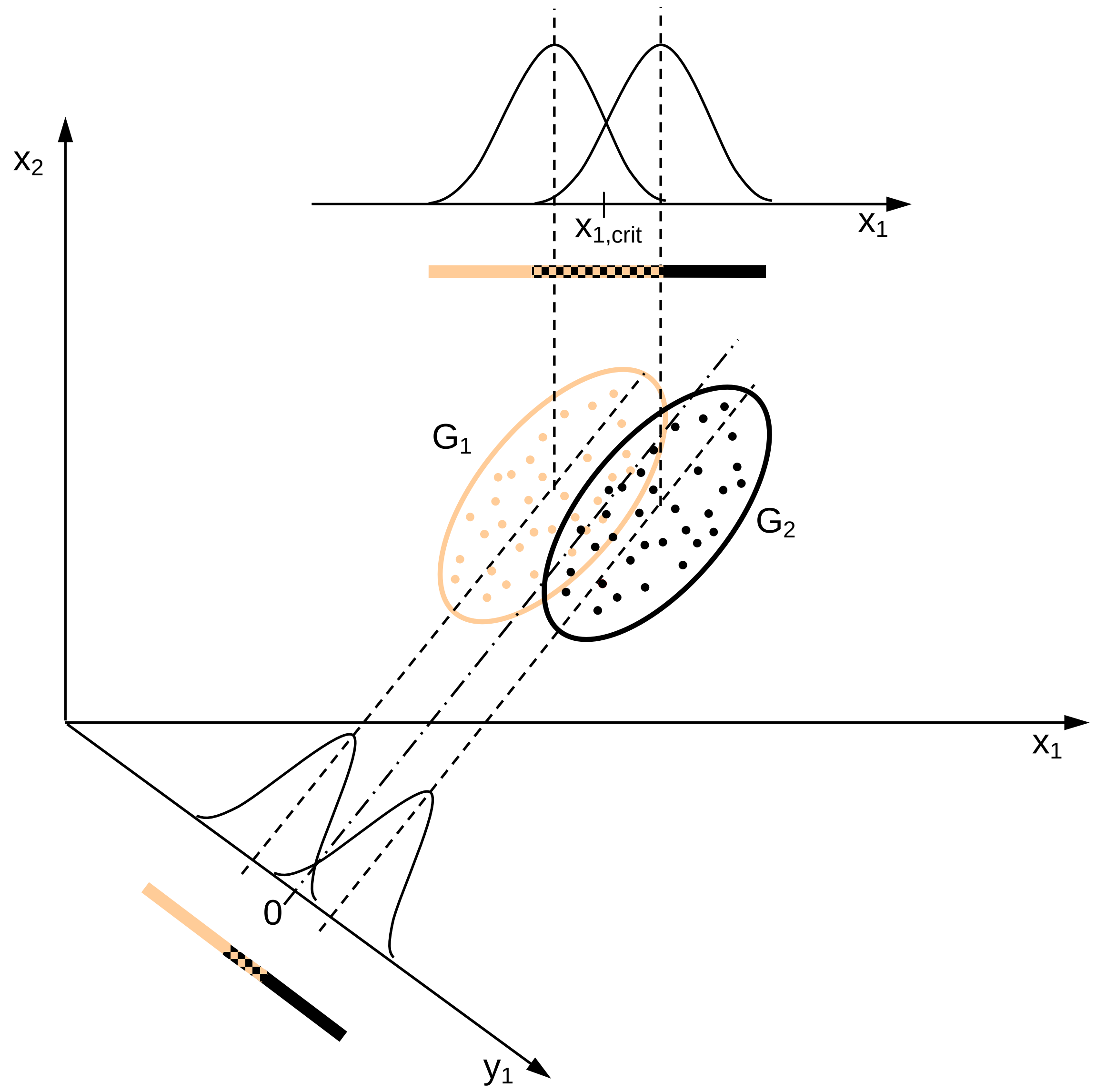


Figure 5-6. Discriminant function

5.3.1.2 Procedure

The discriminant analysis consists of four stages (adapted from Backhaus et al., 1994):

1. Estimation of the discriminant functions: Generally, the discriminant functions have the form:

$$y_j = c + b_1 \cdot x_1 + b_2 \cdot x_2 + \ldots + b_n \cdot x_n \qquad \text{Equation 5-1}$$

with b_i coefficient or root of attribute x_i
c constant

The maximum number of discriminant functions is the minimum of n_{groups}-1 and $n_{attribute}$. The functions are independent from each other, i.e. their contributions to the discrimination between the groups do not overlap. The coefficients bi are determined by the maximisation of the discriminant criterion, i.e. the ratio between the total and the within-group variances. The magnitude of the coefficients represents the contribution of the respective attribute to the discrimination. The resulting discriminant value y_j is a metrical representation of the group affiliation. The maximum y_j of a function is called eigenvalue. The eigenvalues determines the relative importance of the respective discriminant functions.

2. Verification of the discriminant functions: The classification ability of the functions is verified by comparing predicted and actual group affiliations. Post hoc predictions use the same data for estimation and evaluation. Therefore, they overestimate the classification quality. A cross-validation is recommended.
3. Assessment of the attributes: The attributes are assessed due to the coefficients b_i in order to explain the differences between the groups and to identify negligible attributes.
4. Classification of new items: With the distance concept, an item o_j with an unknown group affiliation is classified to the group G_i where the Mahalanobis distance (Equation 4-16) between the item and the respective group centroid $\bar{o}_i$ is minimal. With the probability concept, classification probabilities of the item o_j are calculated with

$$P\left(G_i \mid y_{o_j}\right) = \frac{e^{\frac{-d\left(o_j,\bar{o}_i\right)^2}{2}} \cdot P_j\left(G_i\right)}{\sum_{k=1}^{n_{group}} e^{\frac{-d\left(o_j,\bar{o}_k\right)^2}{2}} \cdot P_j\left(G_k\right)} \qquad \text{Equation 5-2}$$

with $P\left(G_i \mid y_{o_j}\right)$ classif. probability with which o_j belongs to G_i
$P_j\left(G_i\right)$ a priori probability for affiliation of o_j to G_i

It applies:

$$\sum_{i=1}^{n_{group}} P\left(G_i \mid y_{o_j}\right) = 1 \qquad \text{Equation 5-3}$$

Classification functions – which are not to be confused with discriminant functions – calculate classification scores S_i for an item for a single group:

$$S_i = c + b_1 \cdot x_1 + b_2 \cdot x_2 + \ldots + b_n \cdot x_n \qquad \text{Equation 5-4}$$

with b_i coefficient or weigth of attribute x_i
c constant

The item is classified to the group for which it has the highest classification score. There are as many classification functions as there are groups. This concept can be applied only if same variances of the groups can be assumed.

5.3.1.3 Example

A discriminant analysis was performend with a reduced data set of the 22 Dresden sub-catchments containing the 9 attributes *DATE_CONSTR*, *PROF_CIRC*, *POP_DENS*, *DIST_ELBE*, *DIST_WATER*, *DIST_BUILD*, *DIST_STREET*, *SLOPE* and *COVERAGE*. The results of the analysis – the statistical measures Wilks' Lambda and tolerance as well as the roots and coefficients b_i, respectively, of the first three of nine discriminant functions – are given in Table 5-4.

Wilks' Lambda describes the separate discriminatory power of the respective attribute. It ranges between 0 and 1. The smaller this value the higher is the discriminatory power. The tolerance describes the redundancy of the attributes. A value of 0 stands for a complete redundancy, a value of 1 for a redundance-free attribute. It can be concluded, that the discrimination is significant (chapter 3.3.2). It is dominated by the attributes *DIST_ELBE*, *POP_DENS*, *DIST_WATER* and *DATE_CONSTR*. The used attributes are slightly redundant. The attributes with a higher redundancy *DATE_CONSTR*, *PROF_CIRC* and *COVERAGE* could be probably linked by the factors network structure or construction period (compare chapter 3.4).

The coefficients of the first two roots which explain 80 % of the observed variance show also the domination of *DIST_ELBE* and *POP_DENS*. Both attributes have the highest absolute values. A graphical representation of the discriminant functions Root 1 and Root 2 is shown in Figure 5-7. Every data point in this figure stands for a reach. A relatively good discrimination between the groups and sub-catchments, respectively, can be observed.

Table 5-4. Results of discriminant analysis for Dresden data without gw information

Attribute	**Wilks' Lambda [-]**	**Tolerance[-]**	**Root 1[-]**	**Root 2[-]**	**Root 3[-]**
DATE_CONSTR	0,790	0,704	0,155	-0,262	-0,133
PROF_CIRC	0,925	0,570	-0,147	0,170	0,364
POP_DENS	0,575	0,893	-0,256	1,250	-0,829
DIST_ELBE	0,350	0,884	-2,022	-0,048	0,006
DIST_WATER	0,706	0,941	-0,269	0,469	1,133
DIST_BUILD	0,924	0,756	-0,011	0,056	0,261
DIST_STREET	0,953	0,798	-0,091	0,115	0,025
SLOPE	0,997	0,998	-0,011	-0,007	-0,018
COVERAGE	0,950	0,672	0,092	0,030	-0,280
constant			0,116	-0,109	0,177
eigenvalue			1,932	1,506	0,376
explained variance, summarised			0,452	0,804	0,892

The quality of the classification of reaches into sub-catchments based on the discriminant analysis is not satisfying. The mean fraction of correctly classified reaches amounts to only 45 % with a range from 0 to 99 % (Figure 5-8). This classification was done post hoc, i.e. with the same data as for estimation of the discriminant functions. The main reasons of this result are the homogeneity and the attribute variances, respectively, of the respective sub-catchments. The homogeneities can be deduced e.g. from clustering results as shown in Figure 4-7. Sub-catchments with a narrow cluster structure, i.e. a high homogeneity, have good classification results and vice versa. Thus, the definition and the use of optimised sub-catchments are indicated for a reliable result transfer.

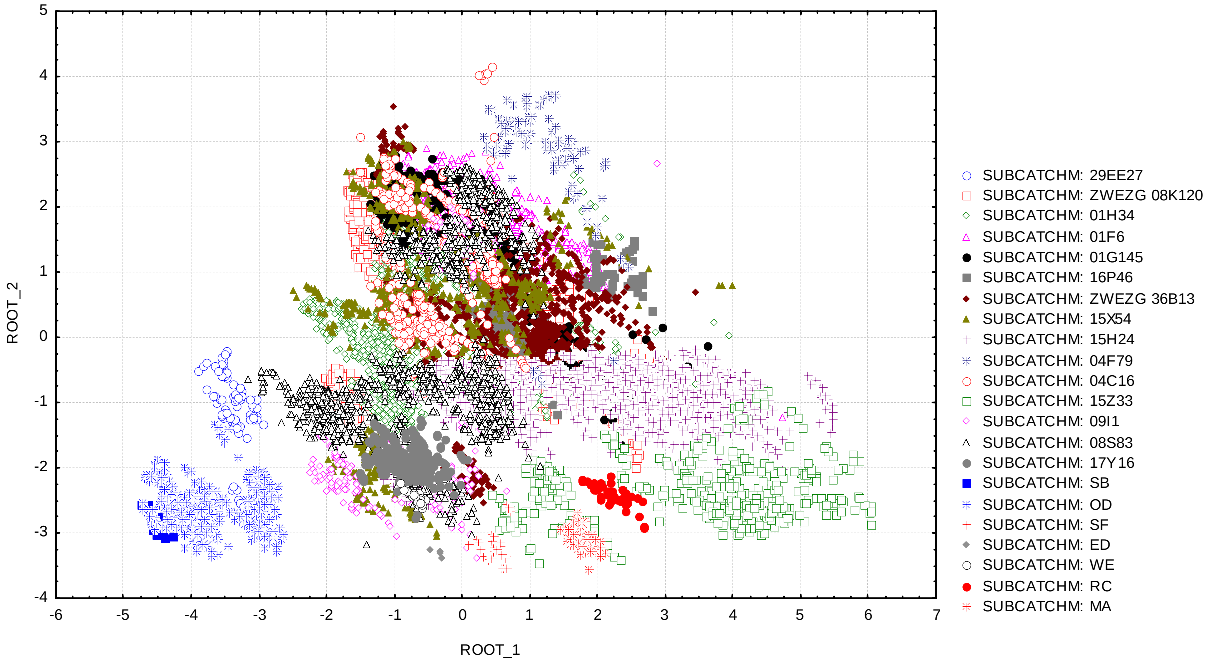


Figure 5-7. Canonical values of Root 1 and Root 2, explained variance 80.4 %, Dresden data without gw

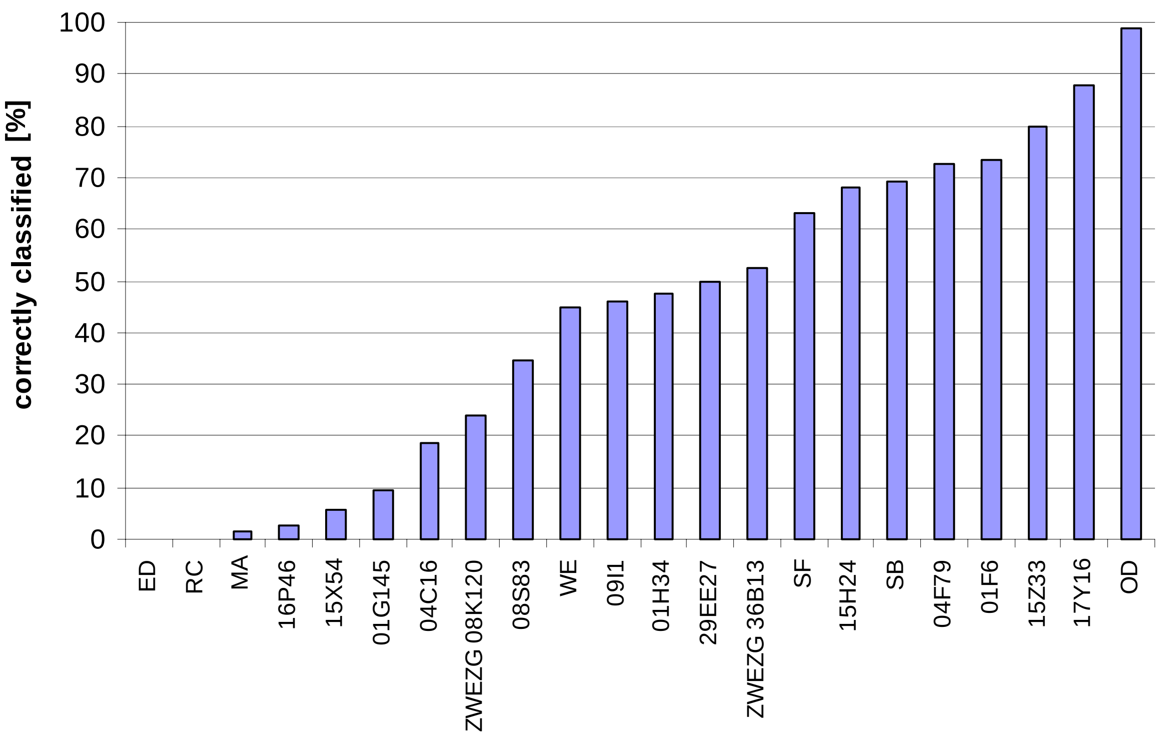


Figure 5-8. Fraction of correctly post hoc classified reaches, Dresden data without gw

5.3.2 Method

The discriminant analysis transfer method classifies reaches of a sub-catchment with an unknown I/I class to sub-catchments with known I/I classes. Due to the classification of individual reaches, the method considers the attribute variations within a catchment. The I/I class transferred to the investigated sub-catchment is calculated as a weigthed mean.

For all reaches *reach*$_j$ with an unknown I/I class and all sub-catchments *sb-ctm*$_i$ with known I/I classes the classification probabilities $P\left(sb-ctm_i \mid y_{reach_j}\right)$ are calculated. By using the probability concept, i.e. by classifying reaches in multiple sub-catchments, a more accurate classification result is expected. The predicted I/I class $cl_{I/I,predicted,j}$ for the reach *reach*$_j$ is determined with

$$cl_{I/I,predicted,j} \underset{reach_j \notin sb-ctm_i}{=} \sum_{i=1}^{n_{sb-ctm}} P\left(sb-ctm_i \mid y_{reach_j}\right) \cdot cl_{I/I,i} \qquad \text{Equation 5-5}$$

The overall predicted I/I class $cl_{I/I,predicted}$ for the investigated sub-catchment is calculated as the reach surface weighted mean:

$$c_{I/I,predicted} = \frac{\sum_{j=1}^{n_{reaches}} cl_{I/I,j} \cdot A_{surface,j}}{\sum_{j=1}^{n_{reaches}} A_{surface,j}} \qquad \text{Equation 5-6}$$

Beside the compliance with the constraints of the discriminant analysis it should be tested whether reaches and sub-catchments with unknown rates match the characteristics of sub-catchments to which they are classified in order to avoid extrapolation. This can be done by a one by one comparison of attribute values and respective minimum and maximum values. But, for a multivariate case this is complex and not effective.

Another possibility is the determination of convex hulls of reach populations. The convex hull is the smallest convex shape which encloses a set of points. A geometric set is convex if for every two points in the set, the line segment which joins them is also in the set (Preparata and Shamos, 1993). A two-dimensional example is shown in Figure 5-9. Imaging the reaches as objects in a multidimensional space where every dimension is related to one attribute (chapter 3.3.3.2) convex hulls for the respective reach populations can be defined. Reaches which are not within one or several hulls should be ignored during classification. Thus, misclassifications can be avoided.

However, the determination of a convex hull in an n-dimensional space with $n > 3$ is extremely complex. Even if the vertices of the hull are known, the construction of its faces is a non-trivial task. Therefore, this procedure was not applied.

For the verification of the method a very simplified procedure is proposed. The constraint of characteristic matching between reaches with unknown I/I rate and sub-catchments with known rates is proved by a comparison of the distributions of all attributes. If the distributions of the respective sub-catchments overlap sufficiently, the constraint is assumed to be fulfilled.

The first step of the discriminant analysis transfer method, the classification of reaches to sub-catchments with known I/I classes, can be conducted by any classification method. Other powerful methods which were investigated for that purpose are artificial neural networks. A comprehensive overview about these methods can be found in Sarle (1997) or Haykin (1994). But, since the discriminant analysis is sufficient and easier to apply, neural networks were not implemented.

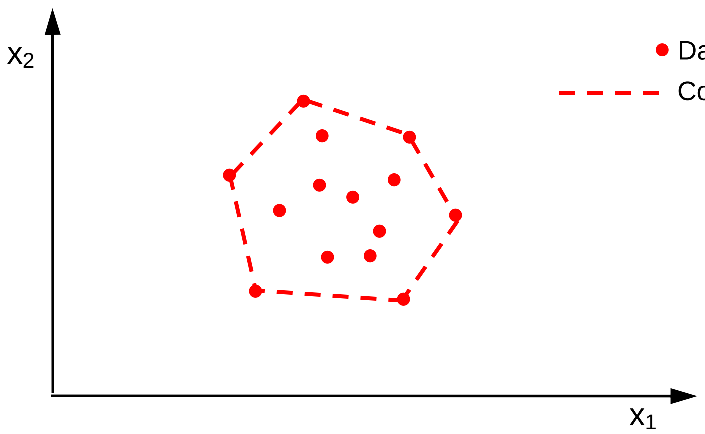


Figure 5-9. Convex hull in a two-dimensional Euclidean space

5.3.3 Verification

5.3.3.1 Cases with artificial I/I rates

Compared to the ANOVA transfer method, the assignment quality can be determined with a higher resolution due to the metrical character of $cl_{I/I,predicted}$. Thus, the assignment quality is not defined by matching classes but calculated as assignment error:

$$e = \left| c_{I/I,predicted} - c_{I/I} \right| \qquad \text{Equation 5-7}$$

The cases described in chapter 5.2.2.1 were analysed with the discriminant analysis transfer method. The constraint of characteristic matching between sub-catchments with unknown I/I rates and that with known I/I rates was fulfilled for all verification cases. The results of the transfer are shown in Table 5-5. Taking 0.3 class-width or 15 % of the total range as a suitable assignment error, 50 % of the sub-catchments were correctly assigned. Assuming a softer error of 1.0 class width 75 % of the sub-catchments were correctly assigned. As observed in chapter 5.2.2, the results suffer from high attribute variances and therefore a suboptimal classification quality.

With a view to the data situation the results are acceptable. But, their significance regarding the applicability of the transfer method has to be attenuated because only one sub-catchment was classified per run, i.e. the ratio of classified sub-catchments and sub-catchments to classify was 11 ÷ 1. Therefore, the potential assignment quality under practical conditions might be overestimated.

Additionally, the following cases were analysed:

- more sub-catchments with artificial I/I rates
- more artificial I/I classes
- weighting of the mean I/I class due to the sewer length

The results of these investigations did not differ significantly from the cases illustrated above. As expected, the use of measured I/I rates instead of I/I classes did lead to a result decline.

Table 5-5. Assignment errors of sub-catchments with artificial I/I classes

Sub-catchment	Class $cl_{I/I}$ [-][1]	Class $cl_{I/I,predicted}$ [-]	Assignment error e [-]
04F79_1	1	1.9	0.88
04F79_2	1	1.2	0.17
F50_1	1	1.3	0.26
F50_2	3	1.3	1.66
16P46_1	1	1.9	0.87
16P46_2	1	1.2	0.16
F42	1	1.0	0.05
F46_1	1	2.4	1.42
F46_2	2	2.7	0.69
01G145_1	3	1.8	1.18
01G145_2	2	1.9	0.06
01G145_3	1	1.2	0.20

[1]Code: 1-low, 2-middle, 3-high; classlimits are given in Table 5-1

5.3.3.2 Cases with measured I/I rates

The discriminant analysis transfer method was also applied to the Dresden data set with groundwater information (Figure 3-4, Table 3-8). The data set was reduced as explained in chapter 5.2.2.2. The measured I/I rates were equidistantly classified in three classes (Table 5-3).

The result of the transfer is shown in Table 5-6. With a tolerated assignment error of 0.3 class width 40 % of the sub-catchments were correctly assigned, with an error of 1.0 class width 60 % of the sub-catchments. A comparison between the assignment errors and the fraction of correctly post hoc classified reaches indicates that a high assignment error occurs parallel to a low classification quality.

Using a reduced data set containing the attributes *DATE_CONSTR*, *PROF_CIRC*, *LENGTH*, *POP_DENS*, *DIST_ELBE*, *DIST_BUILD*, *DIST_STREET* and *SLOPE*, the transfer result was improved. The assignment errors have a maximum of 1.18 class width and 80 % of the sub-catchments were correctly assigned within an accepted error of 1.0 class width. Apparently, the classification quality of this reduced data set is higher. The reason migth be that the attributes which were excluded are assumed to be redundant.

Both observations – the results gained by means of the reduced date set and the comparison between assignment errors and classification quality – underline the strong dependency of transfer results from the homogeneity of investigated sub-catchments.

Table 5-6. Assignment errors of sub-catchments with real I/I classes, with gw information

Sub-catchment	**Class $cl_{I/I}$ [-]**[1]	**Class $cl_{I/I,predicted}$ [-]**	**Assignment error e [-]**	**Fraction of correctly classified reaches [%]**
01F6	2	3.0	1.000	100.0
04C16	3	3.0	0.001	100.0
04F79	3	1.0	2.000	77.8
16P46	1	2.7	1.750	93.8
ZWEZG 36B13	1	1.0	0.052	100.0

[1]Code: 1-low, 2-middle, 3-high; classlimits are given in Table 5-3

5.4 Discussion

The proposed applications of the similarity approach – the ANOVA and the discriminant analysis transfer method – allow for a mathematically founded and reliable transfer of infiltration/inflow measurement results between sub-catchments. It is thus possible to improve the information about the I/I situation in a sewer system with a reasonable financial effort significantly.

Among the two developed methods the ANOVA transfer method is the weaker one. The underlying post hoc tests verify the significance of group differences. Therefore, the assignment of sub-catchments to other sub-catchments with known I/I rates has a binary character. Furthermore, the post hoc tests are relatively selective. Due to the good a priori discrimination of sub-catchments (chapter 3.3.2) the potential catchment coverage is very low. Actually, in case of artificial I/I rates and therewith well defined conditions, the results of only one third of the sub-catchments were transferable. In case of measured I/I rates this rate was even smaller.

The result quality appears to be relatively low. The rates of correct transfer of I/I rates between sub-catchments identified to be similar amounted to approximately 50 %. Keeping in mind the low number of available sub-catchments, the cases with measured I/I rates and known groundwater table are a promising exception. At these verification cases a correct assignment rate of 100 % was observed.

The advantage of the ANOVA transfer method is the compliance with less strict contraints. In comparison to the discriminant analysis transfer method ordinal and nominal attributes can be included and a test whether sub-catchments with unknown rates fit the characteristics of sub-catchments with known rates is not necessary. Unintentional extrapolations are not possible.

The discriminant analysis transfer method treats single reaches. Hence, it has a greater potential of applicability. It considers variations within the data sets and calculates affiliation strengths instead of determining bivalent assignments. This potential is reflected by the verification results. Keeping in mind that just three I/I classes were established and that the ratio of classified sub-catchments and sub-catchments to classify was high, the method yields acceptable results with a total fraction of 50 % to 75 % correctly assigned sub-catchments. Furthermore, the method delivers additional information to assess the results.

The positive verification of both measurement transfer methods is indicated, as the transfer of I/I classes succeeded with an acceptable error for the majority of the sub-catchments identified to be similar. Nevertheless, the methods are not satisfying for practical purposes. The potential catchment coverage as well as the rate of correct assignments are too low.

As shown in Figure 5-4 and Table 5-6, the transfer results depend strongly on the homogeneity of the considered sub-catchments. Thus, an increase of the total homogeneity, i.e. the a priori determination of sub-catchments optimised with regard to their individual homogeneity, is expected to improve the catchment coverage as well as the result reliability significantly. Furthermore, the knowledge of the groundwater situation seems to be very important as indicated in Figure 5-5.

Despite the restrictions for a practical application, the transfer methods might be used as pre test or screening procedure in the run-up to detailed I/I investigations. By determining sub-catchments which are not similar to those with known

I/I rates and by comparing classification results of different sub-catchments, it is possible to define a ranking of further measurements. Thus, the measurement effort might be reduced.

6 Summary

The aim of this work was to develop methods which improve the knowledge about the infiltration/inflow (I/I) situation in sewer systems in order to reduce the effort to handle I/I problems.

The structural integrity of sewer systems, including their water tightness, is demanded by legal regulations and should be guaranteed by the operators. But, a complete water tightness of the assets is de facto not possible due to the large dimension and the underground location of sewer systems. Thus, in most cases infiltration/inflow occurs. This phenomenon has major consequences for the whole sewerage system, both negative and positive. The financial and personnel expenditures of the operators caused by I/I are significant. I/I might as well influence environmental compartments adjunctive with sewers.

The knowledge about relevant processes and influencing factors of I/I is fairly limited. Mostly, it is considered phenomenological. The determination of I/I in a catchment and succeeding operation and maintenance strategies require extensive measurements. Beside the use of permanent measuring points additional measurement campaigns are necessary in larger sewer systems or for detailed I/I investigations. Even for short campaigns the total costs can add up to several thousand Euros per single measuring point. Thus, there is an urgent need for more efficient measurement campaigns aiming at an optimisation and reduction of measuring points as well as at a possibility to transfer available measurement results to other sub-catchments.

Suitable methods that implement these requirements need an approach different from common calculation and modelling techniques since both the knowledge about I/I processes and sewer data are limited. Thus, the methods and procedures developed in this work are based on the assumption “Similar sewer conditions lead to similar infiltration/inflow rates.” With this similarity approach and the adaptation of multivariate statistical methods it is possible to identify homogeneous areas and comparable sub-catchments by looking for and working with similar entities within a sewer system.

The validity and the applicability of the similarity approach were verified by means of comprehensive statistical analyses of limited data sets. With ANOVA techniques it could be shown that sub-catchments with different I/I rates can be discriminated and that larger catchments can be divided in more or less homogenous areas. The relationship between reach-related attributes and measured I/I rates was analysed by means of multidimensional scaling. The analysis showed a good correlation between the specific I/I rate and a value representing sewer, sub-catchment and groundwater data. This correlation is not dominated by the water head between the groundwater level outside and the waste water level inside the pipe. It can be thus concluded that there is a recognisable relationship between independent reach characteristics and dependent I/I rates and that the similarity approach is applicable.

Furthermore, the relevance of reach attributes for I/I was investigated. The results affirm the findings of the literature review. It was not possible to pinpoint one or a small group of attributes as being of overriding importance. Some qualitative statements could be made, though. The attribute groups pipe location and pipe dimensions are less important, building circumstances and external loads are of higher importance. Groundwater information is essential.

With the methods for the effective positioning of measuring points and the determination of the relative usefulness of measuring points, it is possible to improve information on the infiltration status of sewer systems. Applying the similarity approach, optimal positioning can be identified by finding measuring points that maximise the homogeneity of the upstream sub-catchments. Thereby, the differences between reach-related actual and averaged measured infiltration rates are minimised. Assuming errorless measurements, the summarised differences equal the remaining error that is relevant for detailed investigation and developing strategies. The optimisation methods are based on modified cluster analysis. They use similarity figures to quantify the homogeneity of sub-catchments, variance measures to estimate the information yield of measuring points and several algorithms to optimise both values.

The optimisation methods and their options were verified using data of catchments with artificial and measured I/I rates. Despite the unsatisfactory data situation, the verification is justified. For suitable catchments it is estimated, that the potential error reduction amounts up to 40 % compared to non-optimised measuring points configurations. Suitable catchments with a high optimisation potential are relatively well structured and have infiltration that is dominated by diffuse sources. The cases with measured I/I rates provide evidence that the proposed methods are applicable and successful under practical conditions since a good coherence between the optimised arrangement of measuring points and detected changes of measured infiltration rates could be observed. The optimisation methods are very robust against disturbances like random bias or reduced data sets. They yield stable and reproducible results.

The transfer methods allow for the assignment of I/I measurement results to other sub-catchments. Applying the similarity approach, such a transfer is a classification assigning sub-catchments or reaches without I/I measurements to sub-catchments with I/I measurements. The main problem is the varying data availability and representation of sub-catchments and reaches. The smallest entities with definite I/I rates are sub-catchments. But, their classification is complicated due to high attribute differences. A classification of individual reaches is promising as the variability of the attributes is considered. But, the assignment of known I/I rates would be uncertain because such an assignment assumes an equal I/I rate for all reaches. Therefore, two approaches were implemented: a direct comparison of sub-catchments with ANOVA post hoc tests and a classification of reaches by means of discriminant analysis.

The ANOVA transfer method has less strict constraints. But, it yields a lower number of successful assignments of sub-catchments due to the use of selective tests. Verifying the method under well defined conditions, the I/I rates of only one third of the investigated sub-catchments were transferable. The rates of correct transfer of I/I measurement results between sub-catchments identified to be similar amounted to approximately 50 %, just in one scenario to 100 %. The discriminant analysis transfer method has a greater potential due to the consideration of variations within the data sets. With an acceptable error the transfer of I/I classes was successful for up to 75 % of all sub-catchments identified to be similar.

Although the positive verification of the transfer methods is indicated, they are not satisfying for field purposes. The potential catchment coverage and the rate of correct assignments are too low. But, the determination and use of optimised, i.e. homogeneous sub-catchments is expected to improve the coverage as well as the result reliability significantly. At the current state, the transfer methods might be used as a screening procedure in the run-up to detailed infiltration investigations.

The methods based on the similarity approach classify, optimise and compare states, but they do not describe functional relationships, dynamic processes or long term developments. Their main advantage is a high degree of freedom against data needs. The methods can be adapted to nearly every data situation. But, the results gained with the developed procedures are to be considered within the boundary conditions of the given data.

Due to the novel character of the introduced similarity approach and its applications, further research efforts concerning method development and reliable case studies are necessary. Although the basic properties of the methods are understood, the impacts of factors which influence the results are not analysed in detail. This concerns data-related factors like mesh distribution and method options like groundwater information. A matter of particular interest is the nonlinearity of the relations between reach characteristics and I/I rates. In connection with a better knowledge about infiltration processes, an advanced consideration of this phenomenon would have a great potential for result improvement for both the optimisation and the transfer methods. Furthermore, there might be more sophisticated solutions for minor problems than the stepwise splitting of catchments for the optimisation algorithms or the comparison of attribute distributions for the constraint of characteristic matching.

The developed methods were verified mainly by means of generated data. A significant number of case studies with real data, i.e. I/I measurements with a high spatial resolution, are essential for a reliable conclusion to which extent these methods lead to additional information yield and cost savings.

The applied statistical methods were modified in such a way as to enable them to consider reaches within their network relationships. Thus, the optimisation of measuring points and the transfer of measurement results are actually classification procedures with regard to spatial information. Beyond the problem of I/I these procedures have a great potential to support solving other space-oriented problems within urban water management. Provided that reaches have to be investigated and handled in combination with adjacent ones, e.g. during rehabilitation planning, or that measurements are conducted in whole sewer sections, e.g. exfiltration measurements, the similarity approach might be adapted to such investigations.

The methods developed in this work allow for an optimisation and reduction of measuring points and for a transfer of measurement results to other virtual measuring points within a catchment. By using the methods it is possible to improve the knowledge about the infiltration/inflow situation in sewer systems and to reduce the measurement related uncertainty. Both effects result in significant cost savings.

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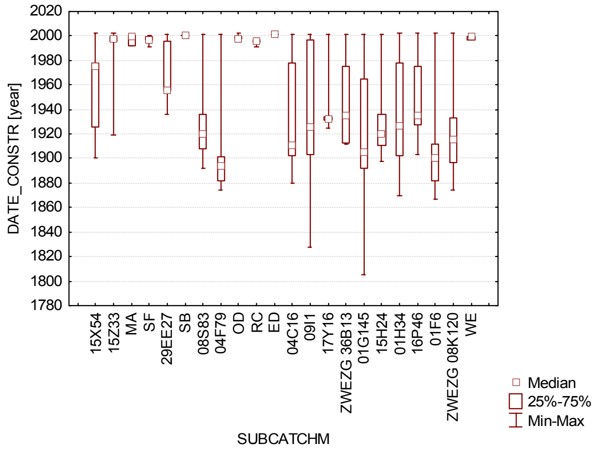
Appendix

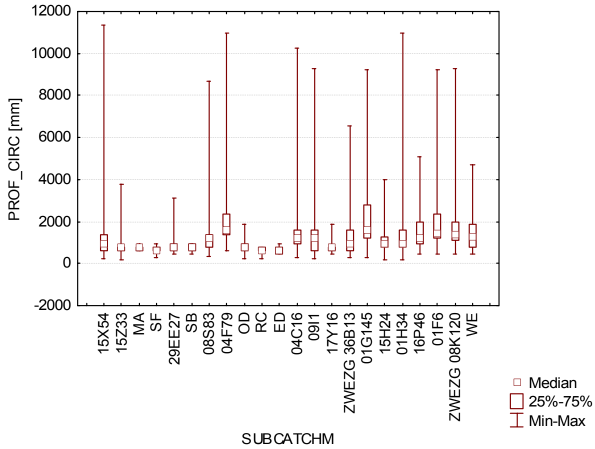
1 Dresden catchment

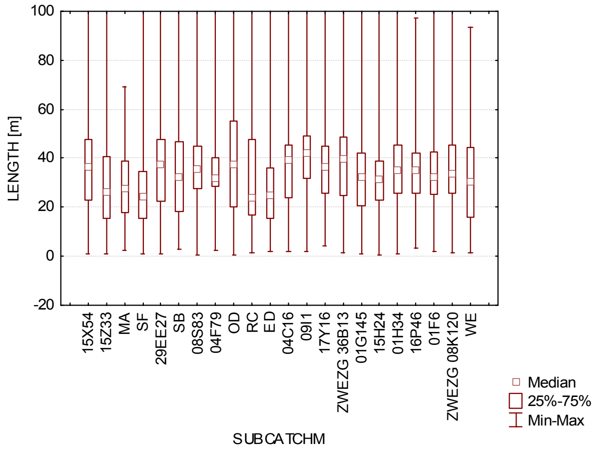
1.1 Characteristic values

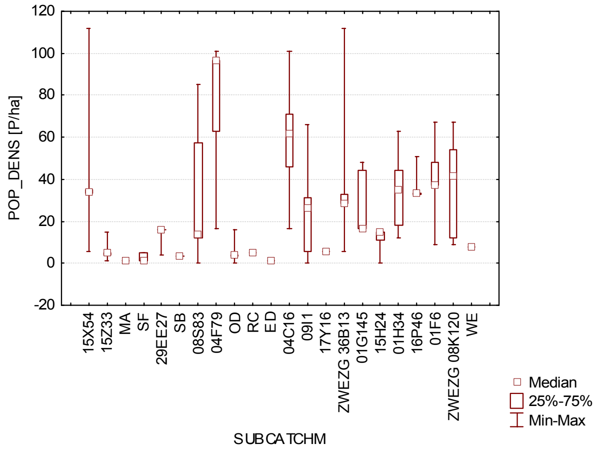
Sub-catchment	Self-contained area	Ground-water informa-tion	Total sewer length [m]	Number of reaches [-]	Total area [km²]	I/I rate [L/m·h]
29EE27			11,675	327	2.82	0.69
ZWEZG 08K120			58,388	1,642	5.58	4.44
01H34			97,381	2,755	13.88	2.55
01F6		X	52,356	1,516	4.07	2.83
01G145		X	36,152	1,086	2.28	2.07
16P46		X	12,136	364	2.07	2.64
ZWEZG 36B13		X	60,896	1,620	9.32	1.45
15X54			67,282	1,872	8.47	0.30
15H24			75,390	2,410	10.30	2.41
04F79		X	24,399	706	2.09	0.78
04C16		X	43,573	1,196	4.18	1.10
15Z33			51,488	1,573	14.68	0.54
09I1			54,971	1,283	12.97	1.19
08S83			84,649	2,325	12.76	0.74
17Y16			12,028	345	3.71	1.25
SB	X		2,757	81	0.75	0.69
OD	X		44,731	1,132	15.91	0.85
SF	X		6,860	229	1.91	0.67
ED	X		9,313	341	1.97	1.02
WE	X		6,134	194	1.14	4.79
RC	X		2,680	81	0.39	1.01
MA	X		2,080	71	0.32	0.58

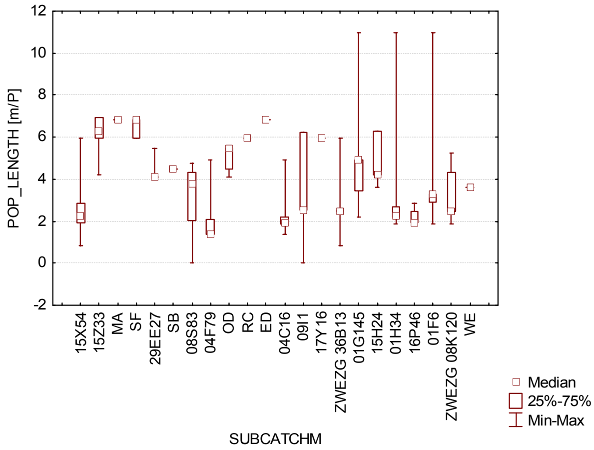
1.2 Metrical and ordinal attributes in box-whisker-plots

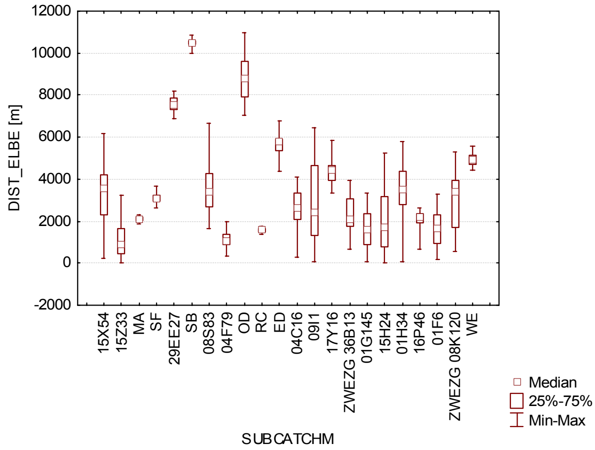


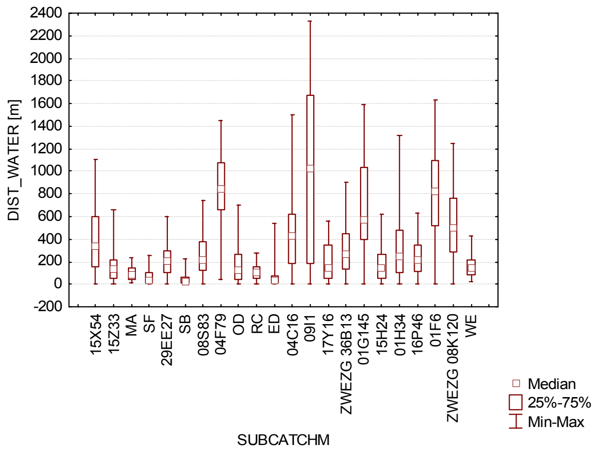


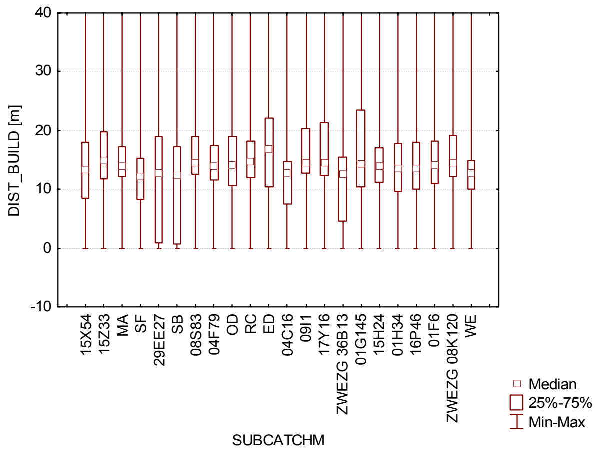


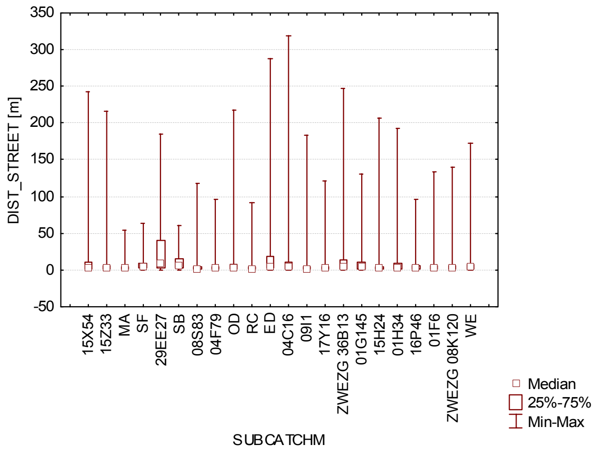







DIST_WATER [m]
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-200
15X54
15Z33
MA
SF
29EE27
SB
08S83
04F79
OD
RC
ED
04C16
09I1
17Y16
ZWEZG 36B13
01G145
15H24
01H34
16P46
01F6
ZWEZG 08K120
WE
Median
25%-75%
Min-Max
SUBCATCHM


DIST_BUILD [m]
40
30
20
10
0
-10
15X54
15Z33
MA
SF
29EE27
SB
08S83
04F79
OD
RC
ED
04C16
09I1
17Y16
ZWEZG 36B13
01G145
15H24
01H34
16P46
01F6
ZWEZG 08K120
WE
Median
25%-75%
Min-Max
SUBCATCHM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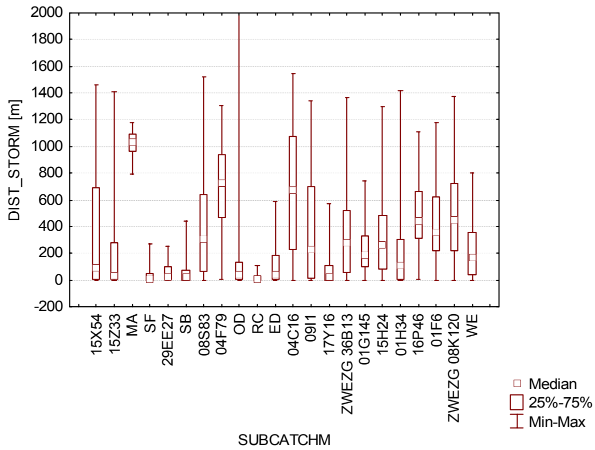
300
250
200
150
100
50
0
-50
15X54
15Z33
MA
SF
29EE27
SB
08S83
04F79
OD
RC
ED
04C16
09I1
17Y16
ZWEZG 36B13
01G145
15H24
01H34
16P46
01F6
ZWEZG 08K120
WE
Median
25%-75%
Min-Max
SUBCATCHM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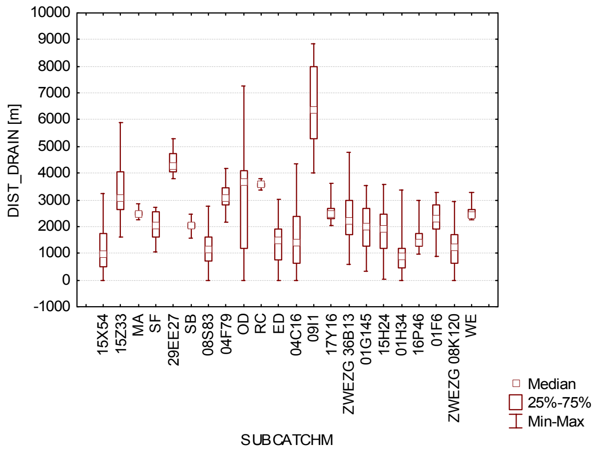
1800
1600
1400
1200
1000
800
600
400
200
0
-200
15X54
15Z33
MA
SF
29EE27
SB
08S83
04F79
OD
RC
ED
04C16
09I1
17Y16
ZWEZG 36B13
01G145
15H24
01H34
16P46
01F6
ZWEZG 08K120
WE
Median
25%-75%
Min-Max
SUBCATCHM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9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
15X54
15Z33
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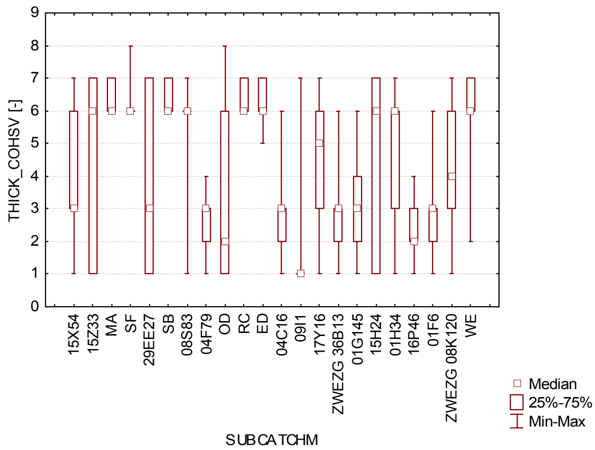
SF
29EE27
SB
08S83
04F79
OD
RC
ED
04C16
09I1
17Y16
ZWEZG 36B13
01G145
15H24
01H34
16P46
01F6
ZWEZG 08K120
WE
Median
25%-75%
Min-Max
SUBCATCHM


THICK_COHSV [-]
9
8
7
6
5
4
3
2
1
0
15X54
15Z33
MA
SF
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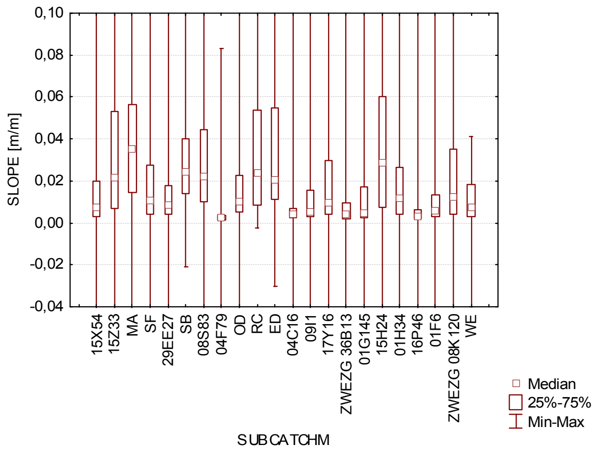
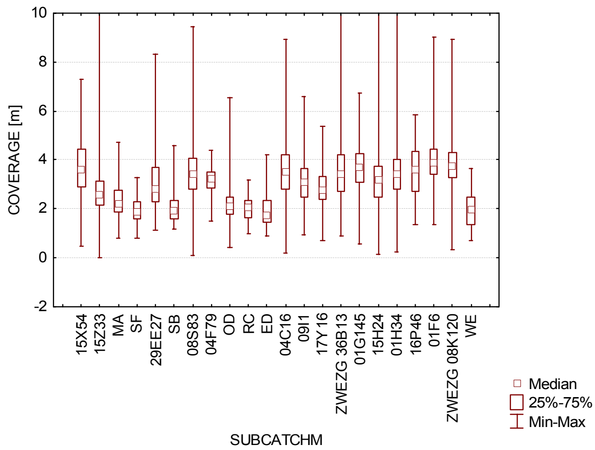
SB
08S83
04F79
OD
RC
ED
04C16
09I1
17Y16
ZWEZG 36B13
01G145
15H24
01H34
16P46
01F6
ZWEZG 08K120
WE
Median
25%-75%
Min-Max
SUBCATCHM

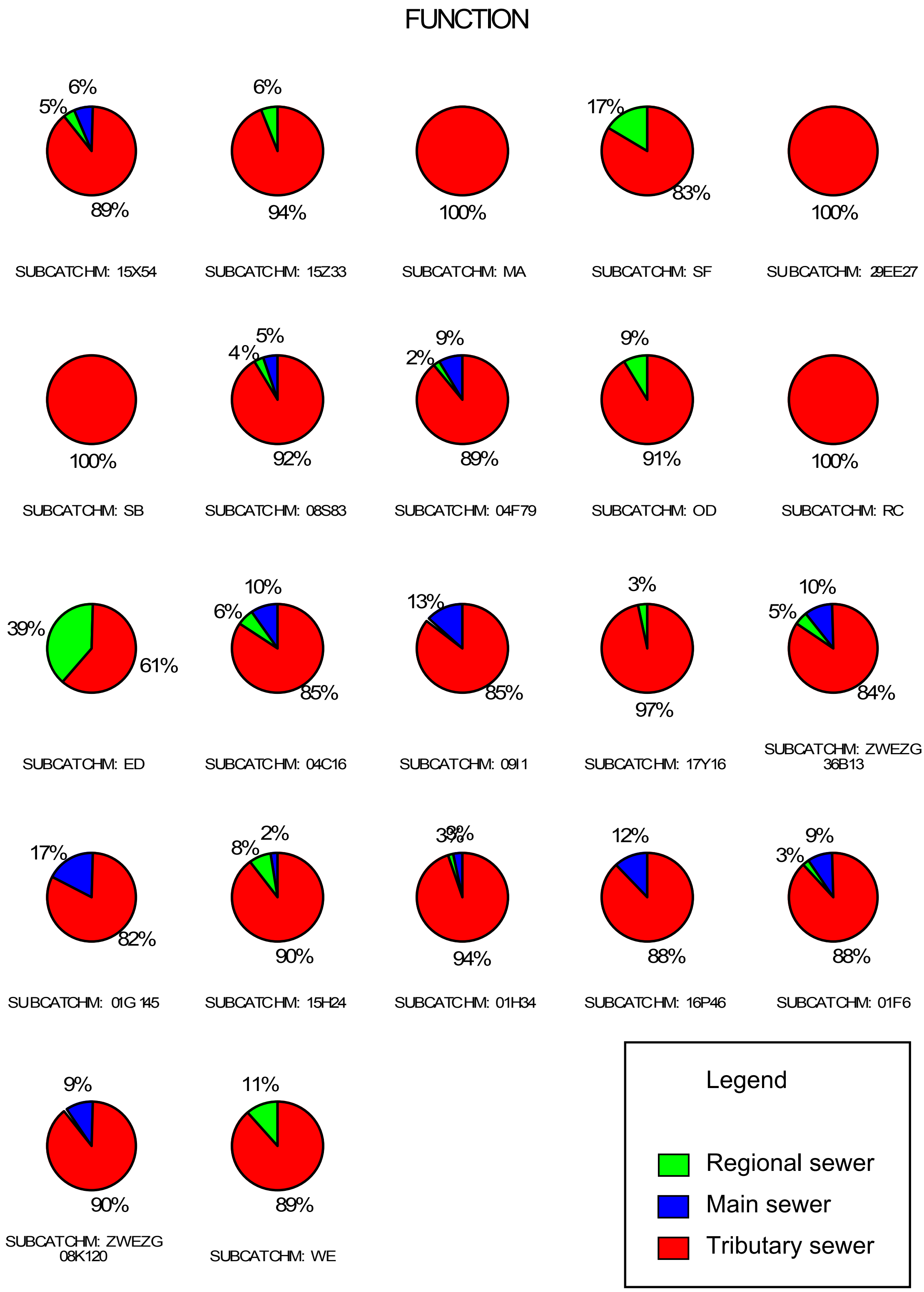


0,10
0,08
0,06
0,04
0,02
0,00
-0,02
-0,04
SLOPE [m/m]
15X54
15Z33
MA
SF
29EE27
SB
08S83
04F79
OD
RC
ED
04C16
09I1
17Y16
ZWEZG 36B13
01G145
15H24
01H34
16P46
01F6
ZWEZG 08K120
WE
SUBCATCHM
Median
25%-75%
Min-Max

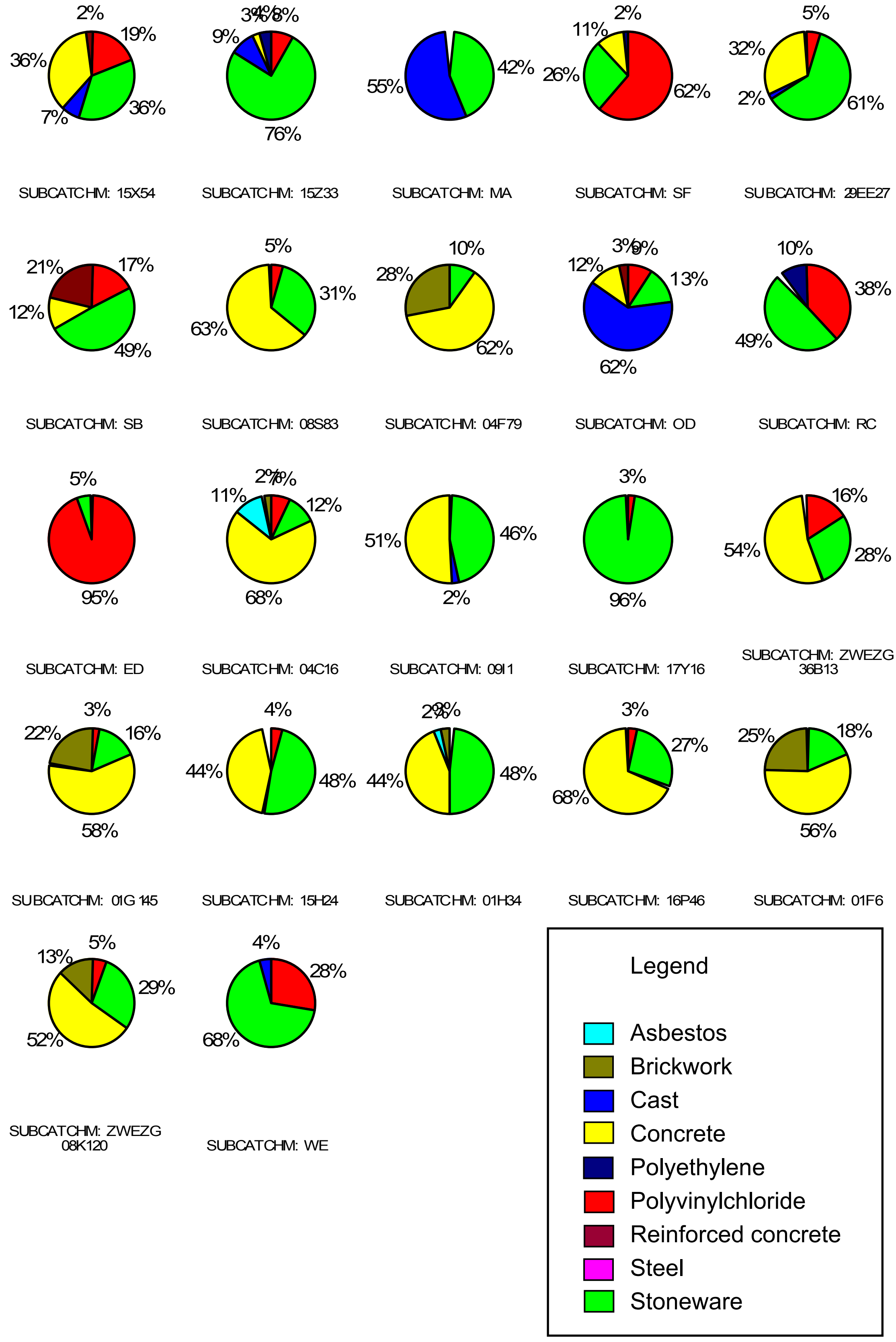


10
8
6
4
2
0
-2
COVERAGE [m]
15X54
15Z33
MA
SF
29EE27
SB
08S83
04F79
OD
RC
ED
04C16
09I1
17Y16
ZWEZG 36B13
01G145
15H24
01H34
16P46
01F6
ZWEZG 08K120
WE
SUBCATCHM
Median
25%-75%
Min-Max

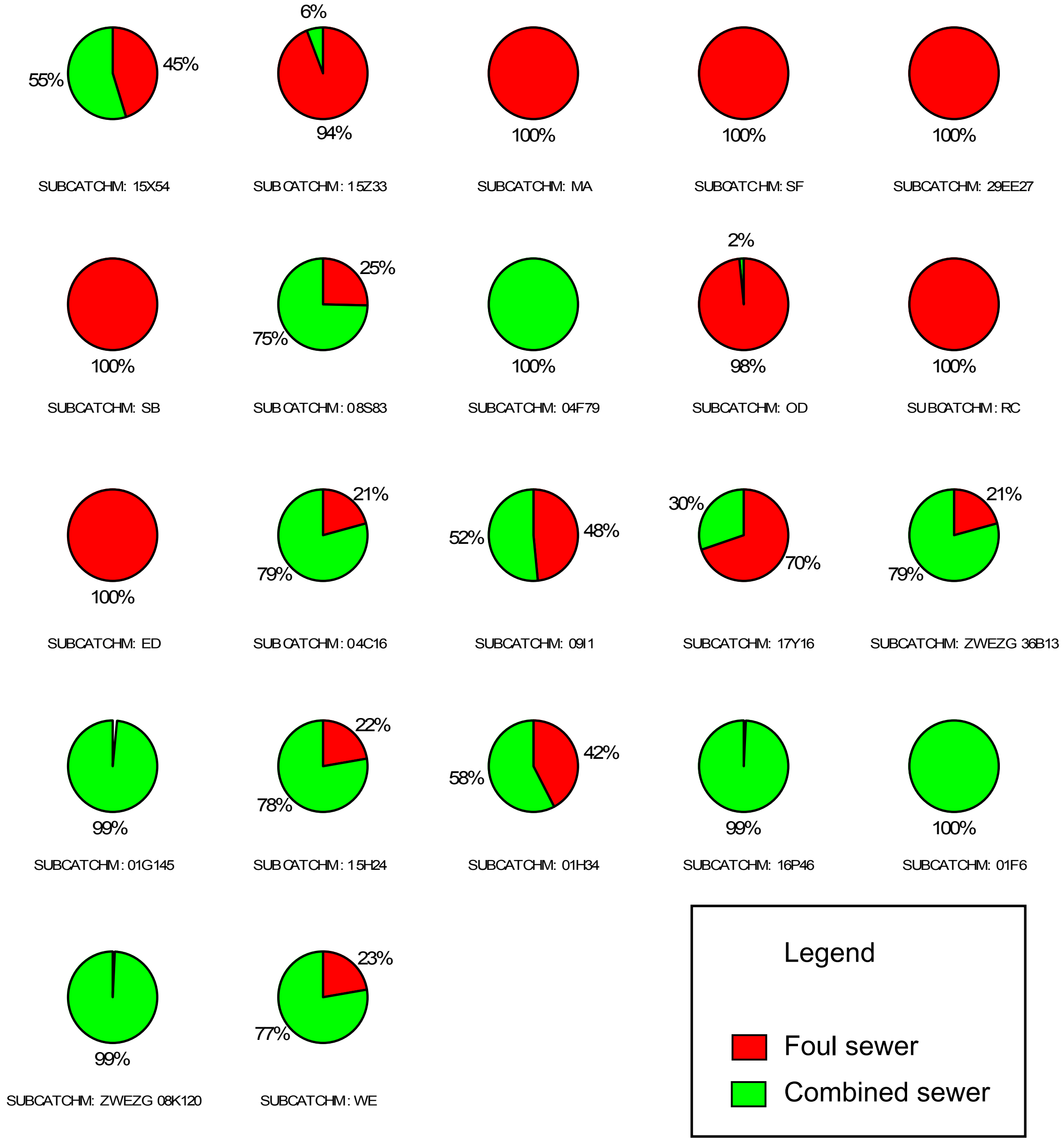
1.3 Nominal attributes in pie charts



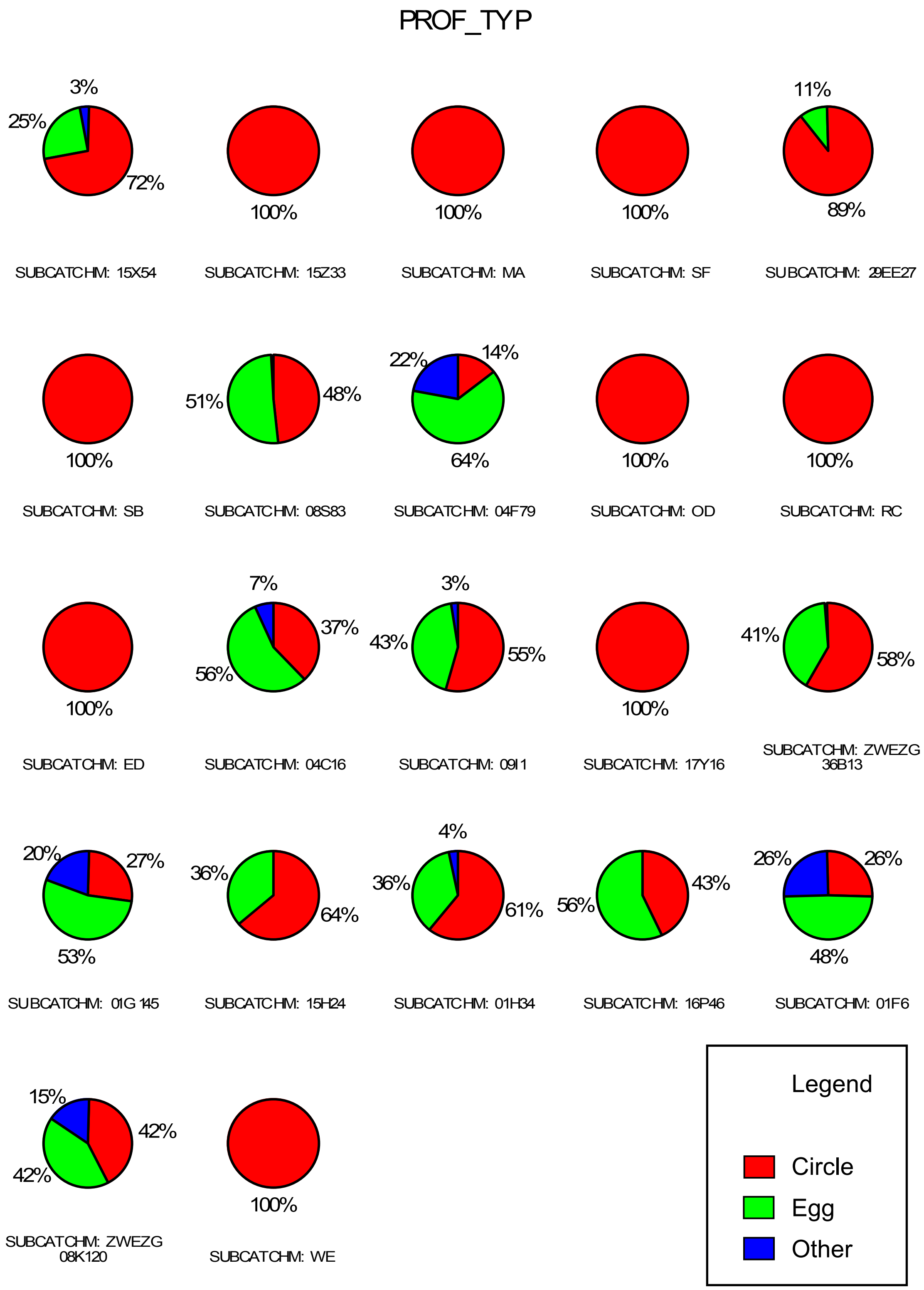
MATERIAL

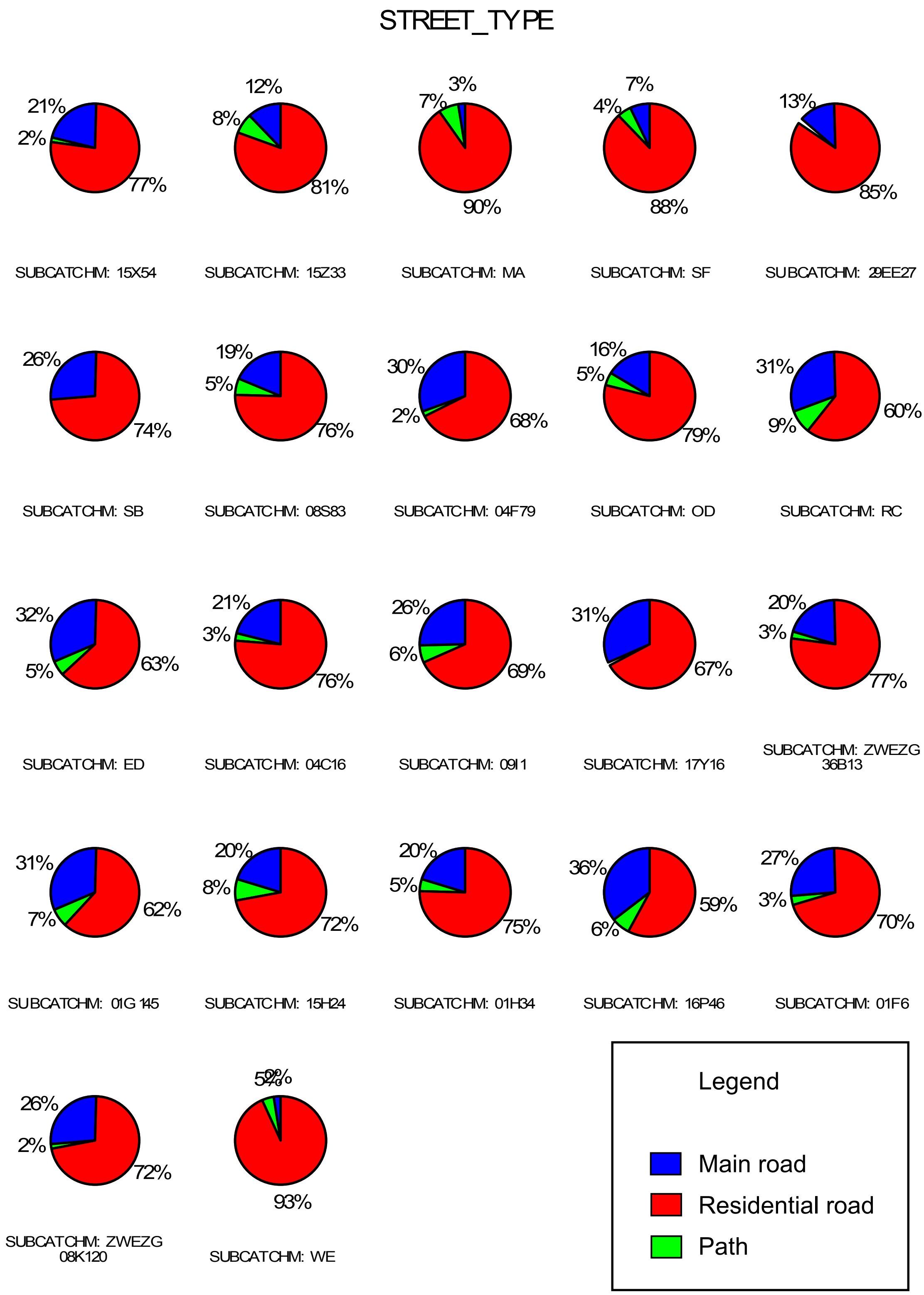

2%
19%
36%
7%
36%
SUBCATCHM: 15X54
9%
76%
SUBCATCHM: 15Z33
55%
42%
SUBCATCHM: MA
11%
2%
26%
62%
SUBCATCHM: SF
5%
32%
2%
61%
SUBCATCHM: 29EE27
21%
17%
12%
49%
SUBCATCHM: SB
5%
31%
63%
SUBCATCHM: 08S83
10%
28%
62%
SUBCATCHM: 04F79
12%
13%
62%
SUBCATCHM: OD
10%
38%
49%
SUBCATCHM: RC
5%
95%
SUBCATCHM: ED
11%
12%
68%
SUBCATCHM: 04C16
51%
46%
2%
SUBCATCHM: 09I1
3%
96%
SUBCATCHM: 17Y16
16%
54%
28%
SUBCATCHM: ZWEZG
36B13
3%
22%
16%
58%
SUBCATCHM: 01G145
4%
44%
48%
SUBCATCHM: 15H24
44%
48%
SUBCATCHM: 01H34
3%
27%
68%
SUBCATCHM: 16P46
25%
18%
56%
SUBCATCHM: 01F6
5%
13%
29%
52%
SUBCATCHM: ZWEZG
08K120
4%
28%
68%
SUBCATCHM: WE
Legend
Asbestos
Brickwork
Cast
Concrete
Polyethylene
Polyvinylchloride
Reinforced concrete
Steel
Stoneware

SEW_SYSTEM



55%
45%
SUBCATCHM: 15X54
6%
94%
SUBCATCHM: 15Z33
100%
SUBCATCHM: MA
100%
SUBCATCHM: SF
100%
SUBCATCHM: 29EE27
100%
SUBCATCHM: SB
25%
75%
SUBCATCHM: 08S83
100%
SUBCATCHM: 04F79
2%
98%
SUBCATCHM: OD
100%
SUBCATCHM: RC
100%
SUBCATCHM: ED
21%
79%
SUBCATCHM: 04C16
52%
48%
SUBCATCHM: 09I1
30%
70%
SUBCATCHM: 17Y16
21%
79%
SUBCATCHM: ZWEZG 36B13
99%
SUBCATCHM: 01G145
22%
78%
SUBCATCHM: 15H24
58%
42%
SUBCATCHM: 01H34
99%
SUBCATCHM: 16P46
100%
SUBCATCHM: 01F6
99%
SUBCATCHM: ZWEZG 08K120
23%
77%
SUBCATCHM: WE
Legend
Foul sewer
Combined sewer


PROF_TYP
3%
25%
72%
SUBCATCHM: 15X54
100%
SUBCATCHM: 15Z33
100%
SUBCATCHM: MA
100%
SUBCATCHM: SF
11%
89%
SUBCATCHM: 29EE27
100%
SUBCATCHM: SB
51%
48%
SUBCATCHM: 08S83
22%
14%
64%
SUBCATCHM: 04F79
100%
SUBCATCHM: OD
100%
SUBCATCHM: RC
100%
SUBCATCHM: ED
7%
37%
56%
SUBCATCHM: 04C16
3%
43%
55%
SUBCATCHM: 09I1
100%
SUBCATCHM: 17Y16
41%
58%
SUBCATCHM: ZWEZG 36B13
20%
27%
53%
SUBCATCHM: 01G145
36%
64%
SUBCATCHM: 15H24
4%
36%
61%
SUBCATCHM: 01H34
56%
43%
SUBCATCHM: 16P46
26%
26%
48%
SUBCATCHM: 01F6
15%
42%
42%
SUBCATCHM: ZWEZG 08K120
100%
SUBCATCHM: WE
Legend
Circle
Egg
Other

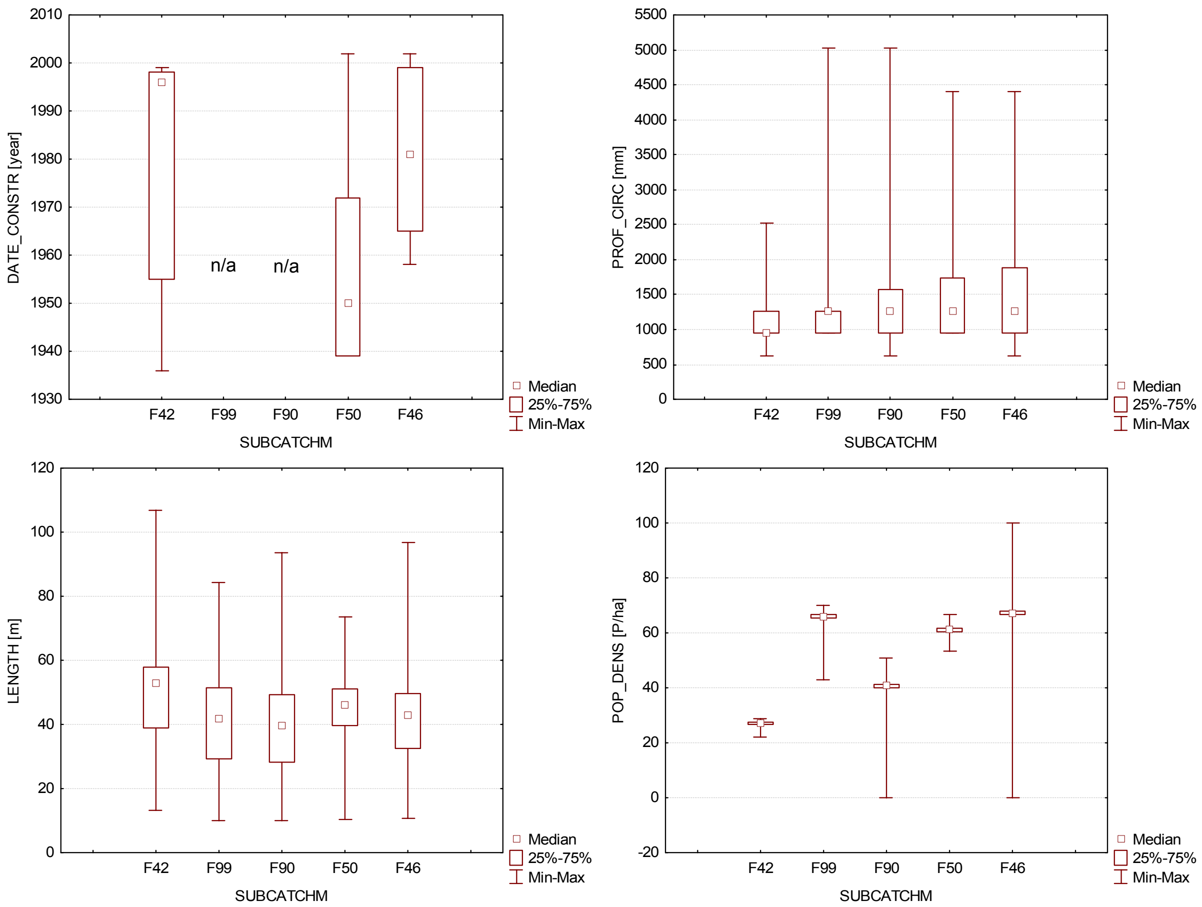

STREET_TYPE
21%
2%
77%
SUBCATCHM: 15X54
12%
8%
81%
SUBCATCHM: 15Z33
3%
7%
90%
SUBCATCHM: MA
7%
4%
88%
SUBCATCHM: SF
13%
85%
SUBCATCHM: 29EE27
26%
74%
SUBCATCHM: SB
19%
5%
76%
SUBCATCHM: 08S83
30%
2%
68%
SUBCATCHM: 04F79
16%
5%
79%
SUBCATCHM: OD
31%
9%
60%
SUBCATCHM: RC
32%
5%
63%
SUBCATCHM: ED
21%
3%
76%
SUBCATCHM: 04C16
26%
6%
69%
SUBCATCHM: 09I1
31%
67%
SUBCATCHM: 17Y16
20%
3%
77%
SUBCATCHM: ZWEZG 36B13
31%
7%
62%
SUBCATCHM: 01G145
20%
8%
72%
SUBCATCHM: 15H24
20%
5%
75%
SUBCATCHM: 01H34
36%
6%
59%
SUBCATCHM: 16P46
27%
3%
70%
SUBCATCHM: 01F6
26%
2%
72%
SUBCATCHM: ZWEZG 08K120
5%
2%
93%
SUBCATCHM: WE
Legend
Main road
Residential road
Path

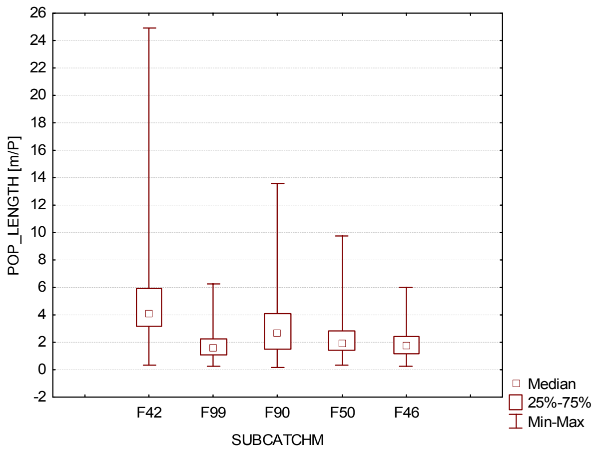
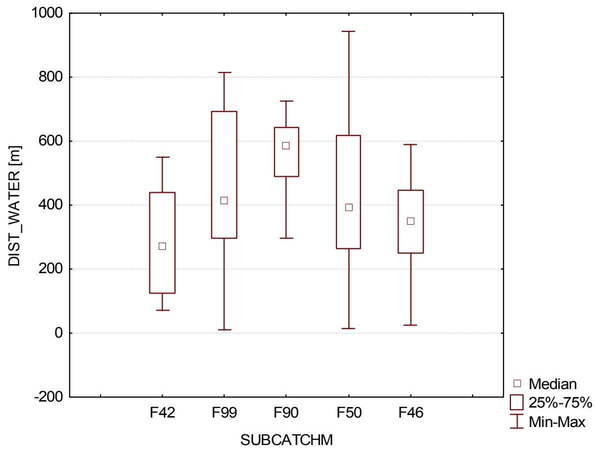
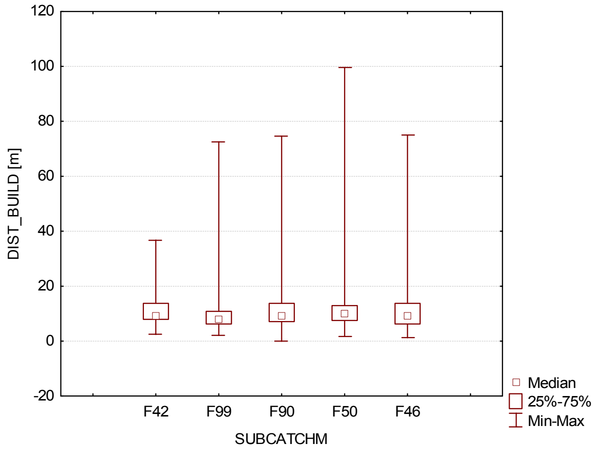
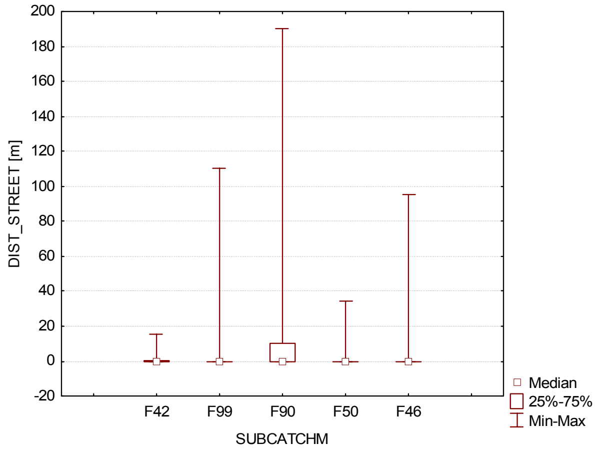
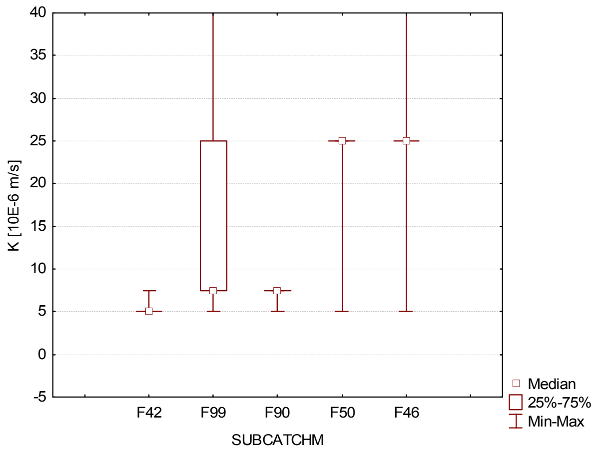
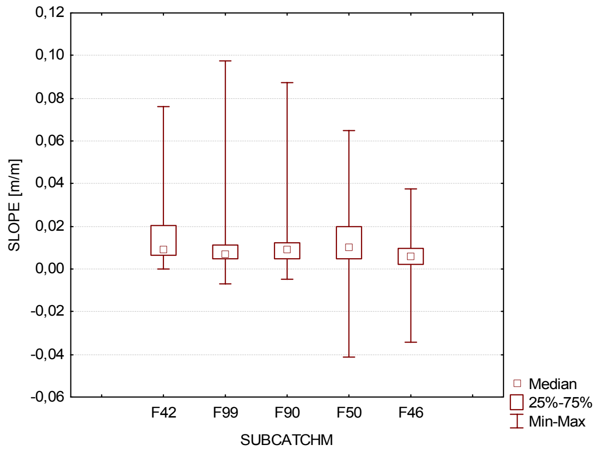
2 Bottrop catchment

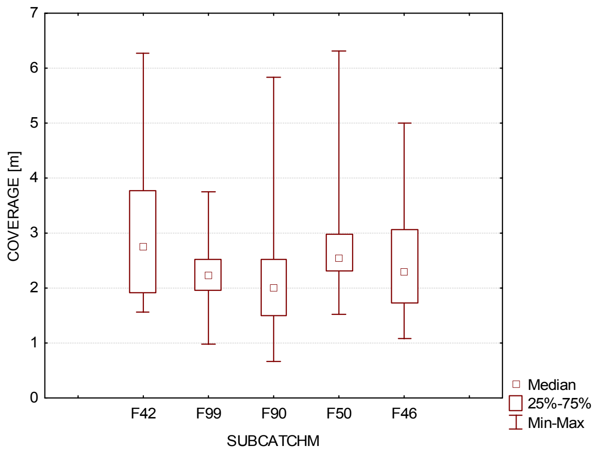
2.1 Characteristic values

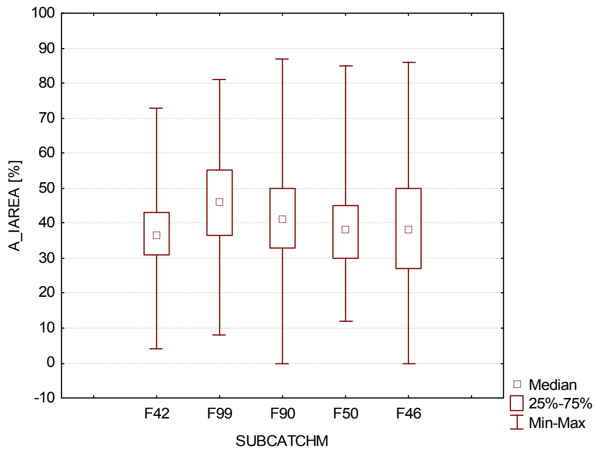
Sub-catchment	Self-contained area	Ground-water in-formation	Total sewer length [m]	Number of reaches [-]	Total area [km²]	I/I rate [L/m·h]
F42		X	2,662	54	0.24	1.76
F99		X	8,586	216	0.62	2.64
F90		X	6,725	173	0.58	2.84
F50		X	9,767	221	0.76	1.81
F46		X	7,665	186	0.59	4.78

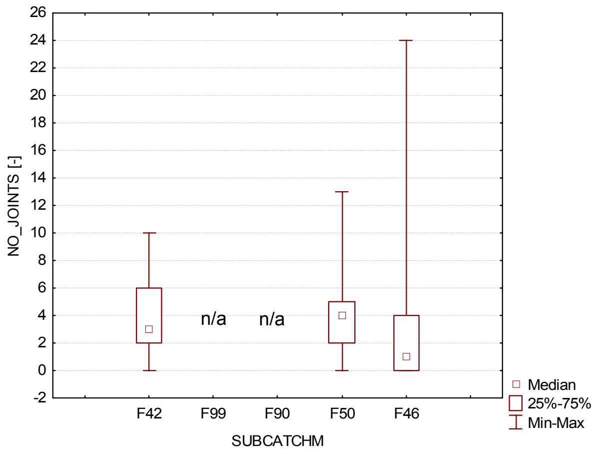
2.2 Metrical and ordinal attributes in box-whisker-plots




POP_LENGTH [m/P]
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
F42
F99
F90
F50
F46
SUBCATCHM
Median
25%-75%
Min-Max

DIST_WATER [m]
1000
800
600
400
200
0
-200
F42
F99
F90
F50
F46
SUBCATCHM
Median
25%-75%
Min-Max

DIST_BUILD [m]
120
100
80
60
40
20
0
-20
F42
F99
F90
F50
F46
SUBCATCHM
Median
25%-75%
Min-Max

DIST_STREET [m]
200
180
160
140
120
100
80
60
40
20
0
-20
F42
F99
F90
F50
F46
SUBCATCHM
Median
25%-75%
Min-Max

K [10E-6 m/s]
40
35
30
25
20
15
10
5
0
-5
F42
F99
F90
F50
F46
SUBCATCHM
Median
25%-75%
Min-Max

SLOPE [m/m]
0,12
0,10
0,08
0,06
0,04
0,02
0,00
-0,02
-0,04
-0,06
F42
F99
F90
F50
F46
SUBCATCHM
Median
25%-75%
Min-Max







2.3 Nominal attributes in pie charts

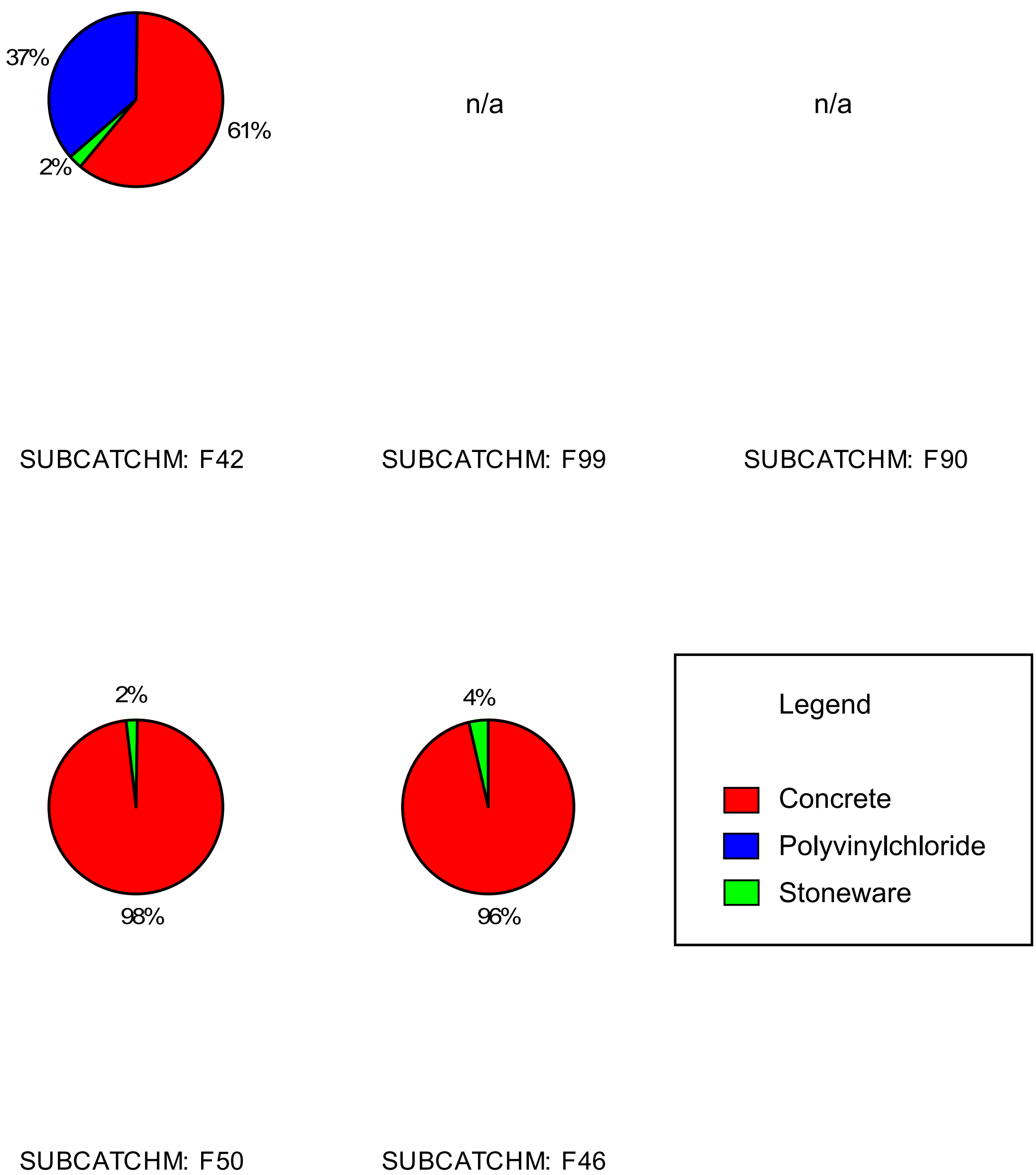
FUNCTION: only tributary sewers

SEW_SYSTEM: only combined sewers

PROF_TYP: only circular profiles

STREET_TYPE: only residential roads

MATERIAL



37%
61%
2%
n/a
n/a
SUBCATCHM: F42
SUBCATCHM: F99
SUBCATCHM: F90
2%
98%
4%
96%
Legend
Concrete
Polyvinylchloride
Stoneware
SUBCATCHM: F50
SUBCATCHM: F46

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