# European study of the performance of various pipe systems, respectively pipe materials for municipal sewage systems under special consideration of the ecological range of effects during the service life

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## Preface

The study on “the performance of various pipe systems, respectively pipe materials for municipal sewage systems under special consideration of the ecological range of effects during the service life” presented here was carried out by Prof. Dr.-Ing. Stein & Partner GmbH, Germany. An external European expert panel contributed significantly to the project by bringing in their specific viewpoints on the sewer network situation of their countries, ensuring a holistic European view of the project. Their specific knowledge did ease the adjustment of the analytic process rules of the used “STATUS Sewer” framework to the specific needs of the project. With their proofing review of the analytical approach used within the project they did certain representative results.

The involved experts of the panel were:

- *Nick Orman* - WRc, Swindon, U.K.;
- *Hans von der Jagt* - Kiwa Water Research, Nieuwegein, Netherlands;
- *Gilbert Sevensson* - Chalmers University, Göteborg, Sweden.

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# 1 Introduction

Drains and sewer systems have been built systematically in Germany since 1842. For more than one century accessible sewers were almost exclusively made from hard burned bricks. From the beginning of the 20th in-situ-concrete sewers became popular for economic reasons. The greater part of our drain and sewer systems are not accessible and consist of prefabricated pipes of different materials. Only in the past 50 years have plastic pipes (PVC, PVC-U, PP, PE, GRP) as well as pipes made from ductile cast iron, reinforced concrete and PRC been used.

A number of studies have identified that vitrified clay, concrete and reinforced concrete pipes are dominating in public sewers within Germany with a length portion of approx. 45% in each case [ATV 2001].

This is historically based and is confirmed for countries like England, which also began very early with the building of drains. In countries like the Scandinavian countries and Australia, which started later with the regular sewer construction due to large distances and high costs, and/ or their networks developed more slowly, the proportion of pipes in each pipe material shift very clearly to plastic pipes. In the private domain (laterals) plastic pipes are now used almost solely.

For some years, an increasing acceptation of plastic pipes can be determined also for the early-canalized countries like England and Germany. This increase of the market shares is already noticeable in the network stock.

The manufacturers give the following reasons for this increase in pipe installation of plastic pipes (sequence without valuation), which are listed without further comment:

- Low weight (transport, handling without heavy equipment) example DN 300: Concrete 137 kg/m, vitrified clay 72 kg/m, plastic 8 to 10 kg/m
- Favourable characteristics to resist aggressive waste water and waste water constituents (corrosion resistance)
- Flexible deformation behaviour (the pipe reacts under normal conditions to overloading with deformation and without cracks)

- Hydraulic smooth materials and closer dimensional tolerances at joints (fewer deposits, less cleaning expenditure, smaller nominal size than possible with clearly rougher pipes)
- Simply cutting to length and adaptation to local situation possible
- Machine installation technology possible
- Recycling/ down cycling ability
- High secured service life
- Installation on curves possible, i.e. saving of manholes
- Material-homogeneous sewer systems (uniform materials for pipes, shaped parts, manholes)

Even if all plastic pipe systems are standardized or certified products, certain uncertainties still exist in the long term evaluation of plastic pipes under practical conditions. Past investigations in to the sewer conditions with consideration of the piping materials were always limited to concrete/ reinforced concrete and vitrified clay due to the predominant length portions of these materials.

This induced the German Federal Ministry of Education and Research (BMBF) to found a research project, which, by evaluation from countrywide inspection data, could give valuable information on defect and defect frequency in plastic drain and sewer systems. [Körkemeyer 2003]

These collections and investigations form the basis for this European project for the evaluation of the ecological impact spectrum of the defects found. Furthermore, additional current inspection data for the investigation of concrete and vitrified clay pipe sections and their installation conditions were integrated into the project.

# 2 Objectives

The object of the work is a far-ranging analysis of the results of condition assessment under the aspect on its environmental effects. In this way, besides the difference of the various materials (concrete and reinforced concrete, vitrified clay and plastics) with respect to their types and frequencies of defect, also differences of environmental effects are defined. Environmental effects are understood to be leaks with the result of water exchange between aquifer and sewer in the form of exfiltration or infiltration depending on the position of the sewer with regard to groundwater level. The focus on infiltration and exfiltration is due to the fact that the majority of environmental impacts of a sewer network during service life are caused directly or indirectly by infiltration and exfiltration. Within this project the overflow of the sewer systems are accounted as exfiltration as long as the capacity overload is caused by defects such as incrustation or sedimentation. Overflow caused by poor planning is not relevant for this study and left out in here.

The analysis is carried out in different steps.

## 2.1 Determination of leaking defects

It can be assumed that a certain type of defects will always lead to leaks. These types of defects are identified at first. Besides the leaks found by the inspector, all statically determined types of defect such as cracks, pipe fractures, etc. are included, as well as displacements from an extent of defect yet to be determined, un-professionally installed connections and leaking joints. A determination and comparison of the number and frequency of this types of defect is carried out on the materials analysed.

## 2.2 Modelling of risk and environmental impact of leaking defects

The extent of the environmentally-referenced effects, according to [Stein 19989], depends on the type of defect, its extent, the composition of the sewage, degree of filling or hydraulic loading of the sewer, pipe diameter or nominal size and the geological or hydro-geological limiting conditions. The span of a possible exfiltration of typical descriptions of defect can sometimes be very large.

The dominating defect types for exfiltration, which occur to rigid materials in almost equal frequency, are the formation of cracks and fragmentation as well as leaking pipe joints. They show, according to investigations by [Dohmann 1999], exfiltration rates of approximately 10 to 130 l/(h*m) with filling to the crown of the pipe (cracks and fragmentation formation), and approximately 30 to 100 l/(h*m) (leaking pipe joints).

The environmentally referenced types of defect are analyzed in accordance with their environmental relevance, thus the size of ex- and infiltration. The results of the analysis form an overall analysis of the defect for the materials under review here. As neither the above mentioned hydro-geological and geotechnical limiting conditions nor the composition of the sewage nor the degree of filling or the hydraulic loading of the sewer are available, only the types and extent of the defect are taken into account, and on which defect type and the corresponding defect extend the impact on the aquifer reaches its maximum.

## 2.3 Definition of scenarios with different ancillary condition

As the amount of the environmental impact is not only based on the defect characteristics, several plausible typical scenarios of the available limiting ancillary conditions are defined such as soil permeability, coefficient, depth of sewer, groundwater level, for example:

- Groundwater level above the pipe crown, subsoil gravel - sand
- Groundwater level above the pipe crown, subsoil: clay - silt
- Groundwater level below the pipe invert, subsoil: gravel - sand
- Groundwater level below the pipe invert, subsoil: clay - silt

...

As information on the corresponding limiting conditions for the respective stretches or types of defect are not available, it is necessary to use typical local situations for the proposed types of scenarios. Therefore, the scenario writing will take real ancillary and limiting conditions into account, which correspond to local situations.

## 2.4 Modelling the environmental impact of different sewer systems within different scenarios

As the previous steps dealt with defect analysis, environmental relevance according to types and extend of defects, typical scenarios and the evaluation of environmental defects according to them, this step models the environmental impact of in- and exfiltration in general, as those impacts are far more then just soil contamination (exfiltration) and additional loads to waste water plants (infiltration). Points like the increase probability of sewer surcharge with the resulting drain of waste water or the impact on the ground water level have not been discussed so far. The model therefore analyses these consequences of in- and exfiltration in waste water networks.

# 3 Approach and Model

## 3.1 Introduction

In general the determination of environmental impacts of any kind are rather complex and an exact calculation is almost impossible. This is due to the fact that all environmental impacts need to be seen in their local context and environment on one hand - which can enormously differ within few kilometres of distance. On the other hand, the global effects of the impacts need to be taken into account as well.

The model used will base upon two main principles, in order to balance the model between simplicity and significance:

- Environmental effects of sewer defects are understood as impacts caused by either infiltration or exfiltration. Therefore, all further considerations only target local effects based on local ancillary conditions.
- All modelling uses relative and descriptive scaling without units to avoid conversion problems and prevent comparisons between different impacts, which can and should not been set into an absolute context.

An appropriate way to meet the request for calculation using variables of different scaling systems (descriptive, numerical) and units is fuzzy logic. It gives the opportunity to keep all variables with their original unit and scale, which prevents transformation problems. The mathematical processing is based on process rules, which are more understandable then complex mathematical formulas and reflect the way of thinking of engineers. Therefore, the model itself is transparent to experts, which are familiar to the modelled problems and not necessarily need to understand the mathematics behind. In that way, the inclusion of expert knowledge is independent of the model.

## 3.2 Data basis and analysis

Within the project, inspection data from different European countries were included for analysis. Within Table1, the data stock available for analysis is shown. Already on this table the countries are showing their preferences. Within Germany the rigid pipe systems are dominating whereas in the Netherlands the share of flexible pipe systems is significantly higher.

**Table1:Available Data Stock**

| Country/ Region | All pipes | Rigid pipes | Flexible pipes | Share of flexible pipes |
|---|---:|---:|---:|---:|
| *Germany* | 1731.72 km | 1640.83 km | 90.89 km | 5.25 % |
| *Netherlands* | 46.69 km | 30.27 km | 16.42 km | 35.17 % |
| *Sweden* | 12.43 km | 3.07 km | 9.36 km | 75.30 % |

As the amount of data is extremely different and only for Germany the data stock is sufficient to get significant results from a statistical analysis, it has been agreed to choose a combined analysis approach. The basis of the modelling of the environmental effects of defects within sewers is the German data pool. The data of the other countries is analyzed and the results are compared with the German figures. In case of major differences regarding the different defect types, these differences are discussed with the local experts to determine the reasons for these variations and to decide in which way the deviations are included in the modelling of the environmental effects of sewer defects.

The reason for the different data situation outside Germany is due to the fact that only in Germany routine inspections are required by law, in all other countries inspections are mostly carried out on utilities request or on municipality initiative.

Another simplification required because of the lack of data of the European countries is the accumulation of all rigid pipe materials like vitrified clay and concrete to the pipe type “rigid” and the accumulation of all flexible pipe materials like PVC and HDPE to the pipe type “flexible”. This accumulation is done for the data analysis of the inspection data and for the modelling of the environmental effects. To avoid imbalance in statistical analysis all data of pipes older than 30 years have been left out as plastic pipes in general are of younger age than rigid pipes. Additionally all sewer sections with diameter larger than 800 mm has been excluded for similar reasons. These exclusions did shrink the German data pool down to the dimensions shown at Table1. Furthermore it was analysed, what age the remaining pipe sections had at inspection time.

The data were analysed with respect to the existing defect groups. None of the groups relevant for the project were excluded, even if they contribute very little to the problem analyzed such as abrasion (often coming from high pressure cleaning).

To provide a transparent and understandable view on the analysis results main viewpoints on the data of the sewer networks have been defined:

- “Distribution of defective sewer sections in relation to the total length of the network depending on defect type” in order to draw a picture of the frequency of defective sections. The share of sewers with particular defects types on the total network length is giving a good overview on the total condition of the network.

- “Network defect rate per kilometre depending on defect type” in order to draw a picture of the frequency of defects per kilometre within the network. How often a particular defect type does appear on average in the total network gives a good indication of the most relevant defect types within a network.

- “Section defect rate per 100 m depending on defect type” in order to draw a picture of the frequency of defects per 100 m within the defective sections. How often a particular defect does appear on average in the defective sections gives a hint whether the defect type is accidentally and is unlikely to have follow ups of the same type or typical and therefore will worsen or be followed by additional defects of the same type.

This main viewpoints help to identify similarities and differences of the defect characteristics between the counties analyzed.

## 3.3 Generating model data by an “Monte-Carlo-Simulation”

A major problem of the analysis of environmental impacts caused by sewer defects is the point that the impacts itself are closely related to the local ancillary condition such as soil permeability or ground water level AND the specific sewer defect characteristics such as extend and position of the defect. However, in almost all cases there exists no link between the specific sewer defect characteristics obtained from inspection data and the local ancillary condition. Very often, there is not even any information on these local ancillary conditions available. As these links are necessary for modelling the environmental effects, the have to be created in a way that promises decent analysis results.

The method chosen to overcome this gap within the data pool is known as “Monte-Carlo-Simulation”. Three main groups of variables account for the environmental impacts:

- Specific sewer defect characteristics gained from inspection data such as extend and position of the defect,
- Specific sewer defect characteristics gained from expert knowledge and hydraulic calculation such as bandwidth and average leaking potential of the defect,
- Local ancillary condition such as soil permeability or ground water defined

The first group of variables and their statistical parameters are known from the analysis of the inspection data. Frequency of occurrence, defect position, defect extends always depending on material and defect type being the results of this analysis, which feed into the model. The second group of variables and their parameters are the result of hydraulic calculations and intense discussions amongst experts (see Chapter 3.3.1). The third group of variables and their parameters are defined within the different scenarios, which were widely discussed amongst experts (see Chapter 3.3.2).

Within the Monte Carlo simulation for each individual variable random values are generated using the probability distribution obtained from the parameters of the variables.

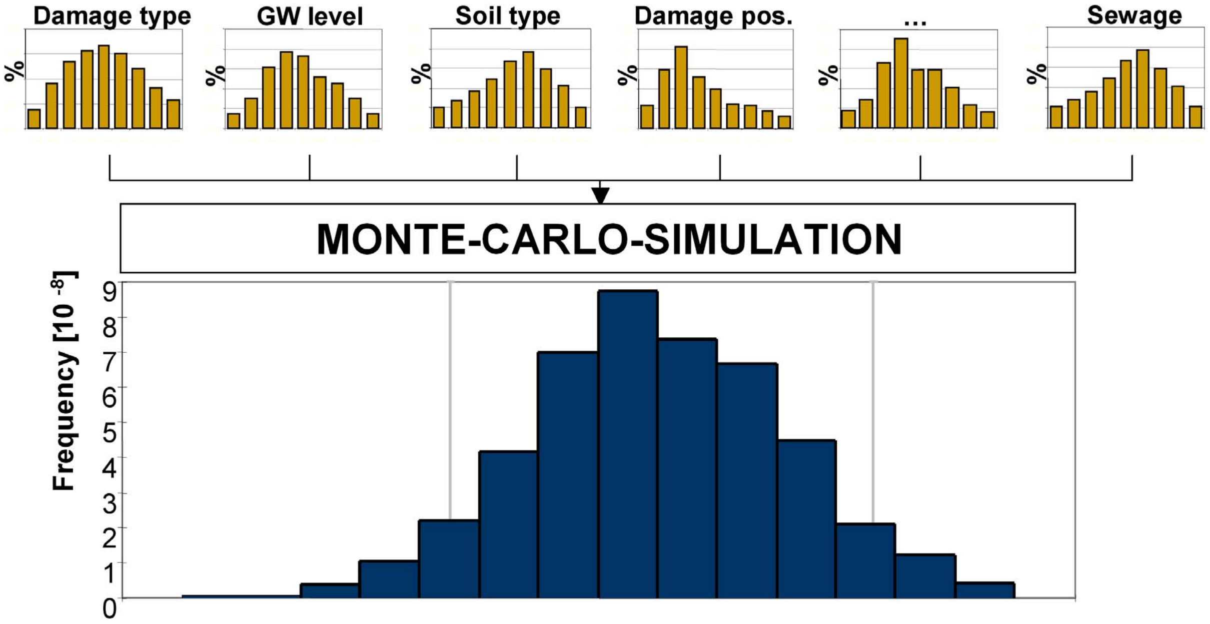


**Figure 1: Monte-Carlo-Simulation**

In several thousand runs characteristic data records are produced for each scenario which result in a probability distributions reflecting altogether the frequency of the occurrence of the individual combinations of the variables, which are essentially correspond to the probability distributions, which would result from real data. Within Figure 1 the Monte-Carlo-Method is visualized.

Result of the simulation is the establishment of the links between the local ancillary conditions and the specific sewer defect characteristics. For each of the defined scenarios with the specific ancillary conditions exist several thousand data sets which reflect the situation of the single defects in a way as if the data for its surroundings would have been recorded together with the recording of the defect. This approach gives reasonable results as long as the viewpoint stays on the network level. For modelling single sections, the ascertainment of the ancillary conditions for this single section by direct measures would be the method of choice - a way that cannot be walked for an entire network because of the resulting costs.

### *3.3.1 Determination of leaking defects*

As exfiltration and infiltration are the basis for the assessment of the environmental impacts within this study, the leakage potential for the different types of defects have to be determined. The potential for infiltration or exfiltration is the infiltrating or exfiltrating volume per unit time regardless the ancillary conditions like soil permeability. This determination starts with hydraulic calculations of the flow rate for each single defect type considering the smallest and the biggest defect extent possible for the particular defect type. As for some of the defect types there is no upper limit, a threshold criteria was introduced. This threshold resulted from the possible flow rate that occurs at that moment, the defect reaches the worst defect class according to the German standards. As these threshold flow rate differ for each defect type, the minimum of the reliably calculable flow rates was set as the threshold. The bandwidth of the potential flow rate stretching from close to zero up to the threshold was split into five categories ranging from very small, small, medium, big up to very big. All flow rates larger then the threshold are sorted into the last group.

For each defect type the minima and maxima have been discussed and revised amongst experts and separate for flexible and rigid pipes average leaking potentials have been assigned. This gives the possibility to determine the parameters for the Monte-Carlo-Simulation if these parameters cannot be determined from inspection data. For those defect types that are recorded by the inspector without any information on the defect extent because the coding system does not give the possibility for this type of information, these values are essential. Additionally the defect types are assigned to certain leakage groups to describe their leakage behaviour. Within Table 2 the agreed values are listed for the different defect types. The defect types are based on the EN 13508 codification system to ensure, that all involved experts have the same defect type in mind whilst discussing. The values assigned for leakage type and leaking potential are not related to or come from this standard but are determined as described before.

All defect types defined as never leaking, indefinable or secondary have no values assigned as they either do not leak or the leakage is not determinable for some reasons or the leakage is accounted elsewhere as this defect type occurs as a follow up to a leaking defect.

**Table 2: Determination of leakage behaviour of defect types**

| Defect Type | | Leakage Type | Leaking Potential Borders | | Leaking Potential Average | |
|---|---|---|---|---|---|---|
| Code | | | Min | Max | Flexible | Rigid |
| BAA-Deformation | | | | | | |
| A | | Secondary | | | | |
| B | | Secondary | | | | |
| BAB-Fissure | | | | | | |
| A | | Never | | | | |
| B | | Likely | Very small | Very big | Very small | Small |
| C | | Always | Small | Very big | Big | Very big |
| BAC-Break/Collapse | | | | | | |
| A | | Always | Medium | Very big | Medium | Big |
| B | | Always | Small | Very big | Big | Big |
| C | | Always | Very big | Very big | Very big | Very big |
| BAD-Defective Brickwork or Masonry | | | | | | |
| A | | Likely | Very small | Very big | None | Medium |
| C | | Always | Medium | Very big | None | Very big |
| D | | Always | Very big | Very big | None | Very big |
| B | A | Indefinable | | | | |
| | B | Always | Medium | Very big | None | Big |
| BAE-Missing Mortar | | | | | | |
| | | Likely | Very small | Very big | None | Medium |
| BAF-Surface Damage | | | | | | |
| A | | Never | | | | |
| B | | Never | | | | |
| C | | Never | | | | |
| D | | Never | | | | |
| E | | Never | | | | |
| F | | Never | | | | |
| G | | Never | | | | |
| H | | Never | | | | |
| I | | Always | Small | Very big | Big | Big |
| J | | Never | | | | |
| Z | | Indefinable | | | | |
| BAG-Intruding Connection | | | | | | |
| | | Indefinable | | | | |
| BAH-Defective Connection | | | | | | |
| A | | Indefinable | | | | |
| B | | Always | Small | Very big | Big | Big |
| C | | Always | Small | Very big | Medium | Medium |

| Defect Type | | Leakage Type | Leaking Potential Borders | | Leaking Potential Average | |
|---|---|---|---|---|---|---|
| Code | | | Min | Max | Flexible | Rigid |
| D | | Likely | Very small | Very big | Medium | Medium |
| E | | Indefinable | | | | |
| Z | | Indefinable | | | | |
| BAI-Intruding Sealing Material | | | | | | |
| A | A | Likely | Very small | Very big | Small | Small |
| | B | Always | Small | Very big | Medium | Medium |
| | C | Always | Small | Very big | Medium | Medium |
| | D | Always | Small | Very big | Medium | Medium |
| | E | Always | Small | Very big | Medium | Medium |
| Z | | Indefinable | | | | |
| BAJ-Displaced Joint | | | | | | |
| A | | Likely | Very small | Very big | Small | Small |
| B | | Likely | Very small | Very big | Medium | Medium |
| C | | Likely | Very small | Very big | Medium | Medium |
| BAK-Lining Defect | | | | | | |
| A | | Indefinable | | | | |
| B | | Never | | | | |
| C | | Indefinable | | | | |
| E | | Indefinable | | | | |
| Z | | Indefinable | | | | |
| D | A | Never | | | | |
| | B | Never | | | | |
| | C | Never | | | | |
| BAL-Defective Repair | | | | | | |
| A | | Always | Small | Very big | Big | Big |
| B | | Always | Small | Very big | Small | Small |
| Z | | Indefinable | | | | |
| BAM-Weld Failure | | | | | | |
| A | | Indefinable | | | | |
| B | | Indefinable | | | | |
| C | | Indefinable | | | | |
| BAN-Porous Pipe | | | | | | |
| | | Indefinable | | | | |
| BAO-Soil Visible through Defect | | | | | | |
| | | Secondary | | | | |
| BAP-Void Visible through Defect | | | | | | |
| | | Secondary | | | | |

| Defect Type | Leakage Type | Leaking Potential Borders | | Leaking Potential Average | |
|---|---|---|---|---|---|
| Code | | Min | Max | Flexible | Rigid |
| BBA-Roots | | | | | |
| A | Secondary | | | | |
| B | Secondary | | | | |
| C | Secondary | | | | |
| BBB-Attached Deposits | | | | | |
| A | Never | | | | |
| B | Never | | | | |
| C | Never | | | | |
| Z | Never | | | | |
| BBC-Settled Deposits | | | | | |
| A | Never | | | | |
| B | Never | | | | |
| C | Never | | | | |
| Z | Never | | | | |
| BBD-Ingress of Soil | | | | | |
| A | Secondary | | | | |
| B | Secondary | | | | |
| C | Secondary | | | | |
| D | Secondary | | | | |
| Z | Secondary | | | | |
| BBE-Other Obstacles | | | | | |
| A | Secondary | | | | |
| B | Secondary | | | | |
| C | Secondary | | | | |
| D | Always | Small | Very big | Small | Medium |
| E | Always | Small | Very big | Small | Medium |
| F | Secondary | | | | |
| G | Always | Small | Very big | Small | Big |
| H | Indefinable | | | | |
| BBF-Infiltration | | | | | |
| A | Always | Very small | Very small | Very small | Very small |
| B | Always | Very small | Small | Small | Small |
| C | Always | Small | Very big | Medium | Medium |
| D | Always | Medium | Very big | Big | Big |
| BBG-Exfiltration | | | | | |
| | Always | | | | |
| BBJ-Vermin | | | | | |

| Defect Type | | Leakage Type | Leaking Potential Borders | | Leaking Potential Average | |
|---|---|---|---|---|---|---|
| Code | | | Min | Max | Flexible | Rigid |
| A | A | Indefinable | | | | |
| | B | Indefinable | | | | |
| | C | Secondary | | | | |
| | Z | Indefinable | | | | |
| B | A | Indefinable | | | | |
| | B | Indefinable | | | | |
| | C | Secondary | | | | |
| | Z | Indefinable | | | | |
| Z | A | Indefinable | | | | |
| | B | Indefinable | | | | |
| | C | Secondary | | | | |
| | Z | Indefinable | | | | |

### *3.3.2 Definition of scenarios*

Ancillary conditions do have a major effect on the environmental impacts but as these conditions are equal for all pipe types/ materials they do not affect the ratio of the magnitude of the impact of one specific pipe type in comparison to another. This specific behaviour of the results is later on explained in Chapter 4.2.

In consequence, the different scenarios with their definition of ancillary conditions do not change the ratio of the environmental impact of different leaking pipe types - if there is any impact - as this ratio is determined only by the defect characteristics. Nevertheless, they show the absolute environmental impact of different leaking pipe types on an ordinal scale as it will be explained in Chapter 4.2.

They therefore just draw a figure of the impact size in relation to these specific border conditions. Hence, a definition of numerous scenarios does not necessarily increase the number of different results that leads to the definition of a small number of very specific scenarios.

All factors accounted within the model that are not listed in the table are either equal for all scenarios or are defect specific values, which come from the inspection data analysis and/ or determined in Table 2. The reasons for leaving some of the factor values equal throughout all scenarios are mainly because the assigned value dominates within Europe and will explained in detail in Chapter 3.4.

For all scenarios the sewage type is set to ordinary domestic wastewater, the net is within normal dense urban areas and the infiltrate is normal groundwater.

The ancillary conditions of the country scenarios have been discussed with the experts from these countries in order to reflect the situation as good as possible. The way these scenario definitions are handled within the model is described in detail in Chapter 3.4.

## 3.4 Risk and impact modelling by “logical trees” and “fuzzy logic”

Determining environmental impacts is always a rather complex task regardless of the aims and causes for such an intention. The reasons for choosing “ logical trees” and “fuzzy logic” as an appropriate way for modelling these impacts have already been briefly explained in Chapter 3.1. Before going into detail in the following Chapters the factors which feed the model with data or which are model outputs/ intermediate data need to be explained in order to ensure transparency. All factors are described in Table 3. For each factor, the descriptive scale is given which is used within the fuzzy inference system. Additionally for all factors it is given, were the values for it come from either scenario definition, or inspection data analysis or whether they are model output.

**Table 3: Key factors determination**

| | Name | Description | Scale (descriptive) |
|---|---|---|---|
| 1 | Sewage level | The variable describes the level of wastewater in a sewer section. This factor varies within the scenarios according to the scenario definition. | At pipe crown |
| | | | Between pipe axis and crown |
| | | | At pipe axis |
| | | | Between pipe axis and invert |
| | | | At pipe invert |
| 2 | Defect Position | The variable describes the circumferential position of the defect/ defect within the sewer. This factor varies within the scenarios according to the inspection data analysis results. | At pipe crown |
| | | | Between pipe axis and crown |
| | | | At pipe axis |
| | | | Between pipe axis and invert |
| | | | At pipe invert |

| | Name | Description | Scale (descriptive) |
|---|---|---|---|
| 3 | Leakage Potential | The variable describes size and extent of the defect and the resulting leaking potential. This factor varies within the scenarios according to the inspection data analysis results and possibly according to Table 2. | Very small<br>Small<br>Medium<br>Big<br>Very big |
| 4 | Soil Permeability | The variable describes the permeability of the surrounding soil not the permeability of backfilling or bedding. This factor varies within the scenarios according to the scenario definition. | Very low<br>Low<br>Medium<br>High<br>Very high |
| 5 | Ground water level | The variable describes the ground water level in relation to the position of the pipe section. This factor varies within the scenarios according to the scenario definition. | Far below invert<br>Below pipe invert<br>Around the pipe axis<br>Above pipe crown<br>High above crown |
| 6 | Infiltration Potential | The variable is intermediate data and describes the potential for infiltration that is calculated from and influenced by the first five factors. | Very low<br>Low<br>Medium<br>High<br>Very high |
| 7 | Exfiltration Potential | The variable is intermediate data and describes the potential for exfiltration that is calculated from and influenced by the first five factors. | Very low<br>Low<br>Medium<br>High<br>Very high |
| 8 | Soil Type | The variable describes the stability of the soil against washing out and therefore the stability of the granular structure of the soil. This factor varies within the scenarios according to the scenario definition. Within the defined scenarios, this factor does not change. The assigned value for all scenarios is “medium” as the soil affected by washing out problems is mostly bedding and backfilling, which tends to be similar throughout Europe. | Very stable to corrosion<br>Stable to corrosion<br>Medium impacted by corrosion<br>Sensitive to corrosion<br>Very sensitive to corrosion |

| | Name | Description | Scale (descriptive) |
|---|---|---|---|
| 9 | Sewage Type | The variable describes the grade of contamination of the wastewater in general and therefore includes domestic and non-domestic wastewater. This factor varies within the scenarios according to the scenario definition. Within the defined scenarios, this factor does not change. The assigned value for all scenarios is “minor contaminated”, as the sewage type is mostly domestic wastewater throughout Europe. The impact of industrial wastewater can be therefore neglected for the general scenarios, but could possibly modelled by specific scenarios in the future. | Not contaminated<br>Minor contaminated<br>Medium contaminated<br>Major contaminated<br>Heavily contaminated |
| 10 | Type of infiltrate | The variable describes the grade of contamination of the infiltrate. This factor varies within the scenarios according to the scenario definition. Within the defined scenarios this factor does not change. The assigned value for all scenarios is “not contaminated”, as the type of infiltrate is mostly clean groundwater throughout Europe. The impact of polluted groundwater can be therefore neglected for the general scenarios, but could possibly modelled by specific scenarios in the future. | Not contaminated<br>Minor contaminated<br>Medium contaminated<br>Major contaminated<br>Heavily contaminated |
| 11 | Objects Distance | The variable describes the distance of the defined objects to the sewer section. This factor varies within the scenarios according to the scenario definition. Within the defined scenarios, this factor does not change. The assigned value for all scenarios varies between “medium” and “close”, as most of the sewers throughout Europe are situated in urban areas. | Very far<br>Far<br>Medium<br>Close<br>Very close |
| 12 | Objects | The variable describes the sensitivity of existing objects such as drinking water abstraction areas, buildings, and drinking water supply systems. This factor varies within the scenarios according to the scenario definition. Within the defined scenarios, this factor does not change. The assigned value for all scenarios varies between “low sensitive objects” and “high sensitive objects”, as most of the sewers throughout Europe are situated in urban areas. | No Sensitive Objects<br>Low Sensitive Objects<br>Medium Sensitive Objects<br>High Sensitive Objects<br>Extremely high sensitive objects |
| 13 | Impact on Ground water Level | The variable describes the impact on the ground water level caused by infiltration. This factor is a result of the modelling expressed on a relative scale. | Very low<br>Low<br>Medium<br>High<br>Very high |
| 14 | Impact on Sewer Stability | The variable describes the impact on the stability of a sewer (and the following consequences such as breaking into the open) caused by infiltration. This factor is a result of the modelling expressed on a relative scale. | Very low<br>Low<br>Medium<br>High<br>Very high |

| | Name | Description | Scale (descriptive) |
|---|---|---|---|
| 15 | Impact on Receiving Water | The variable describes the impact on the receiving water caused by infiltration. This factor is a result of the modelling expressed on a relative scale. | Very low |
| | | | Low |
| | | | Medium |
| | | | High |
| | | | Very high |
| 16 | Impact on Treatment Plant | The variable describes the impact on the treatment plant caused by infiltration. This factor is a result of the modelling expressed on a relative scale. | Very low |
| | | | Low |
| | | | Medium |
| | | | High |
| | | | Very high |
| 17 | Ground Water Pollution | The variable describes the ground water pollution caused by exfiltration. This factor is a result of the modelling expressed on a relative scale. | Very low |
| | | | Low |
| | | | Medium |
| | | | High |
| | | | Very high |
| 18 | Soil Pollution | The variable describes the soil pollution caused by exfiltration. This factor is a result of the modelling expressed on a relative scale. | Very low |
| | | | Low |
| | | | Medium |
| | | | High |
| | | | Very high |
| 19 | Objects Threat | The variable describes the impact on sensitive objects (factor 12) caused by exfiltration. This factor is a result of the modelling expressed on a relative scale. | Very low |
| | | | Low |
| | | | Medium |
| | | | High |
| | | | Very high |

### *3.4.1 Risk and Impact trees*

Appropriate ways to model any multilateral linked factors in order to determine endangerment potentials are logical trees. This logical trees link cause and consequence of single factors and consist of two parts.

The fault tree describes all possible causes, their values, relations and link types and combines them into the resulting top cause which is here the infiltration/ exfiltration potential. Apart from the values of the causes (e.g. height of sewage level) and the relation of the causes (expressed in the tree structure) the link types are important within the tree definition. The linkage can be characterized as “OR”-Gates or “AND”-Gates. With “OR”-Gates, all of the direct linked factors need to contribute in order to reach the next tree node, which means the failure probabilities are multiplied. With “AND”-Gates, just one of the direct linked factors need to contribute in order to reach the next tree node, which means the failure probabilities are added. An example fault tree for the exfiltration potential is given in Figure 2.

The event tree identifies all possible consequences resulting from the defined top cause, which is here the infiltration/ exfiltration potential. An example event tree for the exfiltration potential is given in Figure 3. Both figures show the complexity of the task as the only visualize the fault/ event trees in parts. Unfolding the tree completely would result in an almost complicated figure, which is neither transparent nor easy to handle.

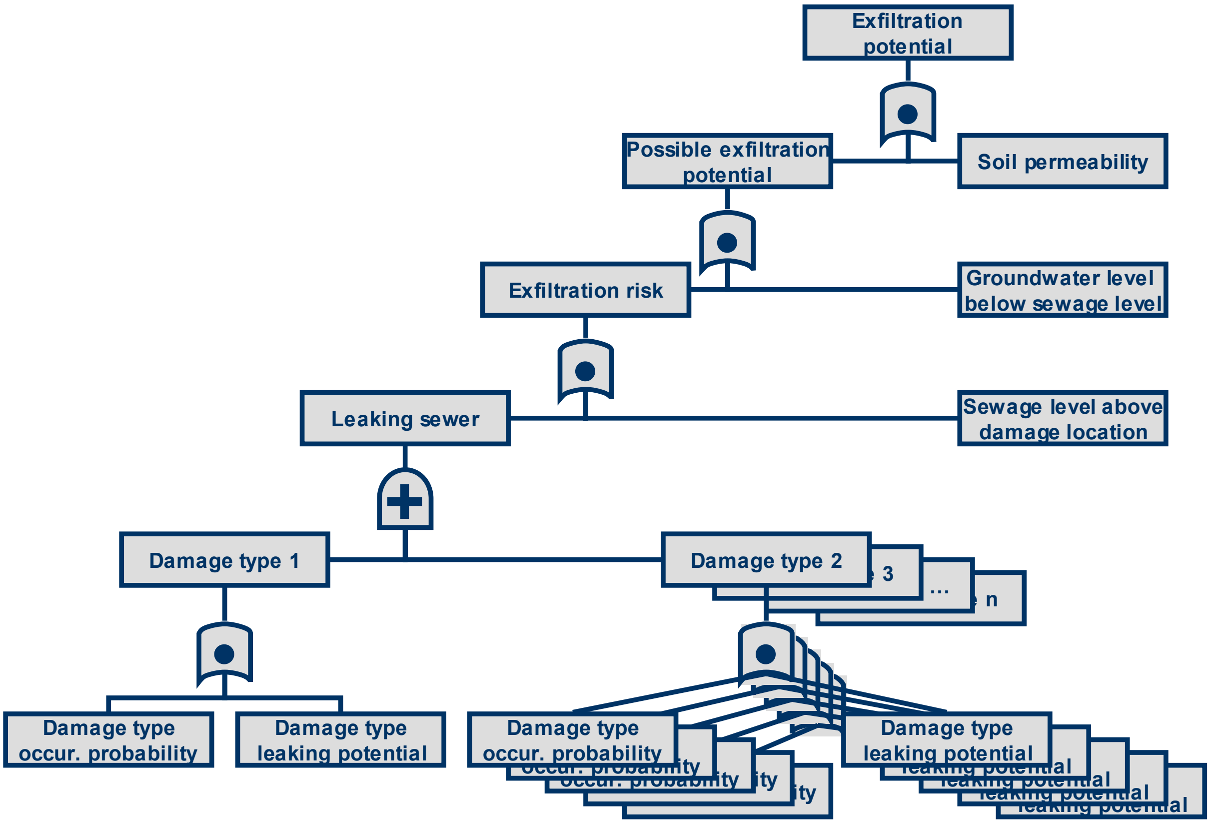


Figure 2: Fault tree example for exfiltration (causes)

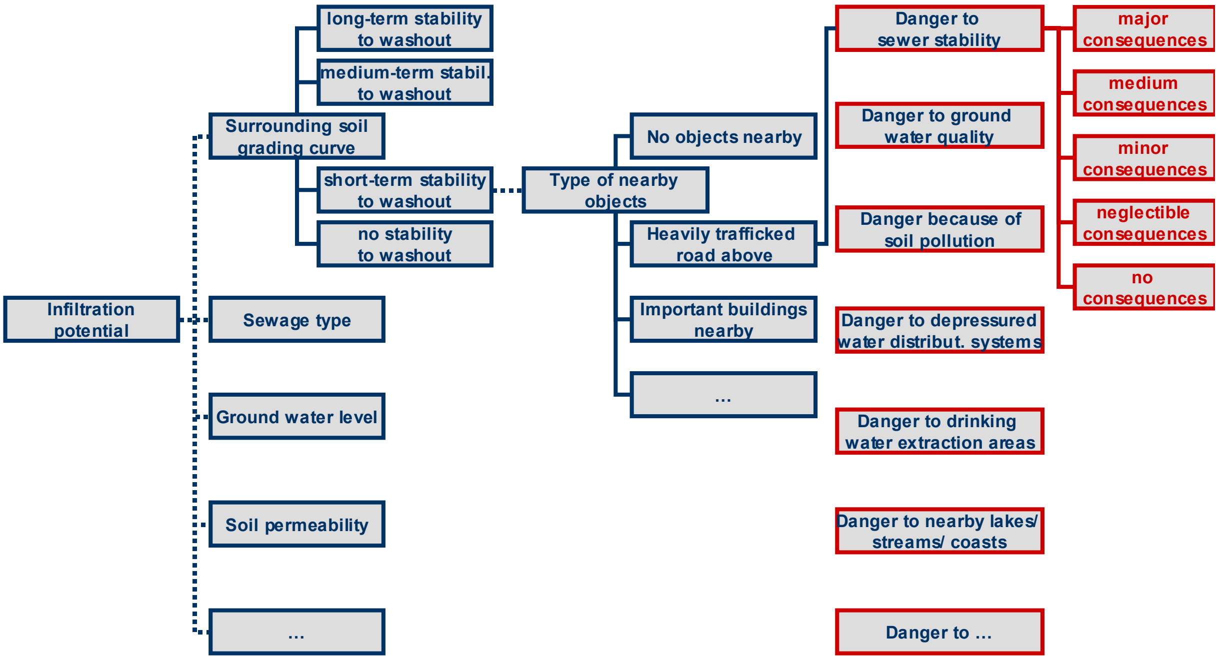


**Figure 3: Event tree example for infiltration (consequences)**

As all link types and relation can be expressed by process rules and the links are in most cases non binary - yes/no connections, the cause-consequence-chart as combination of the fault tree and the event tree can be simplified using a multi-dimensional system. This slims the system dramatically to Figure 4. For this advantage of a transparent system the accompanying handicap of a dramatic increase of process rules need to be accepted.

**Figure 4: Cause-consequence-chart**

The consequences of the handicap are eased by the fact that most of the additional rules are empty rules, as they will never take action and therefore do not need to be defined.

### *3.4.2 Linkage of variables via fuzzy logic*

All factors within the fault/ event trees are of different scale, most of the input variables exist as numeric values with various units attached, the output variables are numeric values without units, values on an ordinal scale. To process these different inputs in order to gain acceptable results can be done in two principle ways - either to transform all variables in a way that they can be used in mathematical formulas - or leave the variables in their original scale and unit and define logical process rules.

Advantage of the first way is the clear mathematical structure defined by formulas, disadvantage is the problem to determine formulas, which are transparent and acceptable to the user of such mathematical model.

The benefit of the second way is on one hand the avoidance of controversial transformations and the other hand the transparent definition of logic rules which reflect the way of human thinking. Rules like: “If pipe defect is above sewage level then no exfiltration can happen.” or “If the ground water level is high above pipe crown, the sewage level is around pipe axis, soil permeability is very high and the defect leaking potential is medium then infiltration potential is high.” are understandable to almost anyone. The mathematical way chosen here to process such rules is “fuzzy logic”.

The fuzzy processing itself follows always the same path.

1. Fuzzification of the input variables according to the vectors and membership functions for the specific variable: e.g. a pipe filled to 50 % would result in a 100 % membership to “sewage level at pipe axis”, a sewage level of 200 mm within a DN 1000 pipe would result in a membership of 30 % to “sewage level at pipe invert” and a membership of 70 % to “sewage level between pipe axis and invert”. In Figure 5 an example of a membership function is shown.

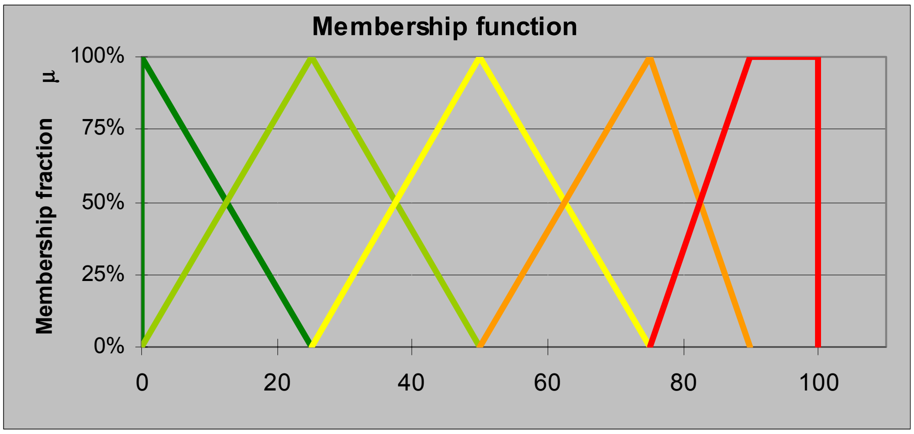
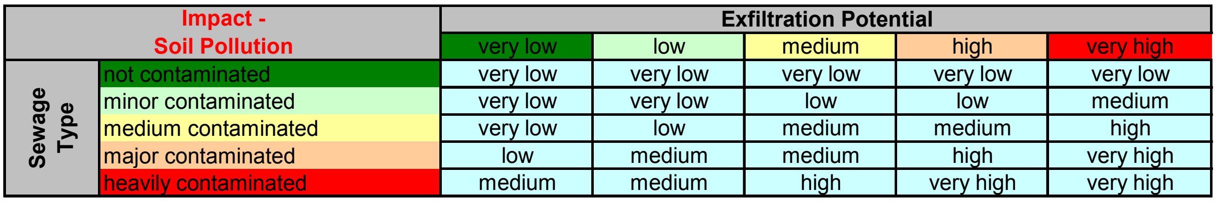


Figure 5: Example of a membership function

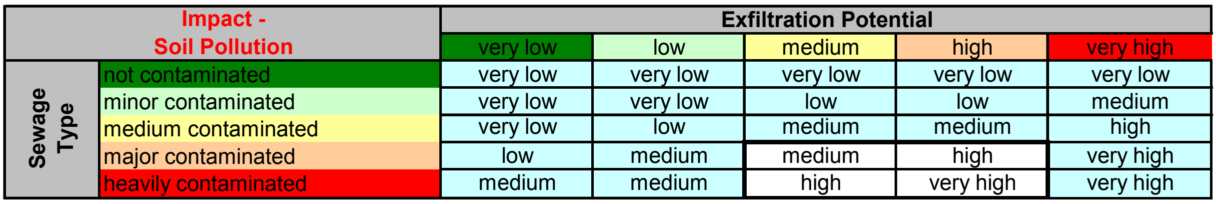
2. The related variables are linked by a fuzzy-inference-matrix that is the expression of the rule sets, which link those variables. In Figure 6 a two-dimensional fuzzy-inference-matrix is shown, defining exemplarily the rule set for linking the exfiltration potential with the sewage type. The result of the rule set is the soil pollution. The rule definition for the example can be read as follows: "If exfiltration potential is low and sewage is minor contaminated the resulting soil pollution is very low". Although it seems that different rules have the same result it is not the case as the numeric result depends on the membership fractions of the two input vectors.



| Impact - Soil Pollution | | Exfiltration Potential | | | | |
|---|---|---|---|---|---|---|
| | | very low | low | medium | high | very high |
| Sewage Type | not contaminated | very low | very low | very low | very low | very low |
| | minor contaminated | very low | very low | low | low | medium |
| | medium contaminated | very low | low | medium | medium | high |
| | major contaminated | low | medium | medium | high | very high |
| | heavily contaminated | medium | medium | high | very high | very high |

Figure 6: Example of a two-dimensional fuzzy-inference-matrix

3. The two input variables for this fuzzy-inference-matrix with their individual membership to the vector select the rules used for further processing as shown in Figure 7.



| Impact - Soil Pollution | | Exfiltration Potential | | | | |
|---|---|---|---|---|---|---|
| | | very low | low | medium | high | very high |
| Sewage Type | not contaminated | very low | very low | very low | very low | very low |
| | minor contaminated | very low | very low | low | low | medium |
| | medium contaminated | very low | low | medium | medium | high |
| | major contaminated | low | medium | medium | high | very high |
| | heavily contaminated | medium | medium | high | very high | very high |

**Figure 7: Example of a two-dimensional fuzzy-inference-matrix with selected process rules**

4. Using the algebraic product and the centroid method a resulting vector is determined which is finally defuzzificated to the resulting value on the target scale. Within Figure 8 this step is visualized.

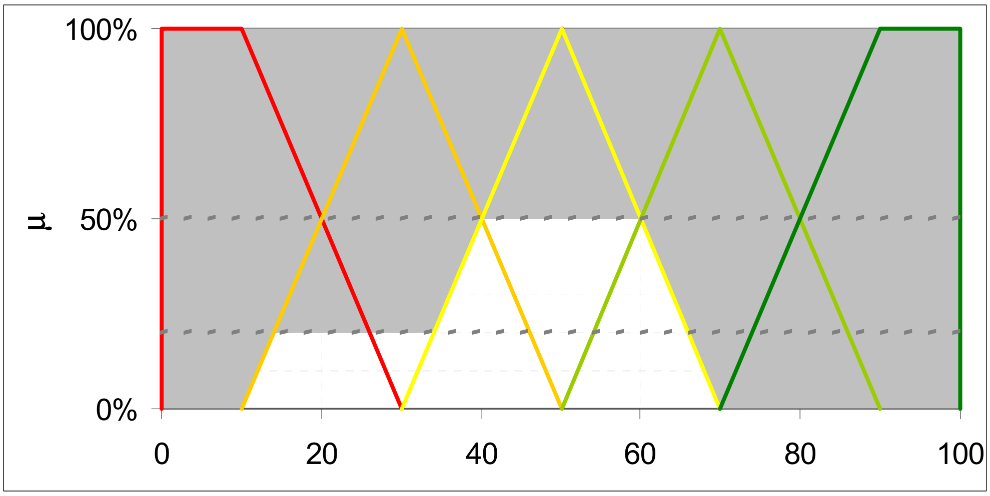


**Figure 8: Example of the centroid area**

This procedure is carried out for each single data set created by the Monte-Carlo-simulation and for each node within the tree.

The extensive multidimensional rule sets have been determined from two-dimensional matrices and sum up to a few hundred true rules - leaving empty rules out. The complete matrices of the involved experts can be found in the annex.

## 3.5 Further aspects of modelling environmental impacts

Building a model for accounting environmental impacts of leaky sewers leads to several questions, which cannot be answered within this study, as it would dramatically expand the scope of the research project. Nevertheless, it is necessary to discuss and mention these aspects and outline possible ways to answer these questions, which are by the way not only relevant for environmental issues but for the assessment of defect induced consequences in general.

### *3.5.1 Service life*

As the absolute environmental impact of the analysed issues depend on the exposure time, they scale according to the service life of the sewer sections. Therefore, the ratio between these impacts and other environmental issues of the life cycle changes accordingly. As the service life depends on many factors apart from material, the average service life has been set to 80 years in German regulations - for all materials. For this reason these scaling effects are neglected here.

### *3.5.2 Data quality*

The analysis of the data within this project as well as recent analyses within past studies show, that the quality of the network data - inspection data and basic data - is imperfect in many ways. Data transformation from extensive paper resources to digital form, inspectors who see defects which are not there or omit defects which are not clearly definable, imperfect coding systems, subjective assessment, logical failures and other inaccuracies lead at the end to imperfect data. Empirical findings from recent researches and analyses show that up to 20 % of the entire data stock is wrong in one way or another. Most of these failures can be found and eliminated via an extensive data mining combined with plausibility checks as they come from inconsistent or inaccurate data handling. Formal failures of defect codes are a typical example. This plausibility analysis has been carried out on all data used within the project to ensure data quality.

Others will remain undetected unless a review of the TV-inspection tapes will take place. This second - significantly smaller - group usually includes most of the inspection failures such as wrong/ inaccurate or incomplete indications. This group does usually not exceed a 5 % share, which has been proved by the recent KRV-analysis. A third group will be detected only by new, costly inspections. This group contains all failures of the second group, which are not correctable via inspection review due to bad video quality or for other reasons.

This does not detract from the significance of the finding as these failures normally apply to the entire network. Nevertheless, it is obvious that any attempt to transfer the results from their relative to an absolute scale will fail. Therefore, a direct comparison with results from other studies or models can only be successful if the relative scaling is kept.

### *3.5.3 Defect development and prognosis*

All of the samples are from different age, some of the inspections were older than 10 years. Within this time span, the defects logged by the inspector may have worsened and new defects may have arisen as the network deteriorates. To eliminate these data failures all inspection data need to be scaled to the same time horizon using a decent aging model. As the defect development due to aging takes place over a rather long period and not for all defect types, it can be neglected within this study. The additional risk caused by this development is rather small compared to the total risk caused by the defects.

Other failures arise from the unfamiliarity with the inspection strategy of the utilities. If operator prefer to select pipes for inspection according to their age, the picture of the network condition drawn by inspection data may be worse than it is in reality. Inspecting a random sample of the network could help to tackle these problems. Nevertheless this issue can be neglected as well, as it causes the networks to appear in a worse condition than the may be in reality. This causes the study to remain on the safe side with the analysis results which has been approved by the external experts.

As snapshots are always from the present or the past, the question of defect development and future environmental impacts remains unanswered too. Aging models, short and long-term prognoses and models for the determination of remaining service life of the sewers would help to answer this question but prognoses of the future environmental impact of sewer networks was not the target of the current study.

### *3.5.4 Empirical knowledge*

Within the utilities exists an enormous practical knowledge on network and sewer behaviour under certain ancillary conditions. So it is widely known, that correct installed sewers have negligible defects and do not cause any trouble. Nevertheless improper installations happen all days for several reasons so the question "What happens if…" need to be answered.

Another experience is that defects tend to occur more often and be more serious in permeable soil than in less permeable soil. But as these experiences are not recorded in the database there is no possibility to use this information, as there is no method to establish this link afterwards.

This is the main problem of the empirical knowledge - it is not recorded or not in a way that would allow the easy usage of this knowledge. A way for integrating this empirical data is by integrating it into the aging and forecasting model. Requirement for this is the recording of ancillary conditions on the section level.

# 4 Results explanation and interpretation

The outcomes of the modelling of the environmental impacts of leaking sewer systems are rather complex and abstract at first sight, which is due to the complexity of the topic itself. The following Chapter 4.2 explains the model results using example scenarios and outlines the scope of interpretation. In Chapter 5.3 the results of the defined scenarios presented without explaining in detail how to construe them.

## 4.1 Data analysis results

## 4.2 Model results

The model itself is fed with a several thousand data sets from the Monte-Carlo-simulation. Within Table 4 few of them are exemplarily shown. These input variables are processed by the fuzzy model as explained before and lead to the numerical model output of the same amount shown at Table 5.

**Table 4: Numerical model input**

| Sewage Level | Ground Water Level | Defect Position | Leakage Potential | Soil Permea-bility | Objects | Objects Distance | Sewage Type | Soil Type |
|---|---|---|---|---|---|---|---|---|
| 93.67 | -391.42 | 12.82 | 3.85 | 0.000014 | 52.85 | 176.82 | 21.66 | 35.04 |
| 22.40 | -293.56 | -73.02 | 13.04 | 0.000022 | 28.60 | 134.63 | 36.51 | 35.41 |
| 42.60 | -317.91 | -68.97 | 17.85 | 0.000003 | 35.73 | 223.93 | 28.74 | 42.08 |
| 27.77 | -320.93 | -38.79 | 15.49 | 0.000016 | 54.31 | 90.18 | 25.85 | 41.10 |
| 25.01 | -425.57 | 18.21 | 8.76 | 0.000044 | 21.51 | 126.58 | 23.46 | 65.66 |
| 76.83 | -414.87 | -15.64 | 5.54 | 0.000003 | 23.18 | 54.19 | 49.90 | 63.32 |
| 80.77 | -430.89 | -52.75 | 4.52 | 0.000002 | 6.43 | 226.72 | 8.81 | 53.71 |
| … | … | … | … | … | … | … | … | … |
| 60.85 | -473.74 | -86.99 | 7.54 | 0.000019 | 40.24 | 831.06 | 18.15 | 21.35 |

This output dataset represent the various combinations of defects and ancillary conditions according to their probability of occurrence, which is on one hand defined by the scenarios and on the other by the analyzed inspection data.

**Table 5: Numerical model output**

| Infiltration Risk | Exfiltra-tion Risk | Ground Water Level | Sewer Stability | Treat-ment Plant | Receiving Water | Ground Water Pollution | Soil Pollution | Objects Threat |
|---|---|---|---|---|---|---|---|---|
| 0.00 | 32.89 | 0.00 | 0.00 | 0.00 | 0.00 | 9.47 | 24.78 | 24.64 |
| 0.00 | 49.51 | 0.00 | 0.00 | 0.00 | 0.00 | 9.45 | 42.42 | 29.27 |
| 0.00 | 54.54 | 0.00 | 0.00 | 0.00 | 0.00 | 8.35 | 43.13 | 23.68 |
| 0.00 | 41.70 | 0.00 | 0.00 | 0.00 | 0.00 | 8.83 | 26.38 | 29.86 |
| 0.00 | 29.99 | 0.00 | 0.00 | 0.00 | 0.00 | 9.45 | 25.00 | 25.11 |
| 0.00 | 42.89 | 0.00 | 0.00 | 0.00 | 0.00 | 8.97 | 49.86 | 39.49 |
| 0.00 | 44.33 | 0.00 | 0.00 | 0.00 | 0.00 | 9.33 | 19.80 | 21.54 |
| … | … | … | … | … | … | … | … | … |
| 0.00 | 47.72 | 0.00 | 0.00 | 0.00 | 0.00 | 8.60 | 29.85 | 10.01 |

Generating the arithmetic mean for all these variables gives the **average environmental impacts caused by the average defect of a specific pipe type within the given scenario considering the bandwidth of possible influences**. Generating the arithmetic mean for all input factors and just process these values within the model would shrink the effort for modelling tremendously due to the fact that relations between input variables and model outcome are rather complex than linear the model results would be different and significance adulterated. The data is shown at Table 6.

**Table 6: Arithmetic mean of pure model results**

| Arithmetic Mean | Example scenario | | |
|---|---|---|---|
| | Rigid pipes | Flexible pipes | Flexible modified |
| Infiltration Potential | | | |
| Exfiltration Potential | 19.3 | 16.6 | 7.6 |
| Ground Water Level | | | |
| Sewer Stability | | | |
| Treatment Plant | | | |
| Receiving Water | | | |
| Ground Water Pollution | 4.9 | 4.0 | 1.9 |
| Soil Pollution | 19.4 | 16.2 | 7.6 |
| Objects Threat | 12.5 | 10.3 | 4.9 |

At Figure 9 the Model results for the example scenario is visualized within the total scope of possible impact severity. It is obvious that ancillary conditions defined in the scenario and the leakage rates determined by the defect characteristics from inspection date lead to a moderate impact to the environment for all pipe types. Yet it needs to be considered that the impact is just moderate because the bandwidth o f possible impact severity. Ancillary conditions with their influence on the model results do in fact limit the possible impact maximum within a certain scenario. The best example for the majority of the ancillary conditions is the total absence of infiltration and therefore environmental impacts caused by infiltration as shown in Figure 9. The ground water level defined in the example scenario is always below the sewer sections, which simply prevents infiltration. The defect grades and characteristics of the sewers are therefore always subordinate to the ancillary condition, which dominantly decide on the magnitude of the environmental impact.

Thus, this type of visualization chosen at Figure 9 is particularly suitable if one needs to compare the different setting defined within the scenario regarding their environmental sensitivity.

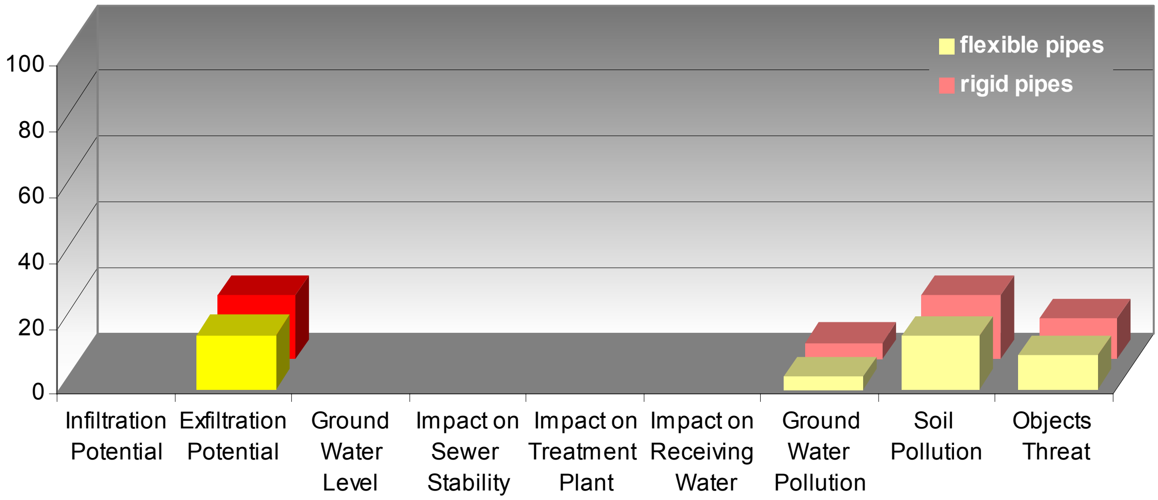


**Figure 9: Model results visualized within the total scope of possible impact severity**

The picture drawn at Figure 10 is completely different. It shows the model results visualized by normalizing the single variables to the maximum within the category. For each category (e.g. exfiltration risk) the maximum value is set to 1 and all the other members of the category scaled accordingly.

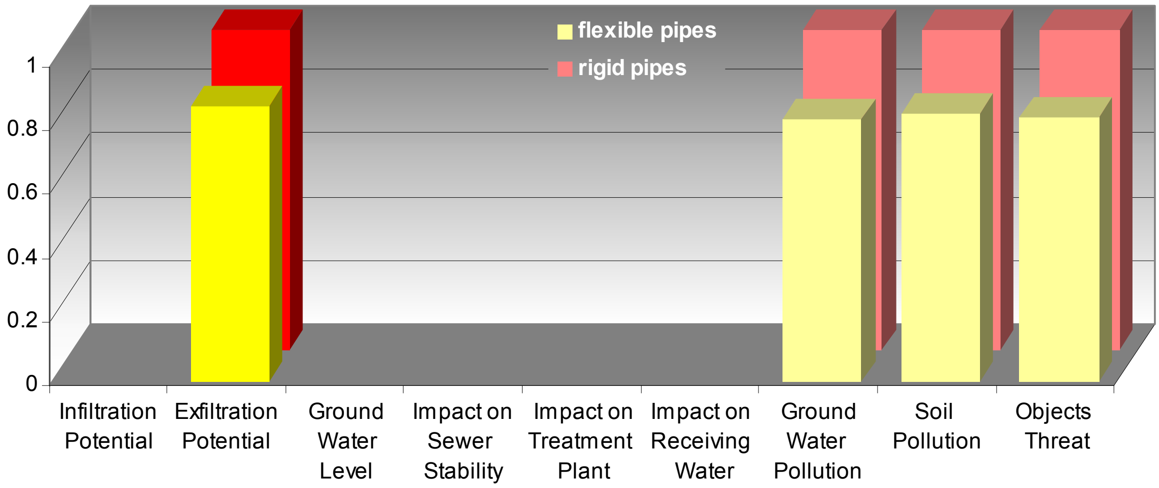


**Figure 10: Model results visualized by normalizing the single variables to the maximum within the category**

This form of data presentation clarifies the difference between the various pipe types. As these differences are only determined by the defect grades and characteristics of the sewers, the ancillary conditions do not affect the differences between the pipe types. As a logical consequence the offset between the categories are (and need to be) almost the same. The only influence of the ancillary condition is again shown by the total absence of infiltration and therefore environmental impacts caused by infiltration. If there is no impact, the difference between the pipe types does not matter and therefore vanishes as shown at Figure 10.

An again different picture is given at Figure 11 where the model results are visualized within the scope of possible impact severity of the single scenario. As the ancillary conditions dominantly decide on the height of the environmental impact within a certain scenario they are limiting the maximum impacts within the total scope of impact severity as explained above. If the target is to see the model result only regarding the specific scenario the maximum of the infiltration and exfiltration potential is set as upper border, which is defined here as five at Figure 11 - like the worst grade in school. All the other value scale accordingly. Within this figure differences of the pipe types, determined by the defect grades and characteristics of the sewers, and the ancillary conditions are shown in front of the context of the specific scenario. The advantage of Figure 11 is the transparency of the model results the handicap is the loss of comparability between the different scenarios.

So far, all presentations of the model results base on the same data and various scaling. At Figure 12 the picture is different as the model results are visualized within the scope of possible impact severity of the single scenario and weighted on an individual scale.

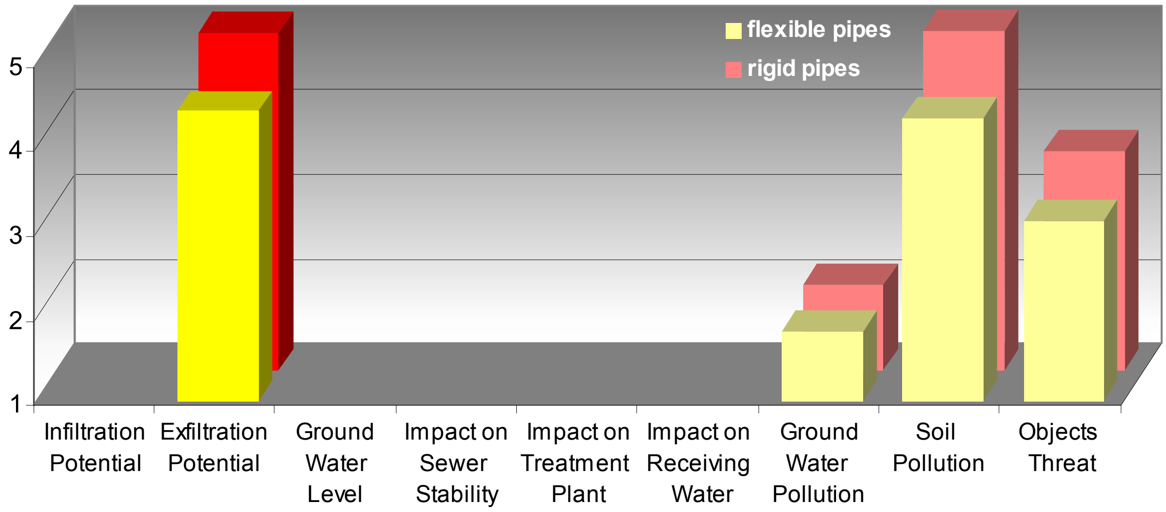


**Figure 11: Model results visualized within the scope of possible impact severity of the single scenario**

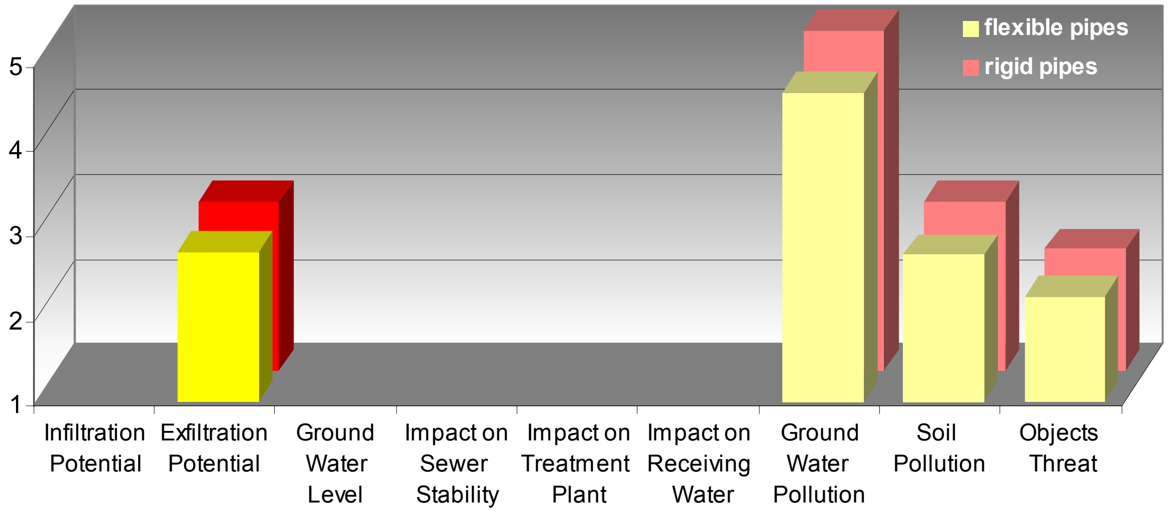


**Figure 12: Model results visualized within the scope of possible impact severity of the single scenario weighted on an individual scale**

For some local situations, the model output may not reflect the true weight of the different category variables. Situations like the dominating importance of one or more factors cannot be taken into account by a general model but must be handled by transforming the model results on an individual weighing scale. For Figure 12 it was assumed that the local groundwater resources are extremely important as they are limited and all of the drinking water is extracted from there. For that reason an individual weighing scale was assigned which reflects this extraordinary importance by weighing these values five times as important as the others, becoming the limiting factor. This is expressed by the increase of the figures for the category “ground water pollution” at Figure 12 and the dropping of all other categories. These local weighing scales need to be determined in case of necessity by local authorities, utilities and experts.

# 5 German results

## 5.1 Data analysis

The following data and figures result from the analysis of the provided network data. Due to the amount of data, which were after exclusions all together 1732 km, the results are a representative overview on the today's situation. The results reveal some interesting aspects of the analyzed pipe material groups. To ensure interoperability and comparability to other European data, all German inspection data has been translated to the EN 13508 code system using the translation standard set by the German association DWA (formerly ATV-DVWK). All other European data has been translated from the national code systems to the EN 13508 code system too.

The average is 6.8 years for flexible and 11.5 years for rigid sewer sections. Nevertheless the existing differences can be neglected as the majority of defects that are time dependent like corrosion or abrasion are from minor relevance for this study.

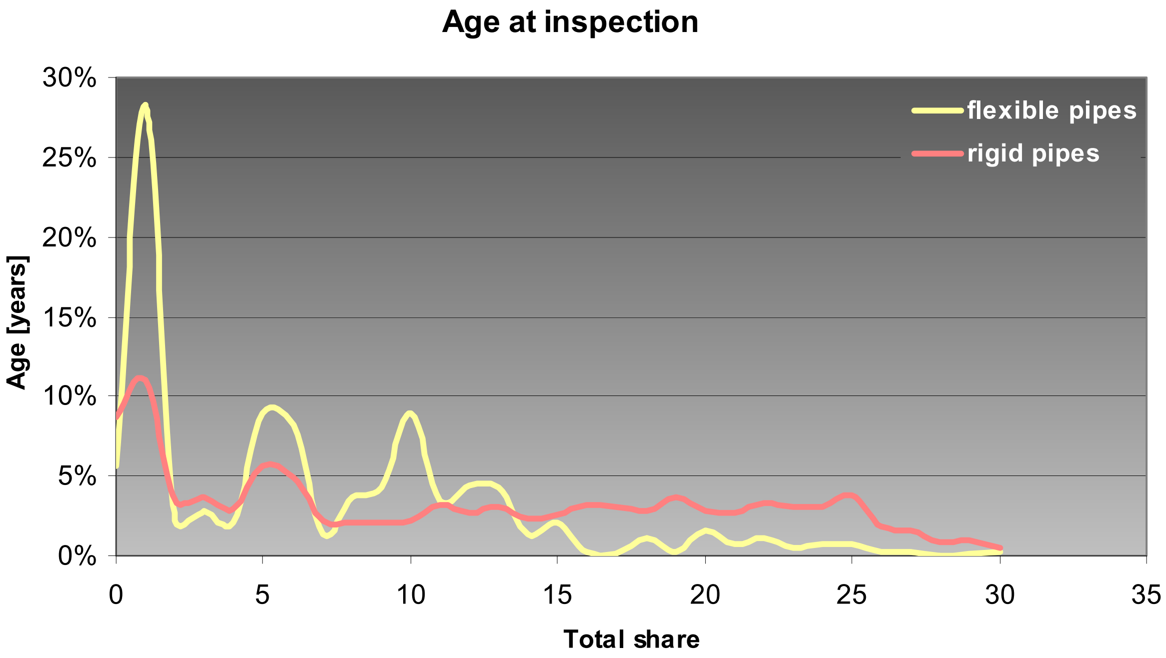


**Figure 13: Age at inspection - Germany**

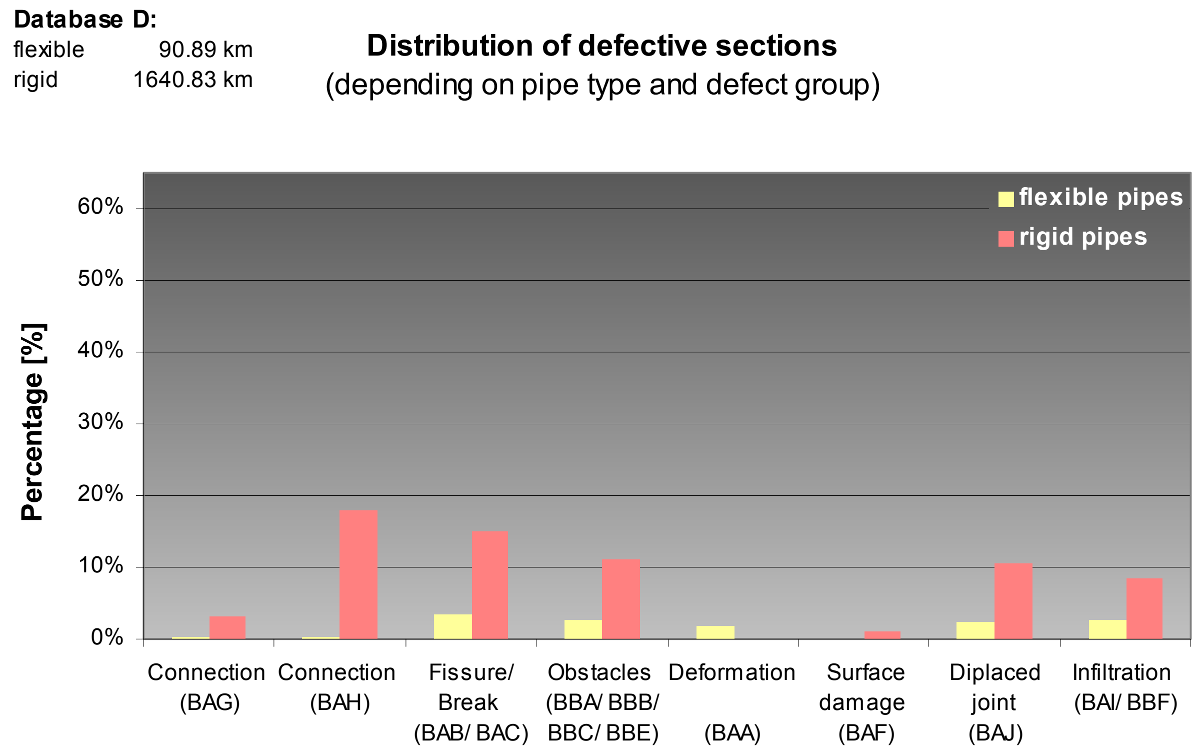


**Figure14: Distribution of defective sections according to the defect type**

In Figure14 and Table 7 the percentage of the defective sections according to the type of defect is shown. As a sewer section can have different types of defect, the accumulation of all shares of one material group may be more then 100 %.

The data is calculated by

$$\frac{\sum \text{Length of all sewers with defects}}{\sum \text{Length of all sewers}}$$

It is shown, that that flexible pipes at almost all defect types relevant for infiltration and exfiltration have a significant lower share of defective sections within the network than rigid pipes. At this point it needs to be explained, that the failure type “sagging” is excluded from analysis as recent research projects revealed that they are not easily can be detected correctly. Additionally the German codes for sagging cannot be translated correctly into the EN codes system (due to the missing equivalent). Instead the translation catalogue suggests displaced joint as a makeshift, which shift statistics.

**Table 7: Data - Distribution of defective sections according to the defect type**

| Data to Figure14 | | Material | |
|---|---|---|---|
| | | Rigid pipes | Flexible pipes |
| Defect Type | Intruding connection (BAG) | 3.1% | 0.3% |
| | Defective connection (BAH) | 17.9% | 0.4% |
| | Fissure/ Break (BAB/ BAC) | 14.9% | 3.5% |
| | Obstacles (BBA/ BBB/ BBC/ BBE) | 11.0% | 2.7% |
| | Deformation (BAA) | 0.1% | 1.8% |
| | Surface damage (BAF) | 1.0% | 0.0% |
| | Displaced joint (BAJ) | 10.6% | 2.3% |
| | Infiltration (BAI/ BBF) | 8.3% | 2.7% |

Table 8 illustrate the average number of defects per kilometer in relation to material and defect type, which has been calculated by:

$$\frac{\sum \text{Number of all defects (type / material)}}{\sum \text{Length of all sewers (type / material)}}$$

It is shown, that that flexible pipes at almost all defect types relevant for infiltration and exfiltration have a significant lower average defect rates (mean of the total network share) than rigid pipes.

Both illustrations show the well-known behaviour of the different material groups such as the fissure issue of rigid sewers and the deformation issue of flexible sewers.

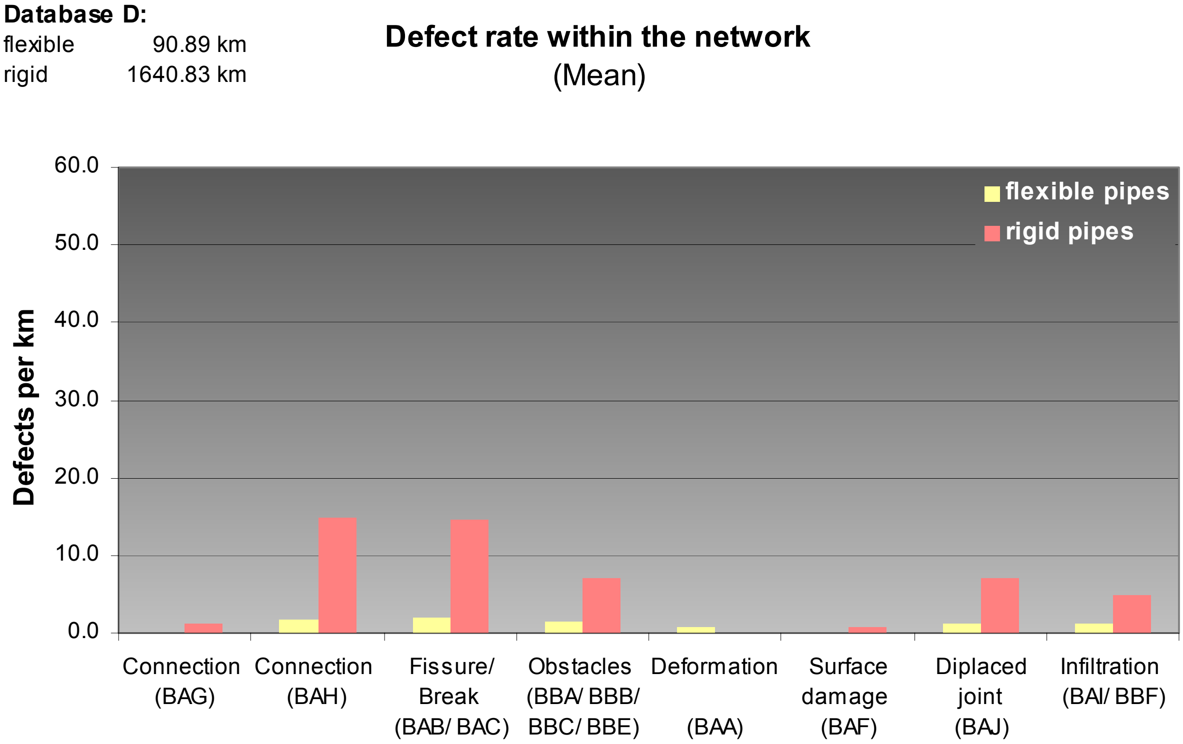


**Figure 15: Defect rate within the Network - Mean of the Network**

**Table 8: Data - Defect rate within the Network - Mean of the Network**

| **Data to Figure 15** | | **Material** | |
|---|---|---|---|
| | | **Rigid pipes** | **Flexible pipes** |
| **Defect Type** | Intruding connection (BAG) | 1.2 def./km | 0.1 def./km |
| | Defective connection (BAH) | 14.8 def./km | 1.8 def./km |
| | Fissure/ Break (BAB/ BAC) | 14.6 def./km | 2.0 def./km |
| | Obstacles (BBA/ BBB/ BBC/ BBE) | 7.1 def./km | 1.4 def./km |
| | Deformation (BAA) | 0.0 def./km | 0.7 def./km |
| | Surface damage (BAF) | 0.7 def./km | 0.0 def./km |
| | Displaced joint (BAJ) | 7.1 def./km | 1.2 def./km |
| | Infiltration (BAI/ BBF) | 4.7 def./km | 1.1 def./km |

Another interesting view is putting the number of defects in relation to the length of the defective part of the network by:

$$\frac{\sum \text{Number of all defects (type / material)}}{\sum \text{Length of all sewers with defects (type / material)}} \cdot 100\text{m}$$

like it is shown in Figure 16.

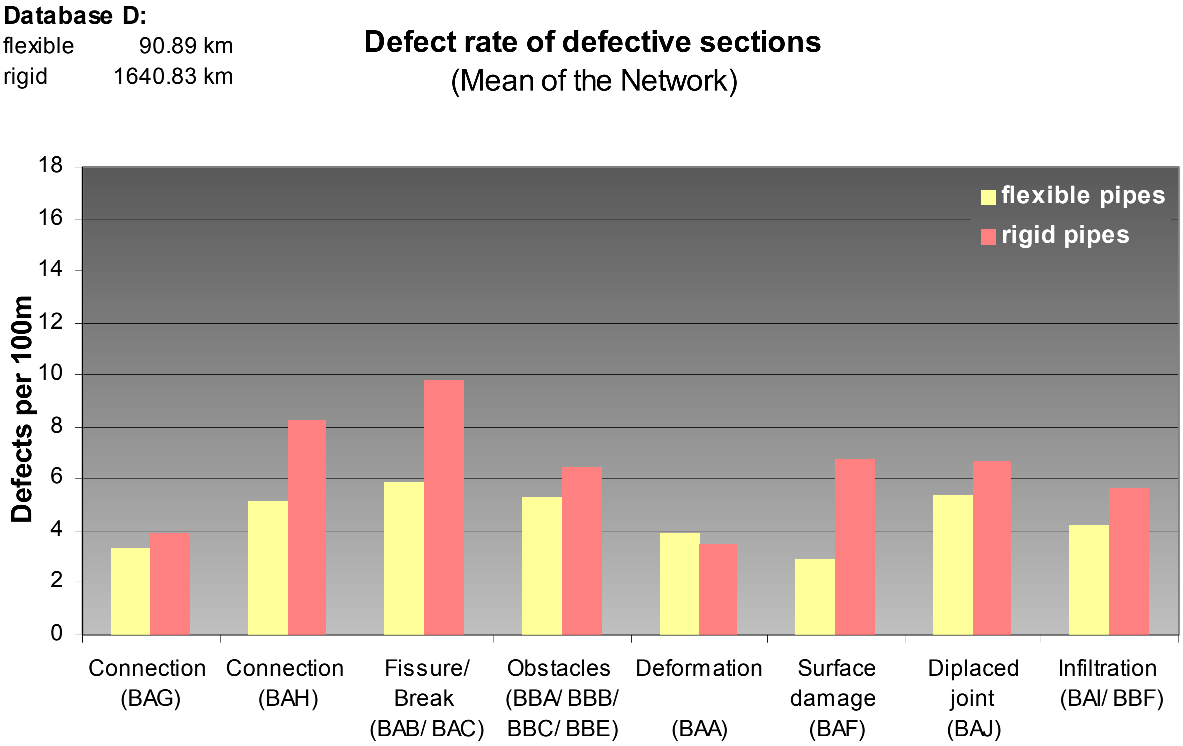


**Figure 16: Mean Defect rate in Defective Sections**

It is obvious that the defect rates of defective sections still show a significant difference between the two material groups confirming the material characteristics outlined by the figures before.

Therefore it can be stated that there is a clear difference in defect behaviour between the two material groups. Additionally it becomes clear, that the true difference between the material groups is the difference in failure frequency within the total network. The main factor in judging the environmental impact of a certain pipe material group can therefore only be the individual defect behaviour regarding leakage in combination with the network defect rates.

**Table 9: Data - Mean Defect Rate of Defective Sections**

| Data to Figure 16 | | Material | |
|---|---|---|---|
| | | **Rigid pipes** | **Flexible pipes** |
| | Intruding connection (BAG) | 4.0 def./100m | 3.3 def./100m |

|  |  |  |  |
|---|---|---|---|
|  | Defective connection (BAH) | 8.3 def./100m | 5.2 def./100m |
|  | Fissure/ Break (BAB/ BAC) | 9.8 def./100m | 5.8 def./100m |
|  | Obstacles (BBA/ BBB/ BBC/ BBE) | 6.5 def./100m | 5.3 def./100m |
|  | Deformation (BAA) | 3.5 def./100m | 3.9 def./100m |
|  | Surface damage (BAF) | 6.8 def./100m | 2.9 def./100m |
|  | Displaced joint (BAJ) | 6.7 def./100m | 5.3 def./100m |
|  | Infiltration (BAI/ BBF) | 5.7 def./100m | 4.2 def./100m |

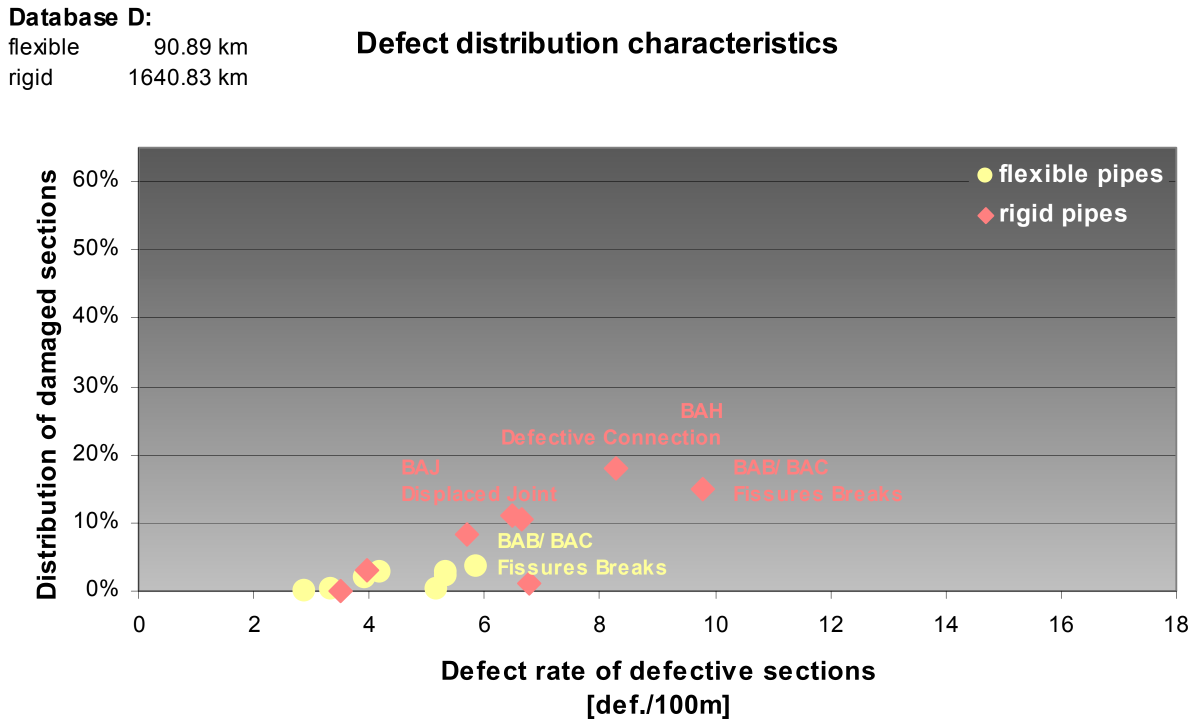


**Figure 17: Relation between defect distribution and defect rate**

At Figure 17 the relation between defect distribution and defect rate is shown, clearly visible that especially for the rigid pipes the defect types most relevant for leakage show an high likelihood of occurrence throughout the network and a high frequency of occurrence within the defective sections. Contrary to that defect frequency and likelihood of occurrence is visibly lower for flexible pipes which causes them performing significantly better regarding leakage.

## 5.2 Scenario definition

The following Table 10 lists the differences between the various scenarios. The mentioned factors are explained in detail in Chapter 3.4.

**Table 10: Scenario definitions**

| Scenario | Sewage level | | Soil permeability | | GW – level | |
|---|---|---|---|---|---|---|
| 1 Coastal region | MODE | 1/3 | MODE | Medium | MODE | Axis |
| Separated Sewage | SPAN | ¼ - ½ | SPAN | Low – high | SPAN | B. invert – a. crown |
| 2 Northern lowlands | MODE | 1/3 | MODE | High | MODE | Axis |
| Separated Sewage | SPAN | ¼ - ½ | SPAN | Low – very high | SPAN | B. invert – a. crown |
| 3 Low mountain range | MODE | 1/3 | MODE | Medium | MODE | Invert |
| Separated Sewage | SPAN | ¼ - ½ | SPAN | Very low – very high | SPAN | F. b. invert – a. crown |
| 4 Northern lowlands | MODE | 1/3 | MODE | High | MODE | Axis |
| Combined Sewage | SPAN | 1/3 - 2/3 | SPAN | Low – very high | SPAN | B. invert – a. crown |
| 5 Southern lowlands | MODE | 1/3 | MODE | High | MODE | Invert |
| Combined Sewage | SPAN | 1/3 - 2/3 | SPAN | Very low – very high | SPAN | B. invert – a. crown |
| 6 Low mountain range | MODE | 1/3 | MODE | Medium | MODE | B. invert |
| Combined Sewage | SPAN | 1/3 - 2/3 | SPAN | Very low – very high | SPAN | F. b. invert – a. crown |
| 7 Low mountain range | MODE | 1/3 | MODE | Medium | MODE | B. invert |
| Combined Sewage | SPAN | 1/3 - 2/3 | SPAN | Very low - high | SPAN | F. b. invert – a. crown |

The seven German scenarios listed cover the German situation in a representative way being defined by grouping areas according to:

- Hydro-geological situation;
- Population density;
- Sewer system

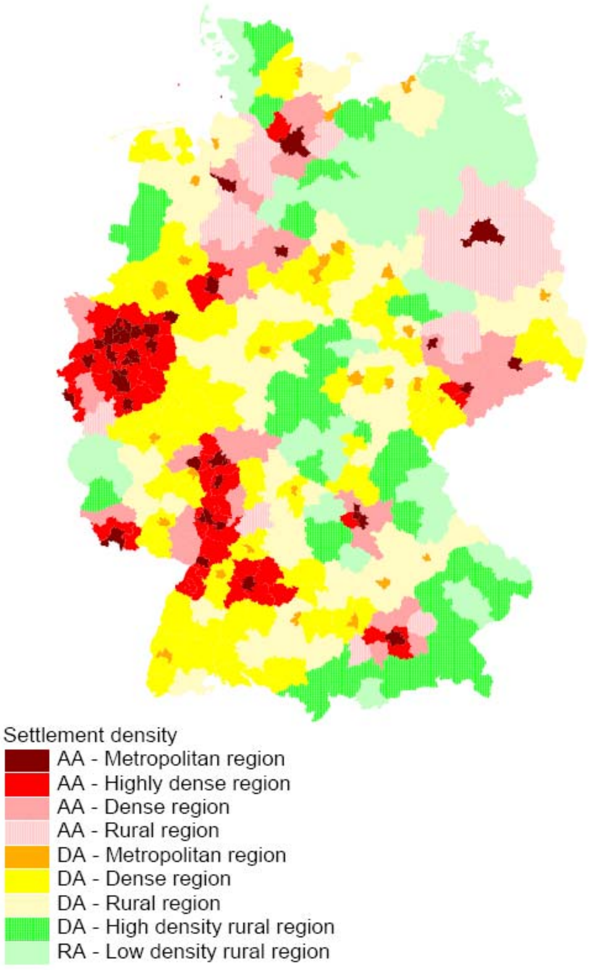


**Figure 18: Settlement density within Germany**

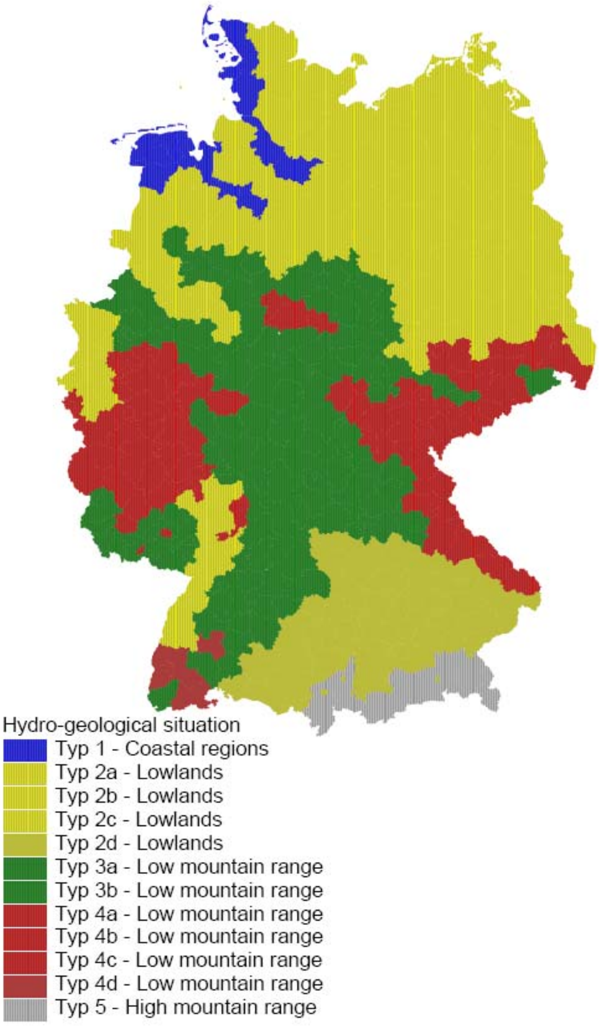


**Figure 19: Hydro-geological situation within Germany**

The figures show the geographic data used for scenario definitions. The settlement density at Figure 18 shows rural areas (green), agglomeration areas (yellow) and urban areas (red) indicating the increasing population density. The different colour shades are subtypes differentiating the density range in more detail. Population density is used as one indicator for the share of total network length of the different regions.

Figure 19 reflecting the general hydro-geological-situation within Germany, differentiating between coastal regions, lowland regions and mountain regions with their individual subtypes. The hydro-geological map provides information on the ancillary conditions in the different regions. Ground water level and soil type are determinable that way for the different scenarios.

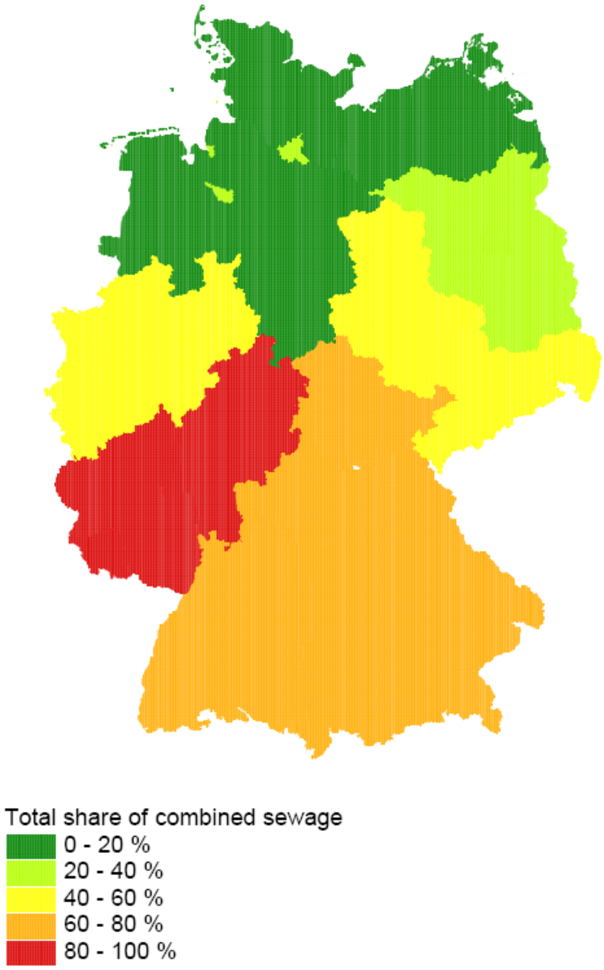


**Figure 20: Share of combined sewage within Germany**

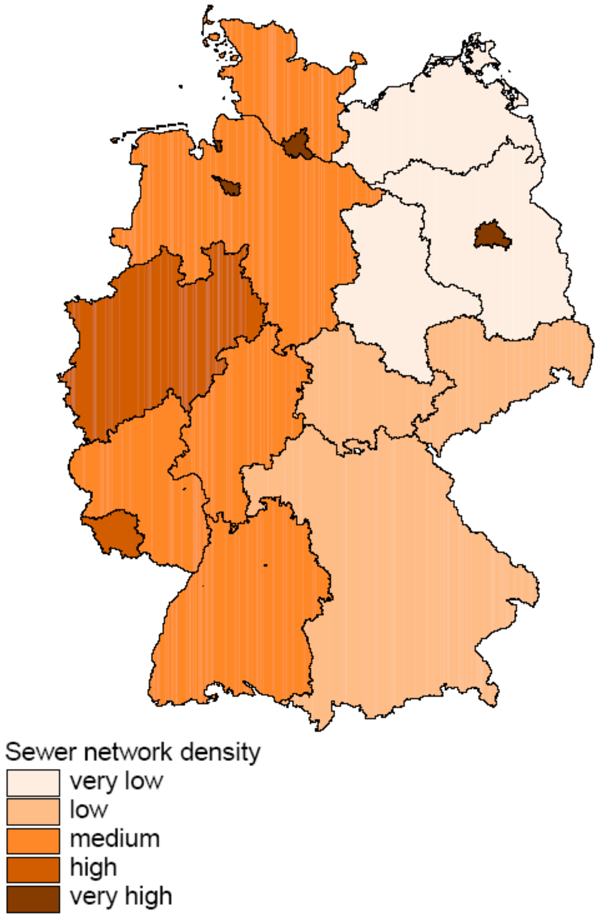


**Figure 21: Sewer network density within Germany**

Information on the share of combined/ separate sewage within the German states as shown at Figure 20 and the network density of the German states shown at Figure 21 is also known from recent surveys by the German association DWA.

All these geographical referenced data have been fed into a geographical information system to determine the German scenarios and what share represent on the German situation in total as shown at Table 11.

**Table 11: Total share of the defined scenarios on the German sewer networks**

| Scenario | | Total share |
|---|---|---|
| 1 | Coastal region - Separated Sewage | 3.69% |
| 2 | Northern lowlands - Separated Sewage | 25.91% |
| 3 | Low mountain range - Separated Sewage | 11.40% |
| 4 | Northern lowlands - Combined Sewage | 7.99% |
| 5 | Southern lowlands - Combined Sewage | 13.85% |
| 6 | Low mountain range - Combined Sewage | 18.56% |
| 7 | Low mountain range - Combined Sewage | 18.60% |

These results are needed later on for the interpretation of the model results in order to determine the average environmental impact of flexible/ rigid pipe systems caused by ex-/infiltration within Germany.

### 5.3 Model results

For Germany, the scenarios defined the chapter before were processed by the model. The results according to Figure 9 are shown at Table 32. As explained before they are shown on the total scale of possible impacts.

It is obvious that the various scenarios defined lead to results, which are significantly different. It shows the importance of consideration of the various ancillary conditions.

To determine the true differences in environmental impact of a network of rigid or flexible pipes it is necessary to relate the model results, which are basing on the average defect of the material group, to the average network defect rates by scaling them with the normalized defect rates of Table 13 which causes the impacts to drop dramatically for the flexible pipes. At Figure 22 this is shown on the absolute scale and at Figure 23 it is shown on the relative scale of environmental impacts caused by in-/ exfiltration.

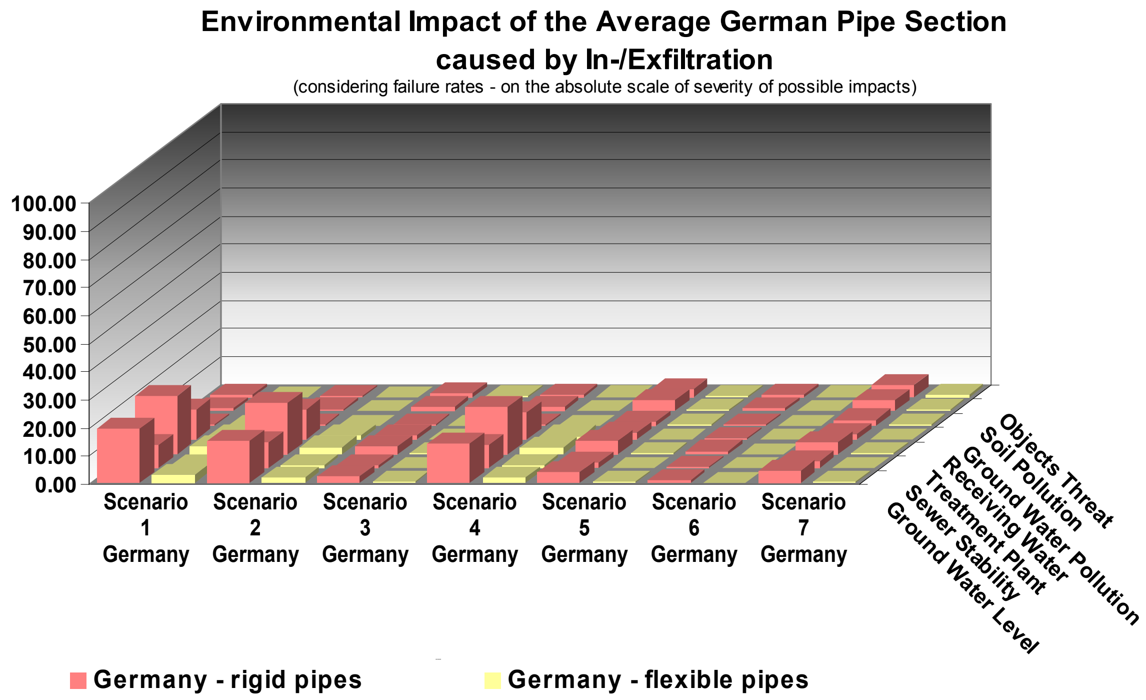


**Figure 22: Environmental Impact of the average German failure causing In-/Exfiltration within the total scope of possible impact severity - considering failure rates**

It is obvious that flexible pipes perform better regarding their environmental impacts caused by in-/ exfiltration. The average defect is less leaky for flexible pipes then for rigid and additional the frequency of occurrence is lower for the flexible pipe systems as it is shown at Table 13.

**Table 12: Environmental Impact of the average German failure causing In-/Exfiltration within the total scope of possible impact severity - considering failure rates**

|  | Germany 1 |  | Germany 2 |  | Germany 3 |  | Germany 4 |  | Germany 5 |  | Germany 6 |  | Germany 7 |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible |
| Ground Water Level | 19.3 | 2.7 | 15.1 | 2.1 | 2.4 | 0.3 | 14.0 | 1.9 | 3.9 | 0.5 | 1.1 | 0.1 | 4.2 | 0.6 |
| Sewer Stability | 8.6 | 1.3 | 9.2 | 1.3 | 1.4 | 0.2 | 8.5 | 1.2 | 2.3 | 0.3 | 0.7 | 0.1 | 2.6 | 0.4 |
| Treatment Plant | 20.6 | 3.0 | 18.5 | 2.6 | 2.9 | 0.4 | 17.0 | 2.4 | 4.6 | 0.7 | 1.2 | 0.2 | 4.4 | 0.6 |
| Receiving Water | 11.0 | 1.6 | 10.8 | 1.6 | 1.7 | 0.2 | 9.9 | 1.4 | 2.7 | 0.4 | 0.6 | 0.1 | 2.1 | 0.3 |
| Ground Water Pollution | 0.5 | 0.1 | 0.3 | 0.1 | 0.6 | 0.1 | 0.6 | 0.1 | 1.4 | 0.3 | 0.5 | 0.1 | 2.1 | 0.4 |
| Soil Pollution | 1.1 | 0.2 | 0.9 | 0.2 | 1.7 | 0.4 | 1.8 | 0.3 | 4.3 | 0.8 | 1.1 | 0.2 | 4.2 | 0.8 |
| Objects Threat | 0.9 | 0.2 | 0.6 | 0.2 | 1.2 | 0.3 | 1.1 | 0.2 | 2.8 | 0.6 | 1.1 | 0.2 | 4.2 | 0.8 |

**Table 13: Result scaling**

| **Pipe type** | **Average defect rates** | **Normalized defect rates** |
|---|---|---|
| **Flexible pipes** | 8.45 defects per km | 0.17 |
| **Rigid pipes** | 50.26 defects per km | 1 |

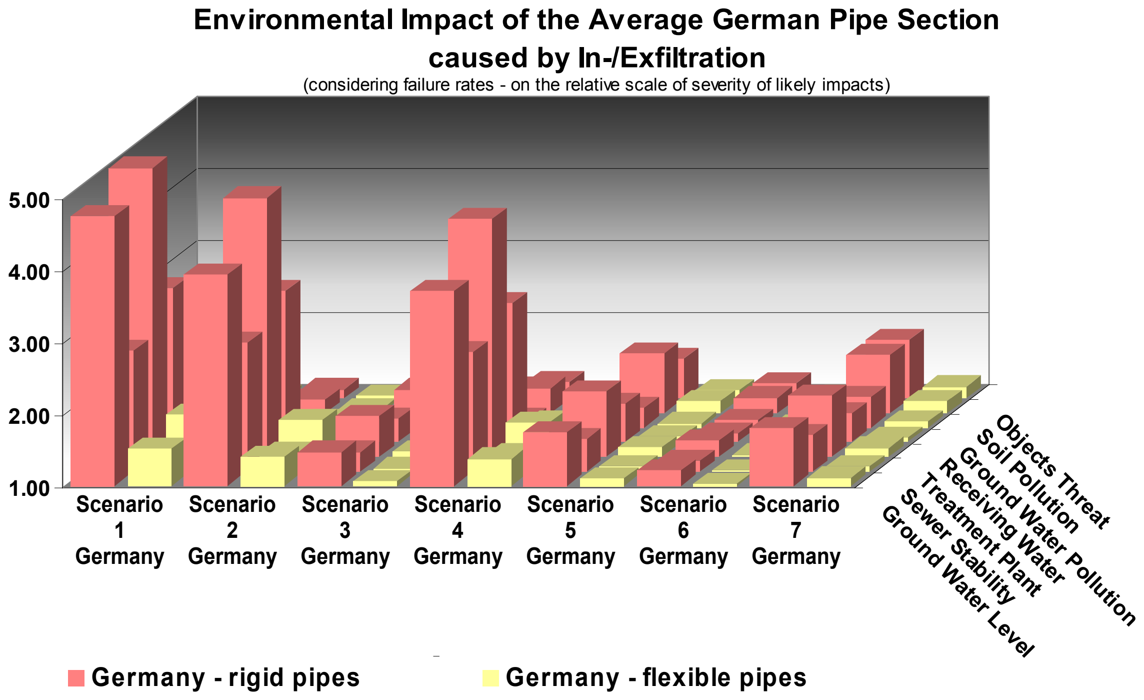


**Figure 23: Environmental Impact of the average German failure causing In-/Exfiltration within the relative scope of likely impact severity - considering failure rates**

The relation of difference between flexible and rigid pipe systems within the single scenarios remains almost equal, as the ancillary conditions are the dominating factors for determining this difference.

**Table 14: Environmental Impact of the average German failure causing In-/Exfiltration within the relative scope of likely impact severity - considering failure rates**

| | Germany 1 | | Germany 2 | | Germany 3 | | Germany 4 | | Germany 5 | | Germany 6 | | Germany 7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible |
| Ground Water Level | 4.74 | 1.53 | 3.93 | 1.41 | 1.47 | 1.07 | 3.71 | 1.38 | 1.75 | 1.11 | 1.21 | 1.03 | 1.81 | 1.11 |
| Sewer Stability | 2.68 | 1.25 | 2.79 | 1.26 | 1.27 | 1.04 | 2.65 | 1.24 | 1.45 | 1.07 | 1.14 | 1.02 | 1.51 | 1.08 |
| Treatment Plant | 5.00 | 1.58 | 4.59 | 1.51 | 1.56 | 1.08 | 4.29 | 1.46 | 1.90 | 1.13 | 1.23 | 1.03 | 1.85 | 1.12 |
| Receiving Water | 3.13 | 1.31 | 3.09 | 1.30 | 1.32 | 1.05 | 2.92 | 1.28 | 1.53 | 1.08 | 1.11 | 1.01 | 1.40 | 1.06 |
| Ground Water Pollution | 1.09 | 1.02 | 1.06 | 1.01 | 1.12 | 1.03 | 1.11 | 1.02 | 1.28 | 1.06 | 1.11 | 1.02 | 1.42 | 1.08 |
| Soil Pollution | 1.21 | 1.05 | 1.18 | 1.04 | 1.33 | 1.08 | 1.34 | 1.06 | 1.83 | 1.16 | 1.21 | 1.04 | 1.81 | 1.16 |
| Objects Threat | 1.17 | 1.04 | 1.12 | 1.03 | 1.23 | 1.06 | 1.22 | 1.04 | 1.55 | 1.11 | 1.21 | 1.04 | 1.81 | 1.16 |

Having determined the net share of the single scenarios (see Table 11 at chapter 3.3.2) it is now possible to cumulate the average environmental impacts for Germany as it is done with Figure 24. The light coloured columns are representing as before the various impacts whereas the strong coloured columns are showing the aggregated average environmental impact cause by in-/ exfiltrating sewer systems.

Network operators tend to see especially impacts on the treatment plant, sewer stability and the receiving water most critical of all the impacts. As impacts on the ground water level are rated ambivalent (tight systems may increase the groundwater level and cause damage to objects) these factors are at the time the dominating impacts caused by in/exfiltration as clearly visible from Figure 24.

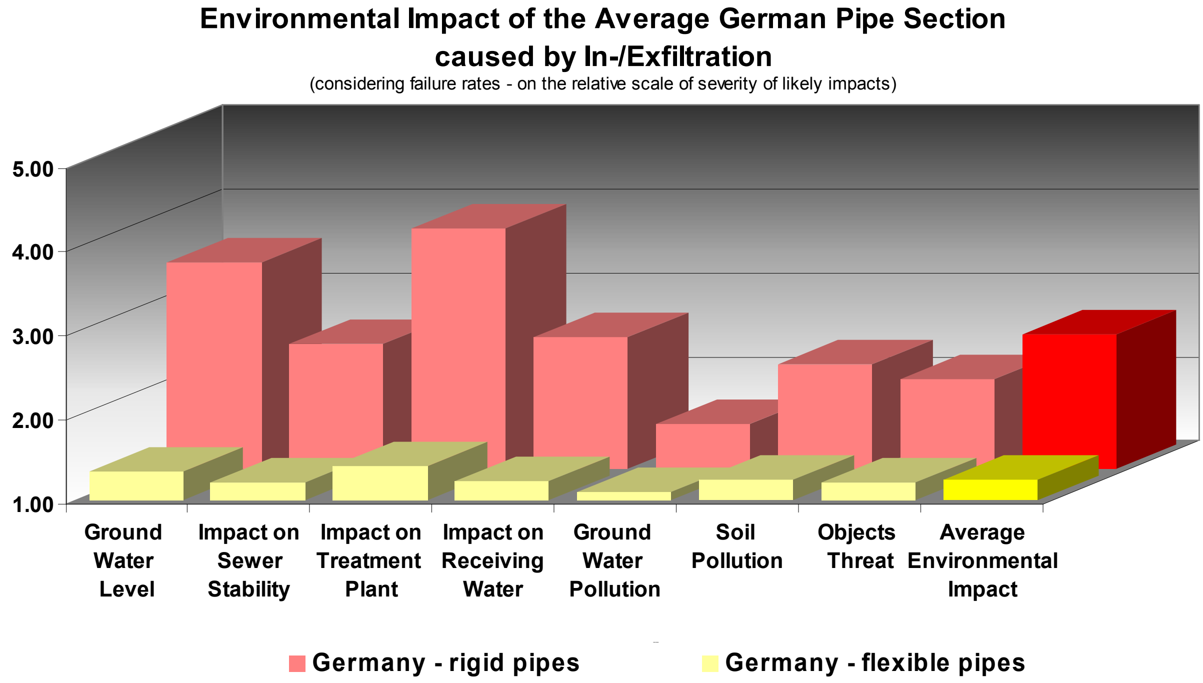


**Figure 24: Environmental Impact of the average German failure causing In-/Exfiltration within the relative scope of likely impact severity - considering failure rates and aggregating scenario results according to net share**

**Table 15: Average German Environmental Impact caused by In-/Exfiltration within the relative scope of likely impact severity - considering failure rates and aggregating scenario results according to net share**

| | Germany | |
|---|---|---|
| | Rigid | Flexible |
| Ground Water Level | 3.46 | 1.34 |
| Sewer Stability | 2.49 | 1.21 |
| Treatment Plant | 3.86 | 1.40 |
| Receiving Water | 2.57 | 1.23 |
| Ground Water Pollution | 1.54 | 1.11 |
| Soil Pollution | 2.24 | 1.25 |
| Objects Threat | 2.06 | 1.21 |
| Average Environmental Impact by In-/Exfiltration | 2.60 | 1.25 |

# 6 Dutch results

## 6.1 Data analysis

The following data and figures have been distributed from Dutch project partners. The results reveal some interesting aspects of the analyzed pipe material groups. To ensure interoperability and comparability to other European data, all Dutch inspection data has been translated to the EN 13508 code system.

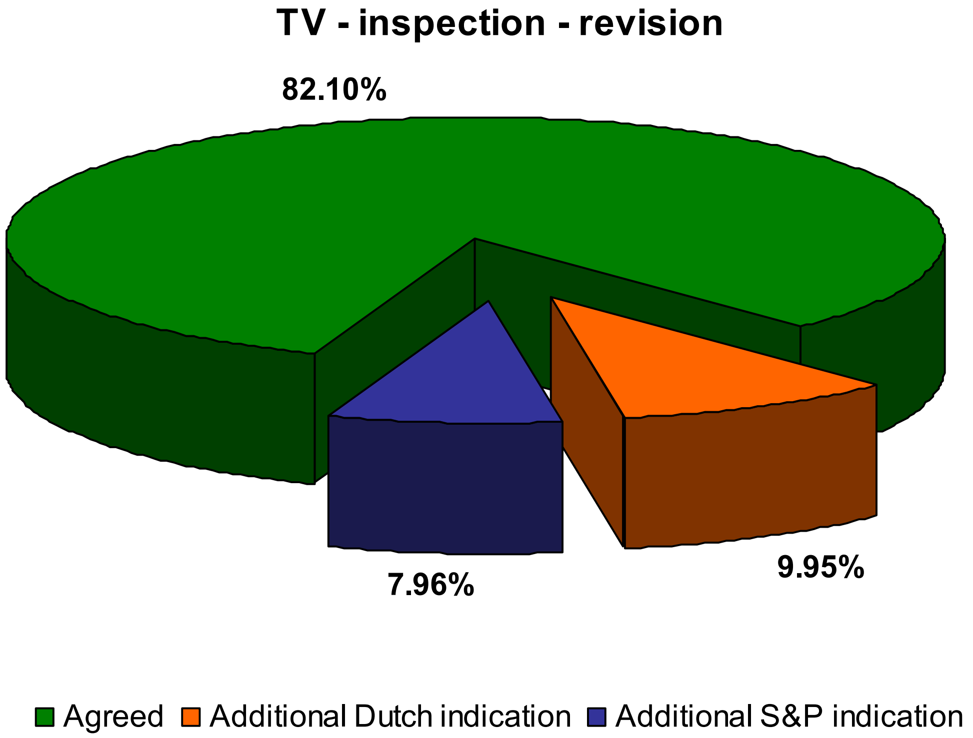


Figure 25: Result of the revision of the Dutch TV-inspections

To ensure comparability the inspection data has been revised additionally to determine the difference in defect assessment. As Figure 25 shows, there is a significant level of congruence, as the differences in indication by the engineers were caused by minor distinctions in interpretation or missing additional defect descriptions.

One example for the differences is shown at Figure 26, where the code for defective connection does not show up in the protocols although it is stated on the TV-tape.

**Figure 26: NL BBF (Infiltration) S&P: BAH (Defective connection) additionally**

In Figure 27 the percentage of the defective sections according to the type of defect is shown. As a sewer section can have different types of defect, the accumulation of all shares of one material group may be more then 100 %.

The data is calculated by

$$\frac{\sum \text{Length of all sewers with defects}}{\sum \text{Length of all sewers}}$$

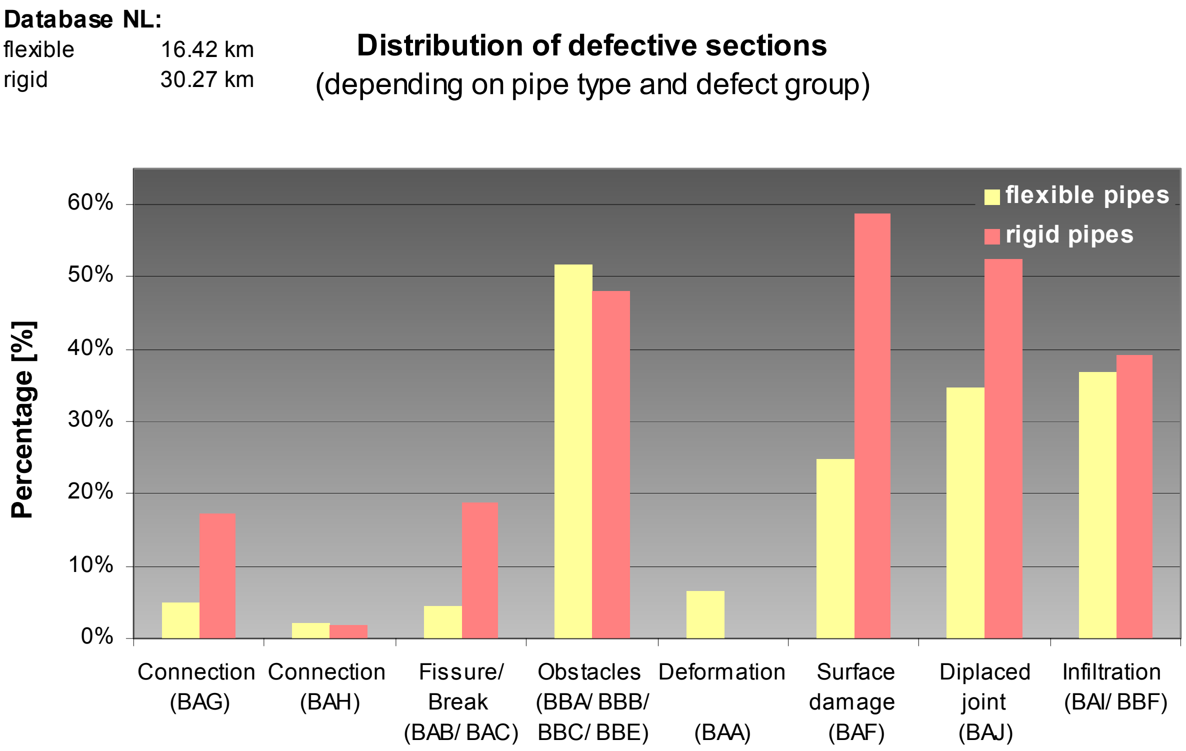


**Figure 27: Distribution of defective sections according to the defect type**

According to the Dutch expert Mr. van der Jagt the high share of infiltration defects (BBF) are due to incorrect defect assessment by the inspectors as most of these indications should have been assessed as defective connection (BAH) a defect which comes from massive installation problems due to missing supervision. Another defect problem resulting from the quality issue is the problem of displaced joints.

**Table 16: Data - Distribution of defective sections according to the defect type**

| **Data for Figure** 27 | | **Material** | |
|---|---|---|---|
| | | **Rigid pipes** | **Flexible pipes** |
| **Defect Type** | Intruding connection (BAG) | 17.1% | 5.1% |
| | Defective connection (BAH) | 1.9% | 2.2% |
| | Fissure/ Break (BAB/ BAC) | 18.8% | 4.5% |
| | Obstacles (BBA/ BBB/ BBC/ BBE) | 47.9% | 51.8% |
| | Deformation (BAA) | 0.0% | 6.6% |
| | Surface damage (BAF) | 58.8% | 24.9% |
| | Displaced joint (BAJ) | 52.6% | 34.8% |
| | Infiltration (BAI/ BBF) | 39.2% | 36.9% |

The following Figure 28 and the related table illustrate the average number of defects per kilometer in relation to material and defect type, which has been calculated by:

$$\frac{\sum \text{Number of all defects (type / material)}}{\sum \text{Length of all sewers (type / material)}}$$

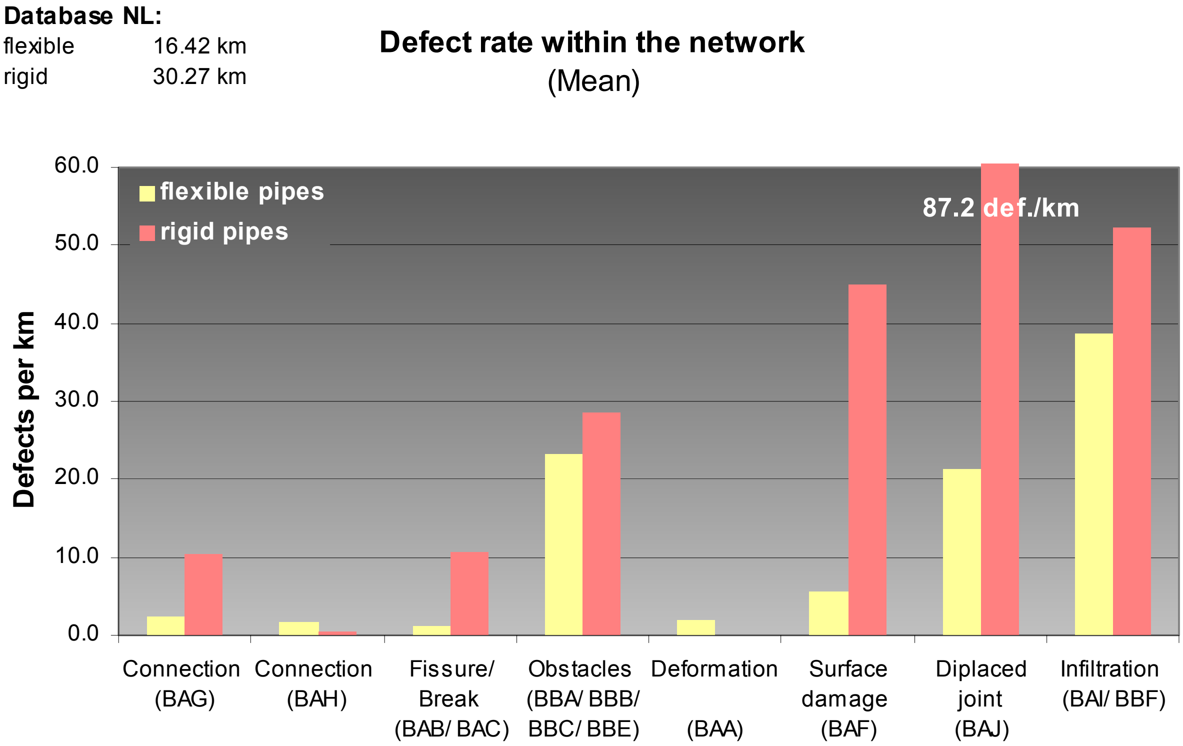


Figure 28: Defect Rate within the Network - Mean of the Network

Table 17: Data - Defect Rate within the Network - Mean of the Network

| Data to Figure 28 | | Material | |
|---|---|---|---|
| | | **Rigid pipes** | **Flexible pipes** |
| **Defect Type** | Intruding connection (BAG) | 10.5 def./km | 2.4 def./km |
| | Defective connection (BAH) | 0.5 def./km | 1.6 def./km |
| | Fissure/ Break (BAB/ BAC) | 10.5 def./km | 1.3 def./km |
| | Obstacles (BBA/ BBB/ BBC/ BBE) | 28.5 def./km | 23.2 def./km |
| | Deformation (BAA) | 0.0 def./km | 1.8 def./km |
| | Surface damage (BAF) | 45.0 def./km | 5.7 def./km |
| | Displaced joint (BAJ) | 87.2 def./km | 21.3 def./km |
| | Infiltration (BAI/ BBF) | 52.3 def./km | 38.7 def./km |

Another interesting view is putting the number of defects in relation to the length of the defective part of the network by:

$$\frac{\sum \text{Number of all defects (type / material)}}{\sum \text{Length of all sewers with defects (type / material)}} \cdot 100\text{m}$$

**Database NL:**

| | |
|---|---|
| flexible | 16.42 km |
| rigid | 30.27 km |

**Defect rate of defective sections**
(Mean of the network)

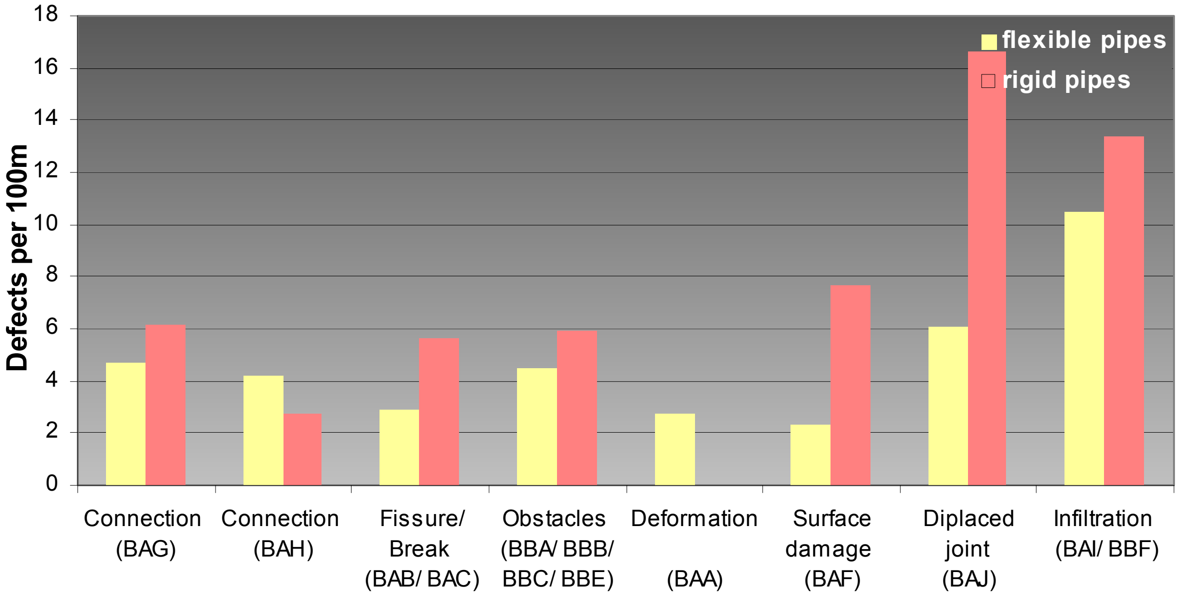


**Figure 29: Mean Defect Rate of Defective Sections**

**Table 18: Data - Mean Defect Rate of Defective Sections**

| **Data to Figure 29** | | **Material** | |
|---|---|---|---|
| | | **Rigid pipes** | **Flexible pipes** |
| **Defect Type** | Intruding connection (BAG) | 6.1 def./100m | 4.7 def./100m |
| | Defective connection (BAH) | 2.7 def./100m | 4.2 def./100m |
| | Fissure/ Break (BAB/ BAC) | 5.6 def./100m | 2.9 def./100m |
| | Obstacles (BBA/ BBB/ BBC/ BBE) | 6.0 def./100m | 4.5 def./100m |
| | Deformation (BAA) | | 2.8 def./100m |

| Data to Figure 29 |  | Material |  |
|---|---|---|---|
|  |  | Rigid pipes | Flexible pipes |
|  | Surface damage (BAF) | 7.7 def./100m | 2.3 def./100m |
|  | Displaced joint (BAJ) | 16.6 def./100m | 6.1 def./100m |
|  | Infiltration (BAI/ BBF) | 13.3 def./100m | 10.5 def./100m |

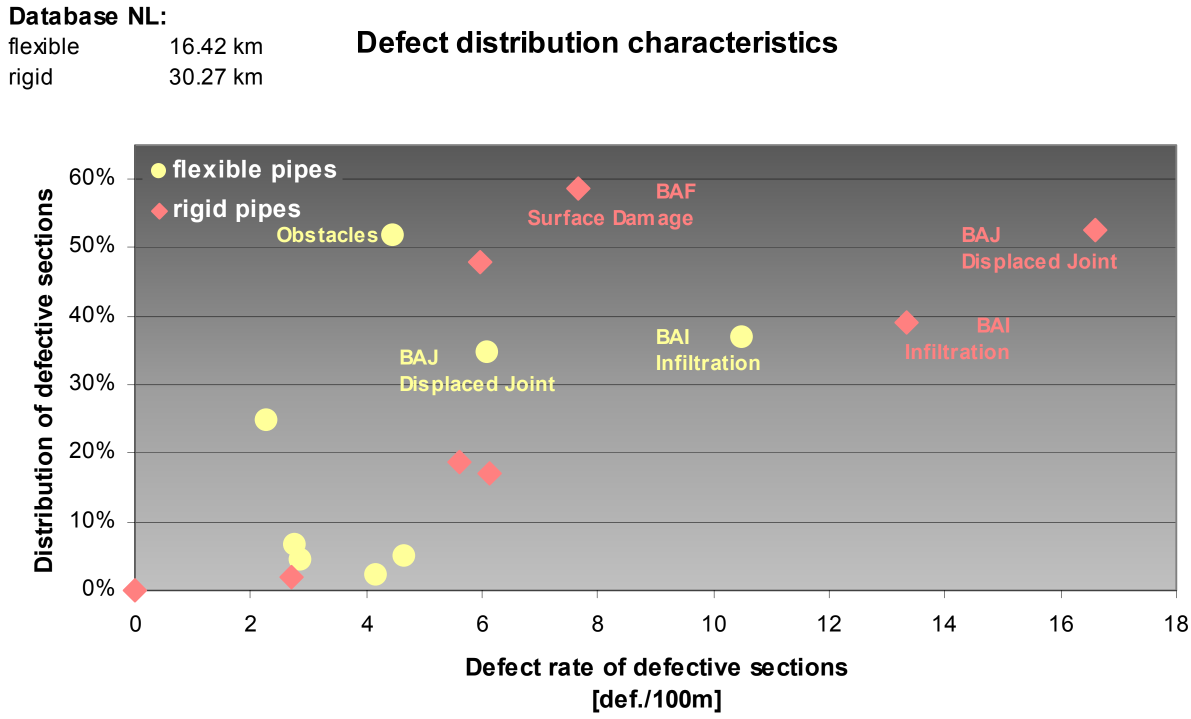


**Figure 30: Relation between defect distribution and defect rate**

At Figure 30 the relation between defect distribution and defect rate is shown.

## 6.2 Model results

For the Netherlands, the scenarios, defined by Dutch experts and displayed at Table 19, were processed by the model. As the Dutch database for the modelling was too small, the German data was adapted for the Netherlands.

Comparing the data analysis figures of Germany and the Netherlands it becomes obvious, that defect rates of defective sections are similar apart from the displaced joint (BAJ) and the infiltration issue. As mentioned before the last problem results mostly from incorrect indications, the other differences come to a significant share from massive installation problems due to missing supervision. Assuming similar supervision, maintenance and rehabilitation behaviour as in Germany the differences in defect characteristics would significantly change and move towards German figures. Therefore the adaptation of the German data was feasible. Thus, direct comparison of the sensitivity of the ancillary conditions for the three Dutch scenarios with the other European scenarios became possible.

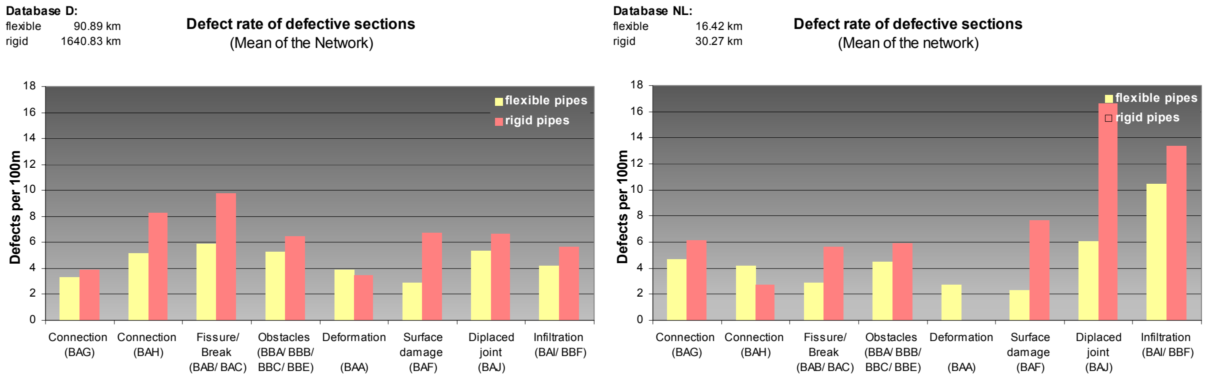


**Figure 31: Comparison of German and Dutch defect rates**

**Table 19: Scenario definitions for the Netherlands**

| **Scenario** | **Sewage level** | | **Soil permeability** | | **GW – level** | |
|---|---|---|---|---|---|---|
| Nr. 1 | MODE | Closer to axis | MODE | Medium | MODE | Axis |
| | SPAN | Invert – axis | SPAN | low - medium | SPAN | b.invert – a.crown |
| Nr. 2 | MODE | Closer to axis | MODE | Low | MODE | Invert |
| | SPAN | Invert – axis | SPAN | Low – medium | SPAN | a.crown (15%) |
| Nr. 3 | MODE | Closer to axis | MODE | Closer to low | MODE | Far below pipe invert |
| | SPAN | Invert – axis | SPAN | v.low – low | SPAN | |

The results according to Figure 9 are shown at Table 34. As explained before they are shown on the total scale of possible impacts.

It is obvious that the various scenarios defined lead to results, which are significantly different. It shows the importance of consideration of the various ancillary conditions.

To determine the true differences in environmental impact of a network of rigid or flexible pipes it is necessary to relate the model results, which are basing on the average defect of the material group, to the average network defect rates by scaling them with the normalized defect rates of Table 21 which causes the impacts to drop dramatically for the flexible pipes. At Figure 32 this is shown on the absolute scale and at Figure 33 it is shown on the relative scale of environmental impacts caused by in-/ exfiltration.

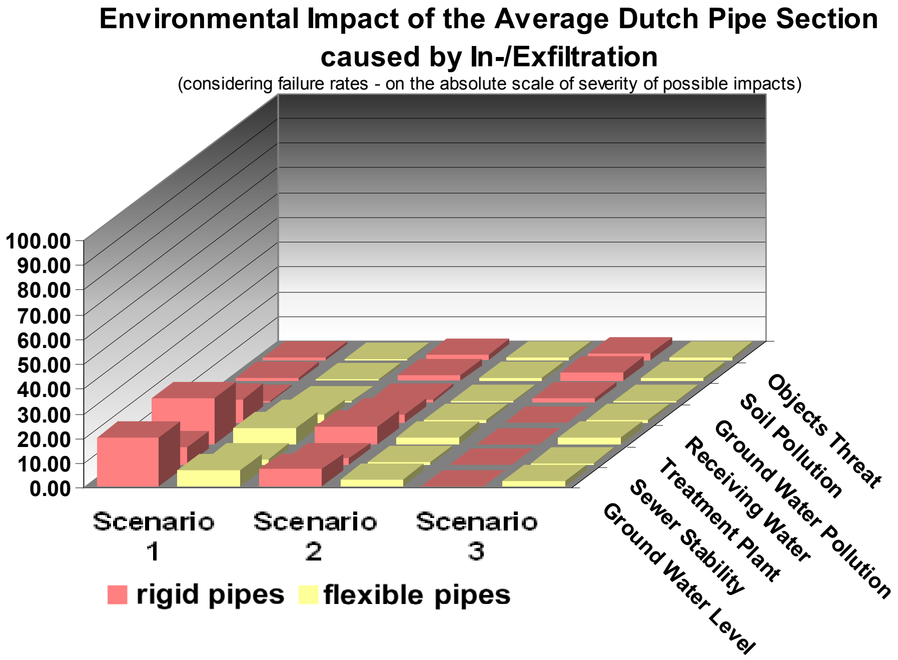


**Figure 32: Environmental Impact of the average failure causing In-/Exfiltration within the total scope of possible impact severity - considering failure rates**

It is obvious that flexible pipes perform better regarding their environmental impacts caused by in-/ exfiltration. The average defect is less leaky for flexible pipes then for rigid and additional the frequency of occurrence is lower for the flexible pipe systems as it is shown at Table 21.

**Table 20: Environmental Impact of the average failure causing In-/Exfiltration within the total scope of possible impact severity - considering failure rates**

|  | Netherlands 1 |  | Netherlands 2 |  | Netherlands 3 |  |
|---|---|---|---|---|---|---|
|  | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible |
| Ground Water Level | 19.5 | 6.3 | 6.7 | 2.5 | 0.0 | 2.2 |
| Sewer Stability | 7.1 | 2.5 | 2.6 | 1.0 | 0.0 | 0.9 |
| Treatment Plant | 18.4 | 6.3 | 7.1 | 2.8 | 0.0 | 2.5 |
| Receiving Water | 9.4 | 3.3 | 3.6 | 1.4 | 0.0 | 1.3 |
| Ground Water Pollution | 0.5 | 0.3 | 1.0 | 0.6 | 1.5 | 0.6 |
| Soil Pollution | 1.2 | 0.6 | 2.4 | 1.3 | 3.5 | 1.4 |
| Objects Threat | 1.0 | 0.5 | 2.0 | 1.1 | 3.0 | 1.2 |

**Table 21: Result scaling**

| **Pipe type** | **Average defect rates** | **Normalized defect rates** |
|---|---|---|
| **Flexible pipes** | 95.91 defects per km | 0.41 |
| **Rigid pipes** | 234.56 defects per km | 1 |

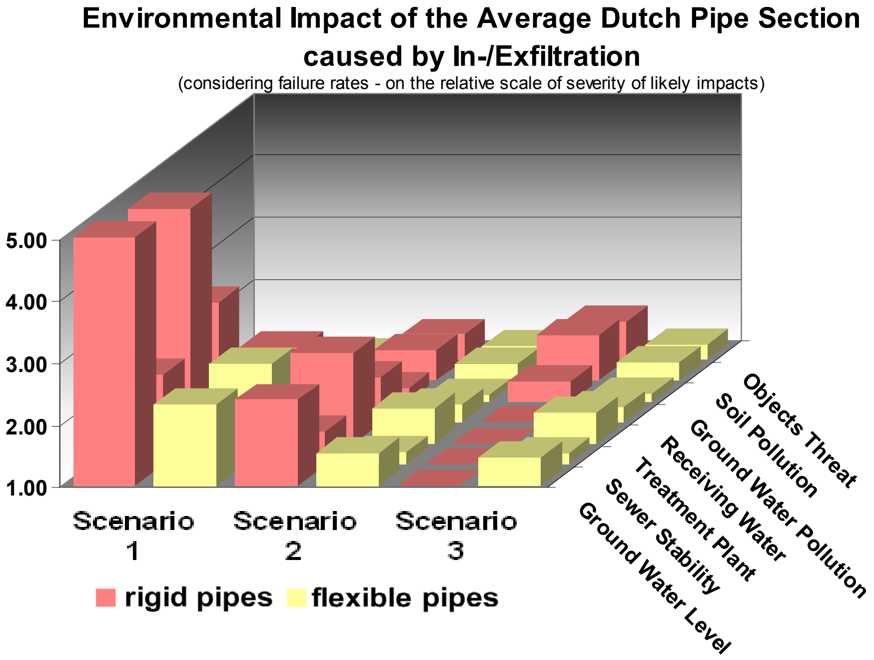


**Figure 33: Environmental Impact of the average failure causing In-/Exfiltration within the relative scope of likely impact severity - considering failure rates**

The relation of difference between flexible and rigid pipe systems within the single scenarios remains almost equal, as the ancillary conditions are the dominating factors for determining this difference.

**Table 22: Environmental Impact of the average failure causing In-/Exfiltration within the relative scope of likely impact severity - considering failure rates**

| | Netherlands 1 | | Netherlands 2 | | Netherlands 3 | |
|---|---|---|---|---|---|---|
| | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible |
| Ground Water Level | 5.00 | 2.30 | 2.38 | 1.51 | 1.00 | 1.46 |
| Sewer Stability | 2.46 | 1.51 | 1.54 | 1.21 | 1.00 | 1.19 |
| Treatment Plant | 4.78 | 2.29 | 2.46 | 1.57 | 1.00 | 1.51 |
| Receiving Water | 2.94 | 1.67 | 1.73 | 1.29 | 1.00 | 1.26 |
| Ground Water Pollution | 1.11 | 1.05 | 1.21 | 1.12 | 1.32 | 1.12 |
| Soil Pollution | 1.25 | 1.12 | 1.48 | 1.27 | 1.72 | 1.29 |
| Objects Threat | 1.20 | 1.10 | 1.41 | 1.22 | 1.61 | 1.24 |

Having determined the net share of the single scenarios by the Dutch experts, it is now possible to cumulate the average environmental impacts as it is done with Figure 34. The light coloured columns are representing as before the various impacts whereas the strong coloured columns are showing the aggregated average environmental impact cause by in-/ exfiltrating sewer systems.

Network operators tend to see especially impacts on the treatment plant, sewer stability and the receiving water most critical of all the impacts. As impacts on the ground water level are rated ambivalent (tight systems may increase the groundwater level and cause damage to objects) these factors are at the time the dominating impacts caused by in/exfiltration as clearly visible from Figure 34.

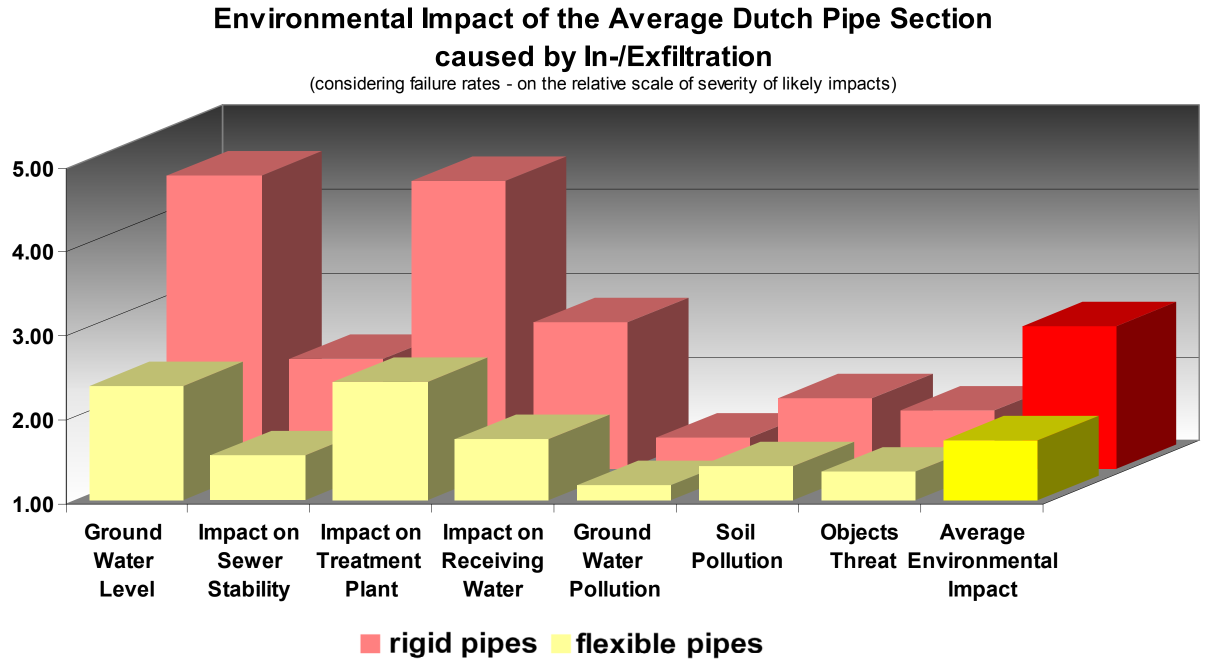


**Figure 34: Environmental Impact of the average failure causing In-/Exfiltration within the relative scope of likely impact severity - considering failure rates and aggregating scenario results according to net share**

**Table 23: Average Dutch Environmental Impact caused by In-/Exfiltration within the relative scope of likely impact severity - considering failure rates and aggregating scenario results according to net share**

| | Netherlands | |
|---|---|---|
| | Rigid | Flexible |
| Ground Water Level | 4.49 | 2.36 |
| Sewer Stability | 2.30 | 1.54 |
| Treatment Plant | 4.44 | 2.42 |
| Receiving Water | 2.75 | 1.73 |
| Ground Water Pollution | 1.37 | 1.18 |
| Soil Pollution | 1.84 | 1.41 |
| Objects Threat | 1.70 | 1.34 |
| Average Environmental Impact by In-/Exfiltration | 2.70 | 1.71 |

# 7 Swedish results

## 7.1 Data analysis

The following data and figures have been distributed from Swedish project partners. The results reveal some interesting aspects of the analyzed pipe material groups. To ensure interoperability and comparability to other European data, all Swedish inspection data has been translated to the EN 13508 code system. The Swedish defect indications within the protocols were mainly plaintext descriptions instead of a code system, which eased the translation into the EN code.

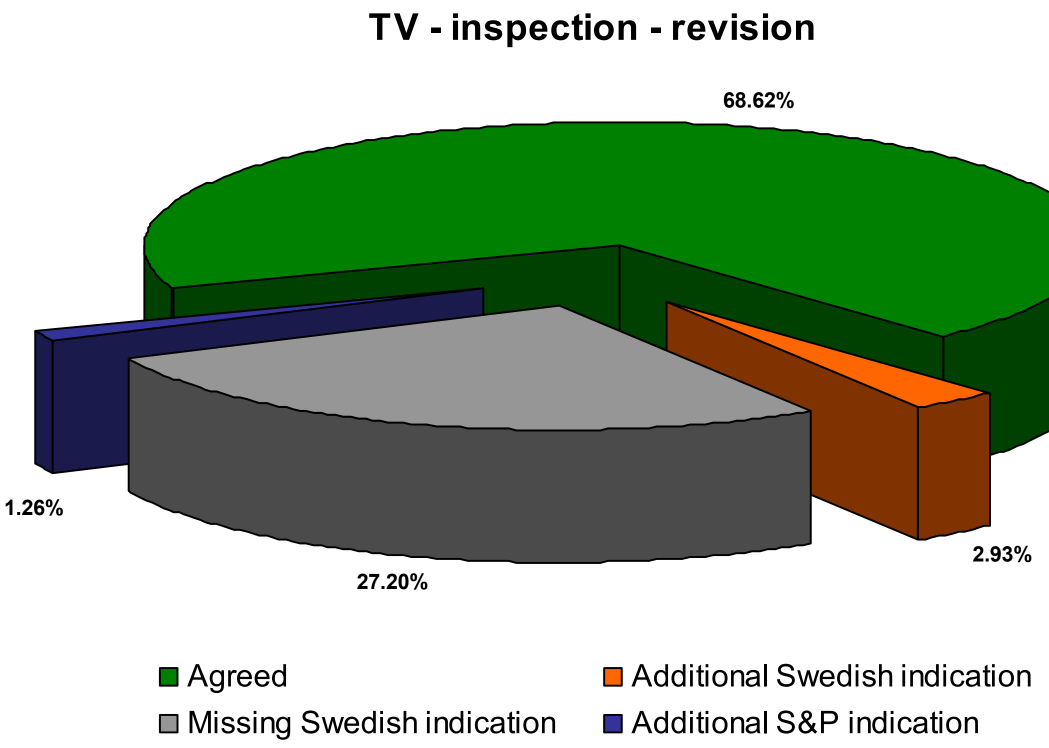


**Figure 35: Result of the revision of the Swedish TV-inspections**

To ensure comparability the inspection data has been revised additionally to determine the difference in defect assessment. As Figure 35 shows, there is a significant level of congruence, due to the fact that the main differences in indication come from indications just missing in the protocols as Swedish protocols are sometimes summary protocols indicating only the number of failures found per sections and not listing the defect indications in detail. As the details are necessary for the data analysis these lacking protocols had to be completed by the TV-revision causing the high percentage of missing indications. Within this group of not recorded failures lays the dark figure of indications truly not or not correctly seen indication. The true differences in defect assessment are with almost 3 % rather small.

In Figure 36 the percentage of the defective sections according to the type of defect is shown. As a sewer section can have different types of defect, the accumulation of all shares of one material group may be more then 100 %.

The data is calculated by

$$\frac{\sum \text{Length of all sewers with defects}}{\sum \text{Length of all sewers}}$$

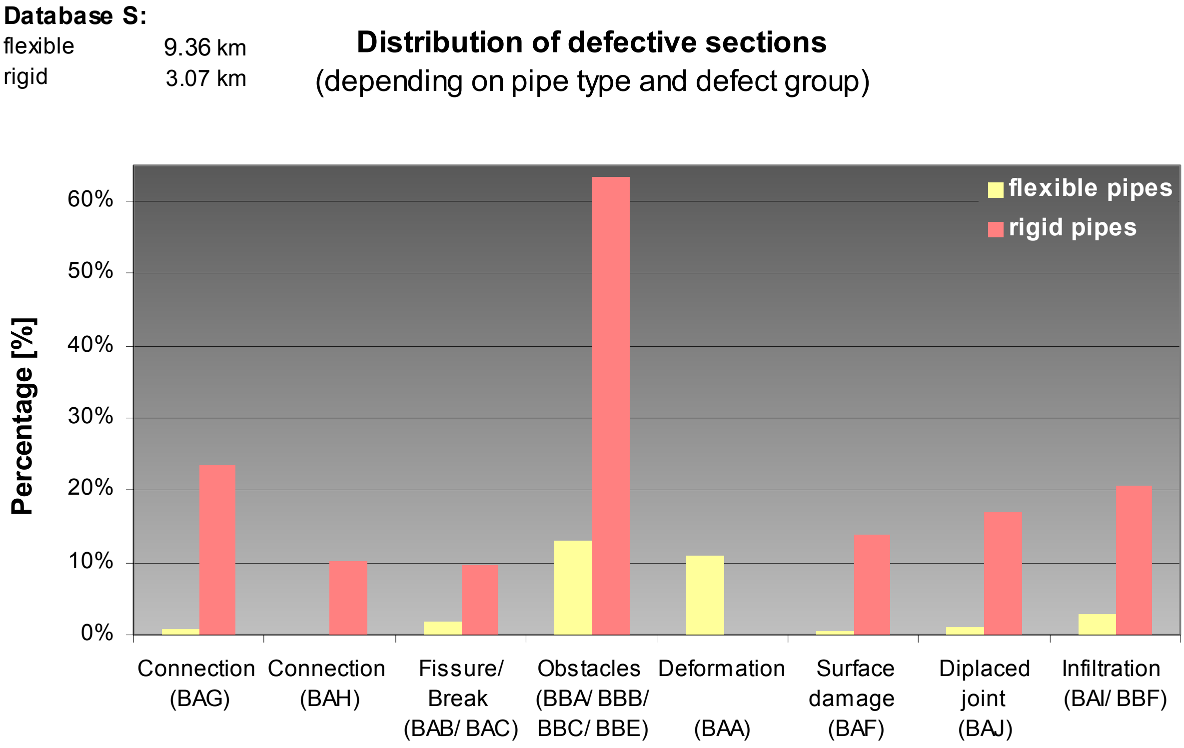


**Figure 36: Distribution of defective sections according to the defect type**

According to the Swedish expert Mr. Sevensson the high share of obstacles, which were mainly sedimentation problems from paper, are not typical for Swedish sewer systems.

The following Figure 37 and the related table illustrate the average number of defects per kilometer in relation to material and defect type, which has been calculated by:

$$\frac{\sum \text{Number of all defects (type / material)}}{\sum \text{Length of all sewers (type / material)}}$$

Table 24: Data - Distribution of defective sections according to the defect type

| Data for Figure 36 | | Material | |
|---|---|---|---|
| | | **Rigid pipes** | **Flexible pipes** |
| **Defect Type** | Intruding connection (BAG) | 23.6% | 0.9% |
| | Defective connection (BAH) | 10.2% | 0.0% |
| | Fissure/ Break (BAB/ BAC) | 9.7% | 1.9% |
| | Obstacles (BBA/ BBB/ BBC/ BBE) | 63.4% | 13.0% |
| | Deformation (BAA) | 0.0% | 11.0% |
| | Surface damage (BAF) | 13.9% | 0.5% |
| | Displaced joint (BAJ) | 16.9% | 1.1% |
| | Infiltration (BAI/ BBF) | 20.7% | 2.8% |

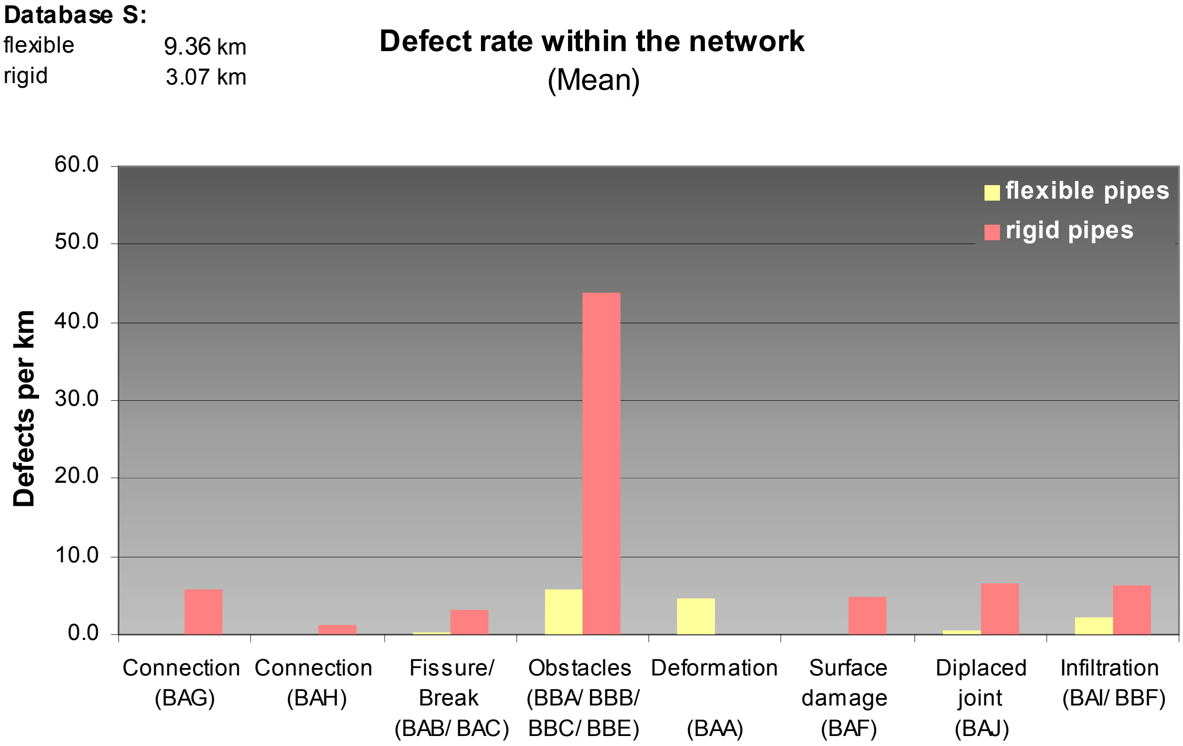


Figure 37: Defect Rate within the Network - Mean of the Network

Table 25: Data - Defect Rate within the Network - Mean of the Network

| **Data to Figure 37** | | **Material** | |
|---|---|---|---|
| | | **Rigid pipes** | **Flexible pipes** |
| **Defect Type** | Intruding connection (BAG) | 5.9 def./km | 0.1 def./km |
| | Defective connection (BAH) | 1.3 def./km | 0.0 def./km |
| | Fissure/ Break (BAB/ BAC) | 3.3 def./km | 0.3 def./km |
| | Obstacles (BBA/ BBB/ BBC/ BBE) | 43.7 def./km | 5.9 def./km |
| | Deformation (BAA) | 0.0 def./km | 4.5 def./km |
| | Surface damage (BAF) | 4.9 def./km | 0.1 def./km |
| | Displaced joint (BAJ) | 6.5 def./km | 0.4 def./km |
| | Infiltration (BAI/ BBF) | 6.2 def./km | 2.1 def./km |

Another interesting view is putting the number of defects in relation to the length of the defective part of the network by:

$$\frac{\sum \text{Number of all defects (type / material)}}{\sum \text{Length of all sewers with defects (type / material)}} \cdot 100\text{m}$$

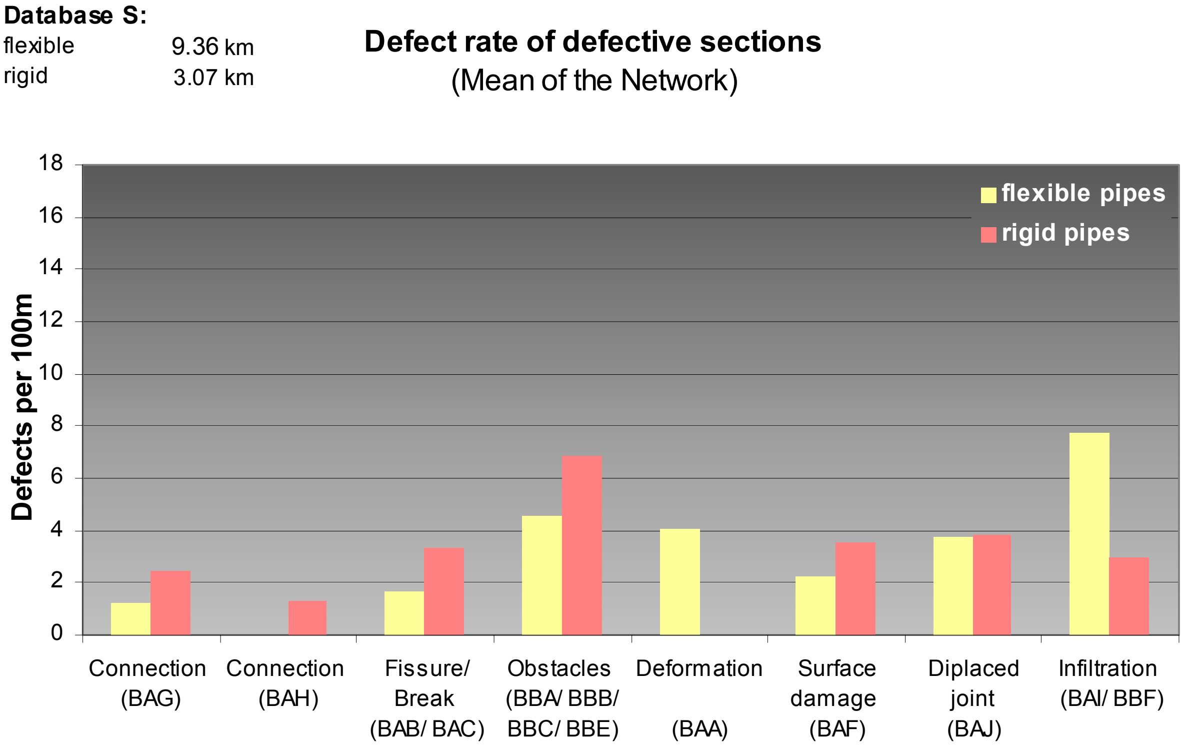


Figure 38: Mean Defect Rate of Defective Sections

Table 26: Data - Mean Defect Rate of Defective Sections

| Data to Figure 38 | | Material | |
|---|---|---|---|
| | | Rigid pipes | Flexible pipes |
| Defect Type | Intruding connection (BAG) | 2.5 def./100m | 1.2 def./100m |
| | Defective connection (BAH) | 1.3 def./100m | |
| | Fissure/ Break (BAB/ BAC) | 3.4 def./100m | 1.7 def./100m |
| | Obstacles (BBA/ BBB/ BBC/ BBE) | 6.9 def./100m | 4.5 def./100m |
| | Deformation (BAA) | | 4.1 def./100m |
| | Surface damage (BAF) | 3.5 def./100m | 2.2 def./100m |
| | Displaced joint (BAJ) | 3.9 def./100m | 3.7 def./100m |
| | Infiltration (BAI/ BBF) | 3.0 def./100m | 7.7 def./100m |

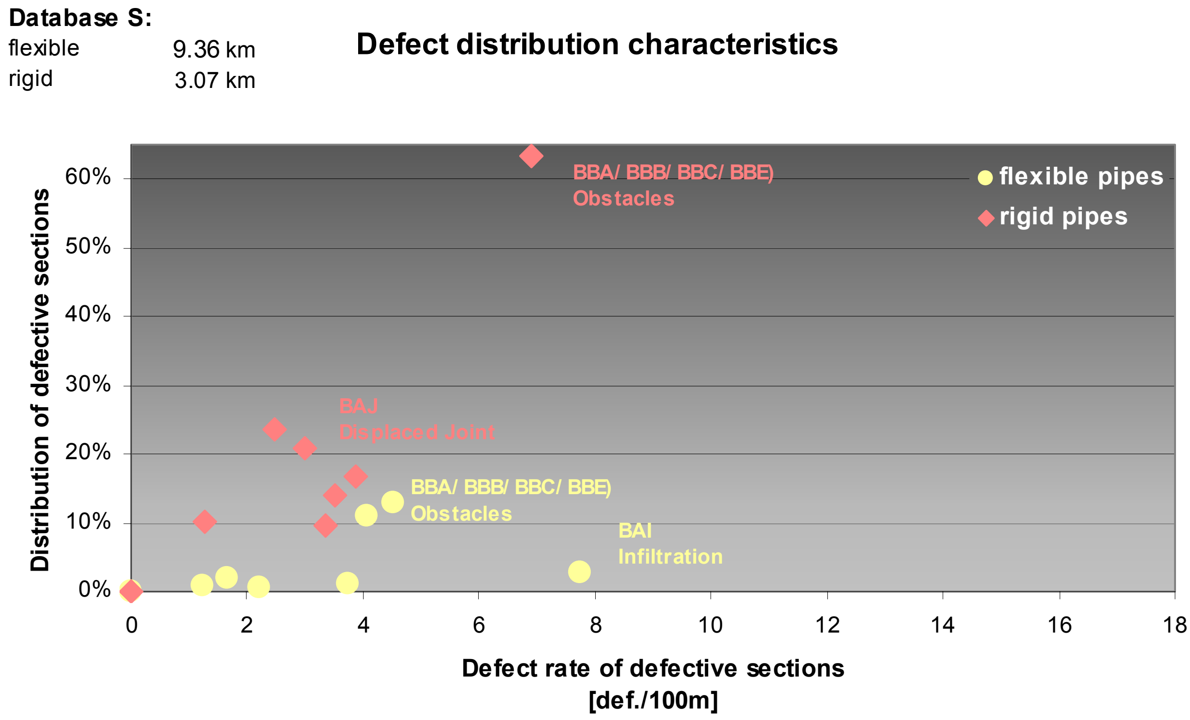


**Figure 39: Relation between defect distribution and defect rate**

At Figure 39 the relation between defect distribution and defect rate is shown.

## 7.2 Model results

For Sweden, the scenarios, defined by Swedish experts and displayed at Table 27, were processed by the model. As the Swedish data base for the modelling was to small, the German data was adapted for Sweden. Thus, direct comparison of the sensitivity of the ancillary conditions for the three Swedish scenarios with the other European scenarios is possible.

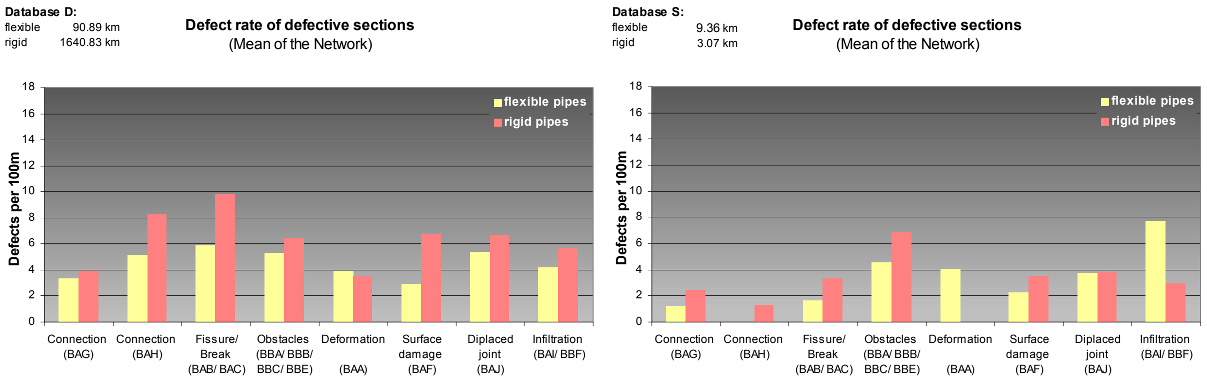


**Figure 40: Comparison of German and Swedish defect rates**

The detailed consideration regarding the adaptation of German date, as they were made for the Netherlands at chapter 6.2, were carried out for the Swedish modelling too.

**Table 27: Scenario definitions for Sweden**

| Scenario | Sewage level | | Soil permeability | | GW – level | |
|---|---|---|---|---|---|---|
| Nr. 1 | MODE<br>SPAN | Closer to axis<br>Invert – axis | MODE<br>SPAN | Medium<br>v.low – medium | MODE<br>SPAN | Axis<br>b.invert – a.crown |
| Nr. 2 | MODE<br>SPAN | Closer to axis<br>Invert – axis | MODE<br>SPAN | v.low | MODE<br>SPAN | Invert<br>a.crown (15%) |
| Nr. 3 | MODE<br>SPAN | Closer to axis<br>Invert – axis | MODE<br>SPAN | Closer to low<br>Low – medium | MODE<br>SPAN | Far below pipe invert |

The results according to Figure 9 are shown at Table 36. As explained before they are shown on the total scale of possible impacts.

It is obvious that the various scenarios defined lead to results, which are significantly different. It shows the importance of consideration of the various ancillary conditions.

To determine the true differences in environmental impact of a network of rigid or flexible pipes it is necessary to relate the model results, which are basing on the average defect of the material group, to the average network defect rates by scaling them with the normalized defect rates of Table 29 which causes the impacts to drop dramatically for the flexible pipes. At Figure 41 this is shown on the absolute scale and at Figure 42 it is shown on the relative scale of environmental impacts caused by in-/ exfiltration.

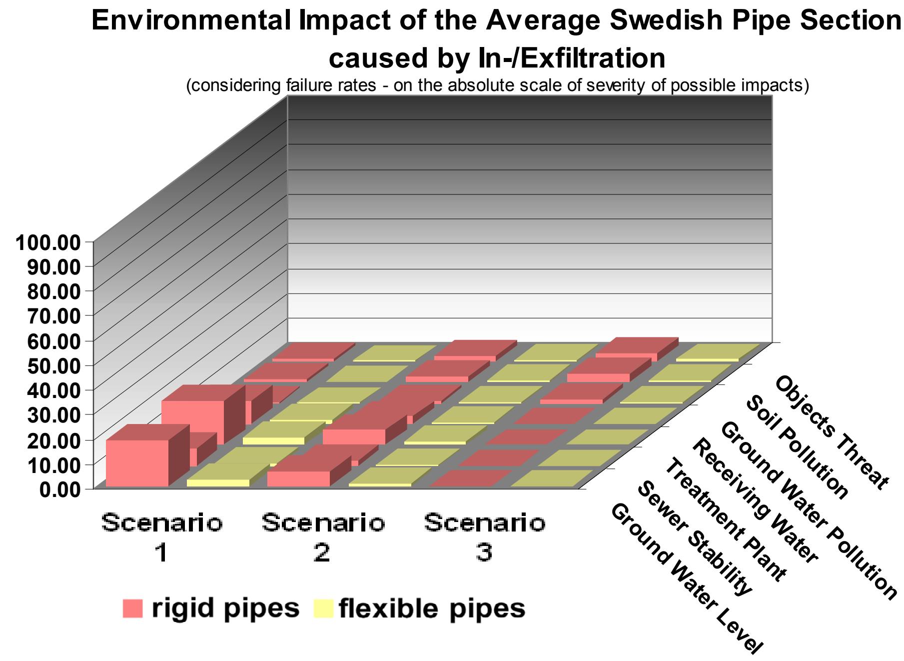


**Figure 41: Environmental Impact of the average failure causing In-/Exfiltration within the total scope of possible impact severity - considering failure rates**

It is obvious that flexible pipes perform better regarding their environmental impacts caused by in-/ exfiltration. The average defect is less leaky for flexible pipes then for rigid and additional the frequency of occurrence is lower for the flexible pipe systems as it is shown at Table 29.

**Table 28: Environmental Impact of the average failure causing In-/Exfiltration within the total scope of possible impact severity - considering failure rates**

|  | Sweden 1 |  | Sweden 2 |  | Sweden 3 |  |
|---|---|---|---|---|---|---|
|  | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible |
| Ground Water Level | 18.8 | 2.9 | 6.1 | 1.1 | 0.0 | 0.0 |
| Sewer Stability | 6.9 | 1.1 | 2.2 | 0.4 | 0.0 | 0.0 |
| Treatment Plant | 17.8 | 2.9 | 6.0 | 1.2 | 0.0 | 0.0 |
| Receiving Water | 9.2 | 1.5 | 3.0 | 0.6 | 0.0 | 0.0 |
| Ground Water Pollution | 0.5 | 0.1 | 1.1 | 0.3 | 1.6 | 0.4 |
| Soil Pollution | 1.2 | 0.3 | 2.3 | 0.6 | 3.6 | 0.9 |
| Objects Threat | 1.0 | 0.2 | 2.0 | 0.5 | 3.0 | 0.8 |

**Table 29: Result scaling**

| **Pipe type** | **Average defect rates** | **Normalized defect rates** |
|---|---|---|
| **Flexible pipes** | 13.46 defects per km | 0.19 |
| **Rigid pipes** | 71.74 defects per km | 1 |

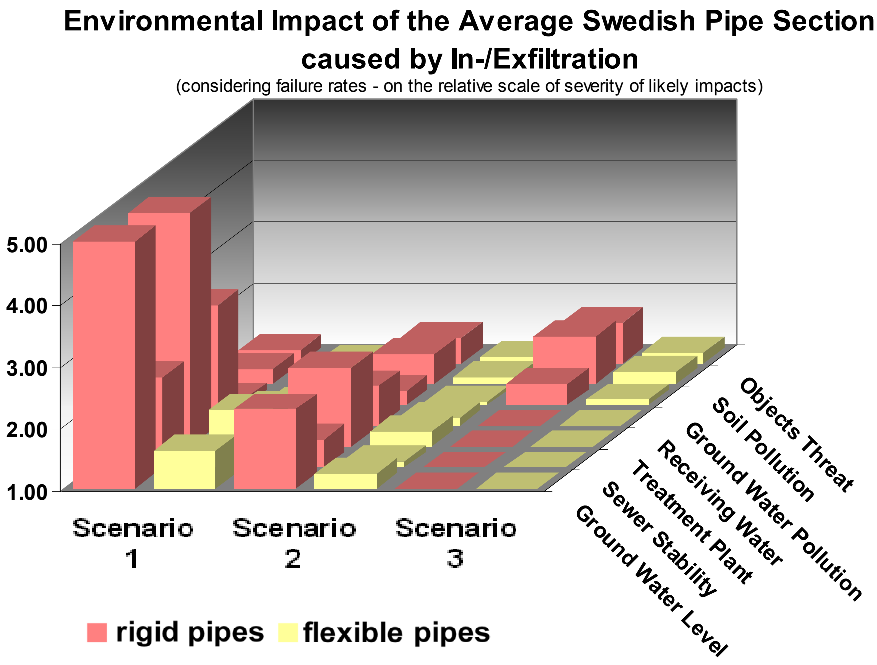


**Figure 42: Environmental Impact of the average failure causing In-/Exfiltration within the relative scope of likely impact severity - considering failure rates**

The relation of difference between flexible and rigid pipe systems within the single scenarios remains almost equal, as the ancillary conditions are the dominating factors for determining this difference.

**Table 30: Environmental Impact of the average failure causing In-/Exfiltration within the relative scope of likely impact severity - considering failure rates**

| | Sweden 1 | | Sweden 2 | | Sweden 3 | |
|---|---|---|---|---|---|---|
| | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible |
| Ground Water Level | 5.00 | 1.61 | 2.29 | 1.24 | 1.00 | 1.00 |
| Sewer Stability | 2.47 | 1.24 | 1.46 | 1.09 | 1.00 | 1.00 |
| Treatment Plant | 4.79 | 1.61 | 2.28 | 1.25 | 1.00 | 1.00 |
| Receiving Water | 2.95 | 1.31 | 1.64 | 1.13 | 1.00 | 1.00 |
| Ground Water Pollution | 1.11 | 1.03 | 1.22 | 1.05 | 1.34 | 1.09 |
| Soil Pollution | 1.25 | 1.06 | 1.49 | 1.12 | 1.77 | 1.20 |
| Objects Threat | 1.21 | 1.05 | 1.42 | 1.10 | 1.65 | 1.16 |

Having determined the net share of the single scenarios by the Swedish experts, it is now possible to cumulate the average environmental impacts as it is done with Figure 43. The light coloured columns are representing as before the various impacts whereas the strong coloured columns are showing the aggregated average environmental impact cause by in-/ exfiltrating sewer systems.

Network operators tend to see especially impacts on the treatment plant, sewer stability and the receiving water most critical of all the impacts. As impacts on the ground water level are rated ambivalent (tight systems may increase the groundwater level and cause damage to objects) these factors are at the time the dominating impacts caused by in/exfiltration as clearly visible from Figure 43.

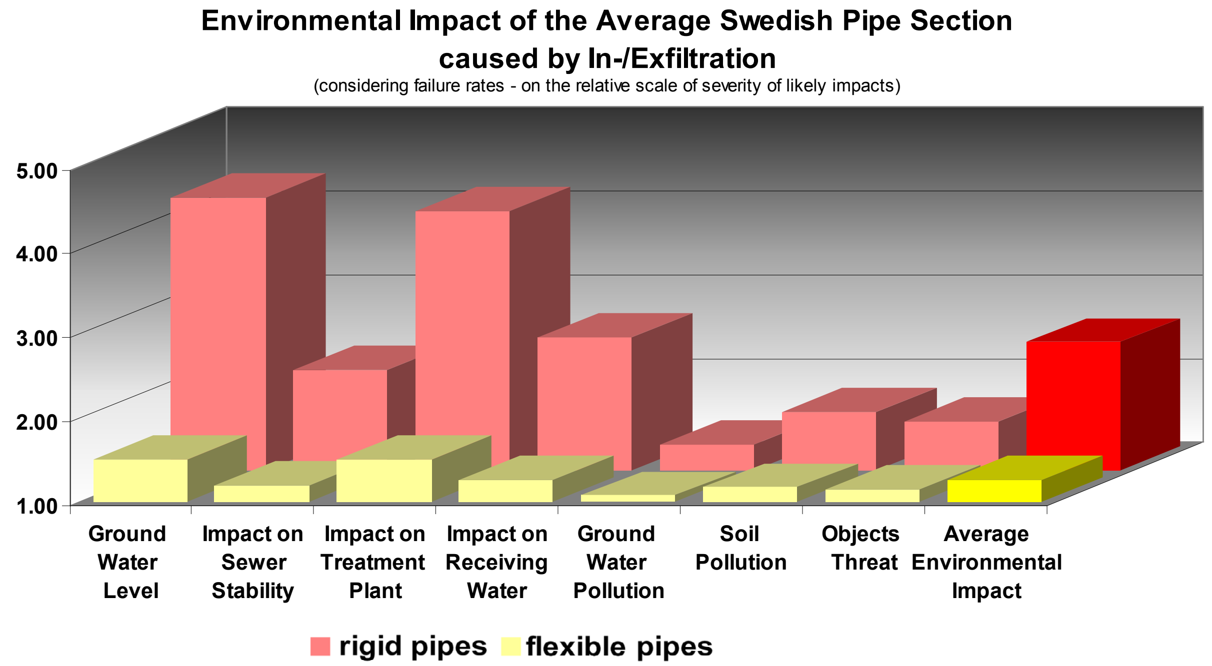


**Figure 43: Average Swedish Environmental Impact caused by In-/Exfiltration within the relative scope of likely impact severity - considering failure rates and aggregating scenario results according to net share**

**Table 31: Average Swedish Environmental Impact caused by In-/Exfiltration within the relative scope of likely impact severity - considering failure rates and aggregating scenario results according to net share**

| | Sweden | |
|---|---|---|
| | Rigid | Flexible |
| Ground Water Level | 4.25 | 1.51 |
| Sewer Stability | 2.19 | 1.20 |
| Treatment Plant | 4.09 | 1.50 |
| Receiving Water | 2.59 | 1.26 |
| Ground Water Pollution | 1.31 | 1.08 |
| Soil Pollution | 1.69 | 1.17 |
| Objects Threat | 1.59 | 1.15 |
| Average Environmental Impact by In-/Exfiltration | 2.53 | 1.27 |

# 8 Conclusion

Although it is rather difficult to determine environmental impacts of drain and sewer systems in general, “STATUS Sewer” and its specific models for environmental issues of sewer systems used as approach in this study gives for the first time acceptable results to compare the environmental impact of flexible and rigid pipe systems caused by their in-/ exfiltration.

Due to the general approach used, in order to draw a conclusion for the pipe systems in general, it is clear, that the results do not reflect the situation of a specific local sewer network, which would require to carry out this approach on this specific local data stock. The findings should be seen as a acceptable indicator for the environmental performance of the pipe systems analysed.

Accepting that – due to different circumstances such as installation problems, material deficiencies and many more – all sewer systems do leak, the question to answer was, which pipe systems promise better performance regarding the leakage problems. These problems are the main environmental issues during service life. As the analysis of the operational period was the aim of the project, it concentrated on the dominating issues infiltration and exfiltration, causing the major environmental impact of such systems in this particular period.

An important point to be noted for the weighing of the different impacts is the fact that almost all environmental effects caused during operation are local impacts, affecting directly the customers of the network operator.

In the result of this investigation given, the following core statements in regard to the analysis data restrictions mentioned (e.g. age limit 30 years, internal diameter not bigger than 800 mm etc.) can be made in summary:

- The environmental impact of the average section caused by in- or exfiltration for flexible pipe systems is 15 %  (less then one-sixth) of that for existing rigid pipe systems. Especially in scenarios with sensitive ancillary conditions flexible pipes show a better environmental performance to rigid pipe systems.

- Considering the number of defects in reference to the installed length of all sewers of this particular material groups analysed in this study, flexible pipe systems have on average just 20 % (one fifth) of the defect rates of rigid pipe systems.

- When considering the number of defects in reference to the installed length of sewers of this particular material, defect rates of flexible pipe systems are on average of 25 % (one quarter) of the defect rates of rigid systems significantly lower for defect types that are the main causes for infiltration and exfiltration such as BAB (Fissures), BAC (Break/ Collapse) or BAH (Defective connection).

As a summary, this study can deduce that, based on the statistical analysis of the gathered data pool and the modelling of the impact caused by in-/exfiltration, sewer system of flexible pipes show a significant better environmental performance regarding infiltration and exfiltration, due to lower defect rates and defect risks. Apart from this main research result, the study has shown again, that improper installation quality as well as impermanent monitoring and missing quality control leads to significant higher defect indications, which does multiply the defect rates.

**Additional country specific conclusion**

Although the Dutch and Swedish databases are relatively small and may not draw a perfect picture of the countries sewage systems they still give an acceptable overview on the country specific situation. Nevertheless, the results from the data analysis show clearly the impact of different inspection strategies, which is for the Netherlands primarily driven by the request of the network operators and not – like in Germany – by laws and regulations. This finally causes significant higher defect rates for the inspected sections, as only sections with defects serious enough to cause an inspection call by the operators are recorded. Additionally the missing practice of TV-based acceptance protocols for the construction works encourages defects caused by deficient construction work and as a consequence higher defect rates.

The relatively small Swedish database consists of a large number of short sections from various conditions for both rigid and flexible pipes. This sample selection made the data more representative for Swedish conditions than if the tapes had been chosen from a limited number of sections. The database can of course not be taken as the Swedish situation in general but gives however a good glimpse of the Swedish conditions.

Bochum, August 2005
Dipl.-Ing Robert Stein
(Prof. Dr.-Ing. Stein & Partner GmbH)

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# Annex

**Table 32: Environmental Impact of the average German failure causing In-/Exfiltration within the total scope of possible impact severity**

| | Germany 1 | | Germany 2 | | Germany 3 | | Germany 4 | | Germany 5 | | Germany 6 | | Germany 7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible |
| Ground Water Level | 19.3 | 15.9 | 15.1 | 12.3 | 2.4 | 2.0 | 14.0 | 11.4 | 3.9 | 3.2 | 1.1 | 0.8 | 4.2 | 3.5 |
| Sewer Stability | 8.6 | 7.6 | 9.2 | 7.9 | 1.4 | 1.2 | 8.5 | 7.2 | 2.3 | 2.0 | 0.7 | 0.6 | 2.6 | 2.3 |
| Treatment Plant | 20.6 | 17.7 | 18.5 | 15.4 | 2.9 | 2.5 | 17.0 | 14.1 | 4.6 | 3.9 | 1.2 | 0.9 | 4.4 | 3.7 |
| Receiving Water | 11.0 | 9.5 | 10.8 | 9.1 | 1.7 | 1.4 | 9.9 | 8.4 | 2.7 | 2.3 | 0.6 | 0.5 | 2.1 | 1.8 |
| Ground Water Pollution | 0.5 | 0.6 | 0.3 | 0.4 | 0.6 | 0.9 | 0.6 | 0.7 | 1.4 | 1.7 | 0.5 | 0.6 | 2.1 | 2.5 |
| Soil Pollution | 1.1 | 1.4 | 0.9 | 1.3 | 1.7 | 2.4 | 1.8 | 2.0 | 4.3 | 5.0 | 1.1 | 1.2 | 4.2 | 4.8 |
| Objects Threat | 0.9 | 1.1 | 0.6 | 0.9 | 1.2 | 1.8 | 1.1 | 1.3 | 2.8 | 3.4 | 1.1 | 1.2 | 4.2 | 4.8 |

**Table 33: Environmental Impact of the average German failure causing In-/Exfiltration within the relative scope of likely impact severity**

| | Germany 1 | | Germany 2 | | Germany 3 | | Germany 4 | | Germany 5 | | Germany 6 | | Germany 7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible |
| Ground Water Level | 4.74 | 4.09 | 3.93 | 3.39 | 1.47 | 1.40 | 3.71 | 3.22 | 1.75 | 1.62 | 1.21 | 1.16 | 1.81 | 1.67 |
| Sewer Stability | 2.68 | 2.47 | 2.79 | 2.52 | 1.27 | 1.24 | 2.65 | 2.39 | 1.45 | 1.39 | 1.14 | 1.11 | 1.51 | 1.44 |
| Treatment Plant | 5.00 | 4.44 | 4.59 | 3.99 | 1.56 | 1.48 | 4.29 | 3.73 | 1.90 | 1.76 | 1.23 | 1.18 | 1.85 | 1.73 |
| Receiving Water | 3.13 | 2.83 | 3.09 | 2.77 | 1.32 | 1.28 | 2.92 | 2.63 | 1.53 | 1.45 | 1.11 | 1.09 | 1.40 | 1.35 |
| Ground Water Pollution | 1.09 | 1.12 | 1.06 | 1.09 | 1.12 | 1.17 | 1.11 | 1.13 | 1.28 | 1.33 | 1.11 | 1.11 | 1.42 | 1.48 |
| Soil Pollution | 1.21 | 1.27 | 1.18 | 1.25 | 1.33 | 1.47 | 1.34 | 1.38 | 1.83 | 1.96 | 1.21 | 1.23 | 1.81 | 1.94 |
| Objects Threat | 1.17 | 1.22 | 1.12 | 1.18 | 1.23 | 1.34 | 1.22 | 1.25 | 1.55 | 1.66 | 1.21 | 1.22 | 1.81 | 1.93 |

**Table 34: Environmental Impact of the average failure causing In-/Exfiltration within the total scope of possible impact severity**

| | Netherlands 1 | | Netherlands 2 | | Netherlands 3 | |
|---|---|---|---|---|---|---|
| | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible |
| Ground Water Level | 19.5 | 15.4 | 6.7 | 6.1 | 0.0 | 5.5 |
| Sewer Stability | 7.1 | 6.0 | 2.6 | 2.5 | 0.0 | 2.2 |
| Treatment Plant | 18.4 | 15.3 | 7.1 | 6.7 | 0.0 | 6.0 |
| Receiving Water | 9.4 | 7.9 | 3.6 | 3.4 | 0.0 | 3.1 |
| Ground Water Pollution | 0.5 | 0.6 | 1.0 | 1.4 | 1.5 | 1.5 |
| Soil Pollution | 1.2 | 1.4 | 2.4 | 3.2 | 3.5 | 3.4 |
| Objects Threat | 1.0 | 1.2 | 2.0 | 2.7 | 3.0 | 2.9 |

**Table 35: Environmental Impact of the average failure causing In-/Exfiltration within the relative scope of likely impact severity**

| | Netherlands 1 | | Netherlands 2 | | Netherlands 3 | |
|---|---|---|---|---|---|---|
| | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible |
| Ground Water Level | 5.00 | 4.17 | 2.38 | 2.25 | 1.00 | 2.12 |
| Sewer Stability | 2.46 | 2.24 | 1.54 | 1.51 | 1.00 | 1.46 |
| Treatment Plant | 4.78 | 4.15 | 2.46 | 2.38 | 1.00 | 2.24 |
| Receiving Water | 2.94 | 2.63 | 1.73 | 1.70 | 1.00 | 1.63 |
| Ground Water Pollution | 1.11 | 1.13 | 1.21 | 1.28 | 1.32 | 1.30 |
| Soil Pollution | 1.25 | 1.29 | 1.48 | 1.65 | 1.72 | 1.70 |
| Objects Threat | 1.20 | 1.24 | 1.41 | 1.54 | 1.61 | 1.59 |

**Table 36: Environmental Impact of the average failure causing In-/Exfiltration within the total scope of possible impact severity**

| | Sweden 1 | | Sweden 2 | | Sweden 3 | |
|---|---|---|---|---|---|---|
| | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible |
| Ground Water Level | 18.8 | 15.2 | 6.1 | 5.9 | 0.0 | 0.0 |
| Sewer Stability | 6.9 | 5.9 | 2.2 | 2.3 | 0.0 | 0.0 |
| Treatment Plant | 17.8 | 15.0 | 6.0 | 6.1 | 0.0 | 0.0 |
| Receiving Water | 9.2 | 7.8 | 3.0 | 3.1 | 0.0 | 0.0 |

| | Sweden 1 | | Sweden 2 | | Sweden 3 | |
|---|---|---|---|---|---|---|
| | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible |
| Ground Water Pollution | 0.5 | 0.7 | 1.1 | 1.4 | 1.6 | 2.1 |
| Soil Pollution | 1.2 | 1.5 | 2.3 | 2.9 | 3.6 | 4.8 |
| Objects Threat | 1.0 | 1.2 | 2.0 | 2.5 | 3.0 | 4.0 |

**Table 37: Environmental Impact of the average failure causing In-/Exfiltration within the relative scope of likely impact severity**

| | Sweden 1 | | Sweden 2 | | Sweden 3 | |
|---|---|---|---|---|---|---|
| | Rigid | Flexible | Rigid | Flexible | Rigid | Flexible |
| Ground Water Level | 5.00 | 4.23 | 2.29 | 2.26 | 1.00 | 1.00 |
| Sewer Stability | 2.47 | 2.26 | 1.46 | 1.48 | 1.00 | 1.00 |
| Treatment Plant | 4.79 | 4.19 | 2.28 | 2.30 | 1.00 | 1.00 |
| Receiving Water | 2.95 | 2.65 | 1.64 | 1.66 | 1.00 | 1.00 |
| Ground Water Pollution | 1.11 | 1.14 | 1.22 | 1.29 | 1.34 | 1.45 |
| Soil Pollution | 1.25 | 1.32 | 1.49 | 1.62 | 1.77 | 2.03 |
| Objects Threat | 1.21 | 1.26 | 1.42 | 1.52 | 1.65 | 1.86 |