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Sealing of sewer pipes – Effects on the purification performance of wastewater treatment plants and their impact on the local water balance

Summary

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Sealing of sewer pipes – Effects on the purification performance of wastewater treatment plants and their impact on the local water balance

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Abstract

Leaking sewers in public wastewater disposal networks and land drainage systems can cause varying degrees of problems, depending on local conditions, resulting from the infiltration of groundwater, stratum water or percolating water. In combined sewer systems, this can result in an increase in combined sewage discharges, leading to an increase in the level of pollution entering water bodies. An increase in the proportion of infiltration water also has a negative effect on the performance of sewage treatment plants.

Rehabilitation of the sewer network is necessary to seal public and private sewage pipes and tunnels and thus effect a significant reduction in the volume of infiltrating water. To take a holistic view, it is not merely the positive effects of reducing the level of extraneous water entering treatment plants and relief structures that are of interest, but also the eco-efficiency of the infiltration water rehabilitation measures themselves that are performed on the sewer network and the consequences of these on the local groundwater balance. The use of energy-intensive techniques or ecologically questionable construction materials in the course of sewer rehabilitation, for example, can also involve environmental risks. Moreover, performing sewer sealing on a large scale creates the danger of groundwater rising to a critical level and putting buildings and vegetation at risk, due to the absence of the drainage effect attributable to leaking sewers.

The aim of the research project is to investigate the benefits, costs and risks associated with the large-scale sealing of leaking sewage pipes and tunnels on the basis of practical examples, to present the findings, and to draw up a list of requirements for sewer rehabilitation.

Summary

1. Background and objective of the research project

Depending on local conditions, leaking sewers in public wastewater disposal networks and land drainage systems may transport a high proportion of extraneous water made up of infiltrated groundwater, stratum water or percolating water. In combined sewer systems, this can lead to an increase in combined sewage discharges and in turn in the level of pollution entering water bodies. An increase in the proportion of infiltration water in combined and sanitary sewers also has a negative effect on the performance of sewage treatment plants. The dilution and cooling of wastewater caused by infiltration water impairs the purification performance of the treatment plant in terms of its ability to eliminate pollutants. It also affects the amount of energy required to power the pumps and treatment facilities.

As a rule, extensive rehabilitation measures are required in the sewage network to seal public or private sewage pipes and tunnels and in turn to significantly reduce the incidence of extraneous water. To take a holistic view, it is however not merely the positive effects of reducing the level of infiltration water entering treatment plants and relief structures that are of interest, but also the eco-efficiency of the infiltration water rehabilitation measures themselves that are performed on the sewer network, and the consequences of these on the local groundwater balance. The actual benefits of large-scale sealing of leaking sewage pipes and tunnels (e.g. reduction in the volume of infiltration water, protection of water bodies and soils) must be weighed up against the costs and risks involved. These may result from the use of energy-intensive techniques or ecologically questionable construction materials in the course of the sewer rehabilitation. Moreover, the use of large-scale sewer sealing in the groundwater results in the risk – due to the absence of the drainage effect of leaking sewers – of groundwater rising to a critical level and putting buildings and vegetation at risk.

The objective of the research project was to draw up proposals for a method of sewer rehabilitation to be used by decision-making bodies as a basis for revising wastewater regulations. For this purpose, the effects that high levels of infiltration water have on the performance of sew-age treatment plants, on the energy balance of treatment plants, and on water pollution caused by combined sewage discharges were described. The effect of infiltration water was weighed up against the cost of renovating public and private sewers. On the basis of specific case studies, the available information relating to eco-efficiency and sustainability of rehabilitation materials and techniques was compiled and – as far as possible – evaluated. Furthermore, possible problems affecting buildings and vegetation caused by the absence of the drainage effect after rehabilitating leaking sewers were also investigated.

In section 3 the background and objective of the project are described in detail. Moreover, in section 3, a comprehensive overview is given regarding the project content, the methods applied, and the institutions involved in the project.

2. Leaking sewers and their effect on the volume of infiltration water

The causes of extraneous water in sewage tunnels and pipes are varied. In addition to infiltration from streams and spring water and the inflow of water from precipitation, it is the infiltration of groundwater into leaking sewer pipes and tunnels that increase the volume of extraneous water.

Hence the rehabilitation of damaged sewer pipes and tunnels is a signficant factor in reducing the volume of infiltration water. To clarify which aspects are relevant and what magnitudes are involved, statistical data and reports on the condition of public and private sewers Germany

were compiled and analysed (see Section 4). Of particular interest are assertions on the overall length and condition of public and private sewers. In this context, available data regarding the age structure and pipe materials was analysed for the purpose of enabling an estimation of the frequency of damage "of relevance to infiltration water" and in turn their relevance to the volume of infiltration water.

The results of the analysis can be summarised as follows:

- Combined and sanitary sewers in Germany represent about 80 % (440,644 km) of the sewerage network, i.e. the infiltration of groundwater into damaged sewers can have a severe impact on the volume of extraneous water. The rehabilitation of sanitary or combined sewage pipelines located in the groundwater or groundwater-fluctuation zone can significantly reduce the volume of infiltration water discharge.
- The length of public stormwater sewers in Germany is 120,937 km (according to Statistisches Bundesamt 2013, page 42). Groundwater is also able to infiltrate leaky storm-water sewers located at groundwater or groundwater-fluctuation level. This results in both a hydraulic and material impact on water bodies (cf. Sections 4.1.1 and 7.1).
- When planning rehabilitation measures to public sewers, private systems must be taken into account, especially when the groundwater level is high. Only by taking a comprehensive view can it be ensured that the groundwater does not enter the sewer as infiltration water through defective private systems once rehabilitation of the public sewer is completed. In this context, it is interesting to note that the total length of private sewers in Germany is two to three times that of the public drainage system.
- Statistics relating to age structure (cf. Section 4.1.2) clearly indicate that the vast majority of sewers are no older than 50 years (68%). With reference to the leak integrity of the sewerage system, the year 1965 is of great significance as the year in which elastomer seals were introduced (Purde, 2006, page 40). Approximately 30 % of all sewers were built before the end of the 1950s. Up to that point, the seals of the pipe joints were created by hand on the building site (e.g. from tar rope with bitumen grout). These have generally become rotten as a result of ageing. It can therefore be assumed that pipes built before the year 1965 will have leaks.
- The predominant pipe materials used in public sewer construction are concrete and stoneware in 2009 and the years before (cf. Section 4.1.3).
- No statements are available relating to the type and frequency of damage occurrences and in turn the penetration of extraneous water on the basis of the pipe materials used.
- The types of damage that might lead to an increased volume of infiltration water and an impact on the local water balance – if the groundwater is at the corresponding level – comprise leaks (5%), fractures (20%), ruptured or collapsed pipes (3%), slipped/jutting connections (20%) and damaged connections (13%) (cf. Section 4.1.4).
- Extraneous water in sewers may originate from several places. In addition to groundwater infiltration through leaking sewer pipes and tunnels, extraneous water can include water from streams and springs as well as precipitation. No statistical analyses of the proportions of the various components in relation to the overall volume of extraneous water are available. The large proportion of damage "of relevance to infiltration water" (60% of all damage determined, cf. Section 4.1.4) with a simultaneous high volume of infiltration water (23% of total sewage volume, cf. Section 4.1.5) does however suggest that a large amount of the extraneous water is attributable to groundwater infiltration through leaking sewers. It can be assumed that a considerable proportion of sanitary sewage pipes and tunnels in Germany are located in the

groundwater or groundwater-fluctuation zone. Statistical investigations for Bavaria (Puhl, 2008, page 30/31) show that about 20% of public combined sewage and sanitary sewage pipes are situated in the groundwater or groundwater-fluctuation zone.

- Private sewer networks have an even higher infiltration potential than public sewers. This is first of all because their total length is between two and three times greater than that of the public sewer network (cf. Section 4.1.1). Furthermore, it is undisputed among experts that the condition of private drainage systems in Germany is poorer than that of public sewers, even if no statistically reliable investigations have been made (Berger/Falk 2009, page 13). It is essential that private systems are included in infiltration water rehabilitation projects because the groundwater level can rise once the drainage effect formerly attributable to leaking public sewers is absent, while infiltration water can still enter the sewerage system via leaky private pipelines.
- There are more than 68,000 stormwater overflows throughout Germany and the volume of infiltration water represents 23% of the total wastewater volume (cf. Section 4.1.5). The professional rehabilitation of leaking sewers and the consequent reduction in infiltration water would play a role in reducing the frequency of discharges from stormwater structures with overflows.

Over the course of the project, the situation relating to extraneous water was analysed and described on the basis of concrete examples – the sewage works of the Town of Billerbeck, the Lake Starnberg Wastewater Organisation (Abwasserverband Starnberger See), and the municipality of Schwanau (cf. Section 4.2). It became clear that the treatment plants operated by the Town of Billerbeck and the Abwasserverband Starnberger See were suitable for further investigation into the effects of infiltration water (cf. Section 6), because extensive information was available regarding the operation of the treatment plants as was infiltration water measurement data. The district of Ottenheim in the municipality of Schwanau was selected for the investigations into the effects of stormwater overflows (cf. Section 7), since extensive data was available.

3. Legal and technical regulations relating to the handling of leaking sewers

There are a number of relevant legislative issues in the context of leaking sewers and drains and their rehabilitation that deal with the construction, operation and maintenance of sewers as well as a number of regulations concerning groundwater protection and management.

Against this background, research was made to locate appropriate legislative regulations on European, Federal and State levels (cf. Section 5.1). Research was also carried out to ascertain the extent to which statements on the subject of "leak integrity" and "interactions between the groundwater level and the drainage effect of leaking sewers/the effects of rehabilitation measures on the local groundwater level" could be found in standards and technical regulations relating to the construction, operation and maintenance of sewage tunnels and pipes. (cf. Section 5.2).

The main objectives of the individual legal regulations are varied and include the protection of surface water bodies, the protection of the quantity and quality of the groundwater, and harmless sewage disposal.

The objective of the EU Water Framework Directive (EWFD) is to achieve good quality status of water bodies in all member states.

The measures programmes planned for the individual river regions are set out in Germany on state level.

Even though the Water Framework Directive contains nothing that is of direct relevance to the subject of sewage disposal, its specifications are nevertheless relevant to wastewater treatment. One of the primary aims of the Directive is to maintain a balance between groundwater abstraction and recharge. The infiltration of groundwater into leaking sewers affects this balance. Hence, it is written in the Federal German brochure on the implementation of the Directive's measures plan that (cf. BMU/UBA 2010, page 61) "...the aim is above all to reduce the quantity of extraneous water percolating into the sewer network through leaks". This will be of particular importance in those areas which are having to adapt to increasing levels of seasonal dryness as a consequence of climate change. Annex I of the EC Directive on the treatment of municipal sewage (Directive 91/271/EWC) also makes reference to the requirement of preventing leaks.

On Federal level, there are regulations that must be observed in both water law (Water Resources Act, WHG) and criminal law (Criminal Code § 324 StGB) in the context of groundwater infiltration and the rehabilitation of leaking sewers. The Water Resources Act does not demand directly that sewers be free of leaks, but compliance with the generally accepted rules of engineering practice[1] is required (cf. Czychowski/Reinhardt 2010, § 60 Rn. with reference to BVerfGE 49, 135), which leaves room for interpretation. The term 'Fremdwasser' (infiltration / extraneous water) is not mentioned in the Water Resources Act.

The term 'Fremdwasser' is not as yet legally regulated (cf. LUBW 2007). Reference can only be made to the problem of extraneous water by way of the ban on the dilution of sewage to comply with permitted pollutant concentrations and by way of the demand to comply with the generally accepted rules of engineering practice in the construction and operation of sewage treatment facilities (cf. LUBW 2007).

Whether infiltration water can be considered sewage in the sense of the WHG is disputed. There are contradictory legal interpretations (e.g. Wellmann/Queitsch/Fröhlich 2010, WHG-Kommentar, § 55 WHG Rz.11 or Fischer 2011, page 1828). According to Nisipeanu/Maus (2007, page 91), infiltration water is by definition "wastewater in the legal sense" and thus sewage. For instance, groundwater that infiltrates the sewer system through leaks becomes sewage when it is collected together with wastewater in dry weather. According to Nisipeanu/Maus (2007, page 324), groundwater, spring water, drainage water and surface water are not themselves wastewater until they have become mixed with wastewater discharges in dry weather and are therefore legally also not sewage. In such cases, the municipal obligation to dispose of sewage does not apply. It can be concluded that the municipality is not obliged, as the operator of the sewer network, to take measures against rising groundwater (e.g. by constructing drainage conduits).

An economic incentive for operators of sewage treatment plants to process as little infiltration water as possible could derive from the Wastewater Levy Act (AbwAG), since a treatment plant's purification performance drops off with lower concentrations of contaminants.

It is possible to exercise an influence on the inflow of extraneous water by way of the dilution ban laid down in the Wastewater Regulations (§ 3 Para. 3 AbwV).

One of the aspects taken up from the Water Framework by the Groundwater Regulations Directive is the requirement to guarantee a sufficient volume of groundwater. However, exemption clauses are possible that create scope for interpretation as to whether, how, to what extent and in what timeframe a sewer requires rehabilitation.

In the Criminal Code, § 324 StGB makes the contamination of water bodies punishable by law. If a municipality is aware of leaking sewers that are contaminating the groundwater, it must

1 'Allgemein anerkannte Regeln der Technik' ('generally recognised rules of engineering practice') are, according to Czychowski/Reinhardt 2010, the principles and solutions that have been tested, have proven themselves in practice and have become accepted among the majority of experts active in the respective technical field.

be established whether the non-action on the part of those working on their behalf is a criminal offence. However, as a rule, it will most probably be very difficult to prove the causalities and culpability.

State regulations vary in terms of their depth of detail. Almost all of them require that sewage treatment plants be functioning properly and operationally safe and that they are built and operated in accordance with the generally accepted rules of engineering and on the basis of optimum technical knowledge, whereby the well-being of the public must not be impaired. In individual cases, the states act on the regulations from the EC Urban Wastewater Treatment Directive stating that leakages must be avoided.

Standards and technical regulations should be taken as recommendations and technical suggestions. The majority of normative regulations concerning the construction, operation and repair of sewers and sewage pipelines can be found in the publications of the German Institute for Standardisation (DIN) and the German Association for Water Management, Sewage and Waste (DWA). The leak integrity of underground pipelines is a requirement made at several points throughout these publications.

The requirements concerning the treatment of 'infiltration/extraneous water' is discussed only marginally in the DIN and DWA publications.

In contrast to legal regulations, technical regulations additionally consider the interactions between the groundwater and the drainage effect of leaking sewers/the effects of rehabilitation measures on the local groundwater level. The DWA pamphlet DWA-M 182 "Infiltration water in drainage systems outside buildings" mentions possible conflicts of use and stresses the need to take a holistic view: "Therefore, before performing large-scale sewer rehabilitation, an appraisal should be made of the effects that sealing a sewer network will have on the groundwater body. The rehabilitation plan must take into account the drainage effect of a sewer network under heavy influence from infiltration water, to avoid any possible damaging effects of rehabilitation."
There is no uniform definition in Germany of the term "Fremdwasser" ("infiltration/extraneous water"). In coordination with the Umweltbundesamt (Federal Environment Agency), a definition was taken as a basis for this report that was devised in conjunction with the research project "Umgang mit Dränagewasser von privaten Grundstücken" ("Handling Drainage Water from Private Properties") (Bosseler/Dyrbusch 2012, page 54) and which is essentially based on the definition from the pamphlet DWA-M 182 (cf. DWA-M 182, page 9):

"Extraneous water is water that flows into a sewage treatment system, the characteristics of which have neither been modified through domestic, industrial, agricultural or other use, nor has it been collected and duly fed into the system from precipitation onto built-up or paved areas. Due to its quality, extraneous water requires no sewage treatment, but it hinders and unduly encumbers treatment plants due to its quantity, and is undesirable from the point of view of water body conservation. Extraneous water may, for example, be groundwater that infiltrates the sewer via leaking pipelines or shafts or else drainage water that is fed illicitly into the sanitary sewer."

In conclusion, it can be established that according to the current legal situation, many responsible bodies are under pressure to minimise infiltration water. Legal and technical frameworks provide partial scope for interpretation. However, legislation provides little backing or orientation to councils in handling rising groundwater levels in the wake of rehabilitation measures. In particular, this concerns both the question of who is responsible for groundwater manage-ment as well as the legal situation as regards the diversion of infiltrating groundwater to avoid negative consequences of sewer sealing (e.g. wetness in buildings caused by a rise in the groundwater). In areas where water management is problematic, it might make sense under defined marginal conditions to incorporate drainage water in the obligation to dispose of sew-age.

The control of groundwater to avoid damaging buildings and vegetation in settlement areas has only been enacted in special cases in Germany. One example of this is the Emscher region. The Emschergenossenschaft ('Emscher Association') has been assigned to perform this task on the basis of the Emscher Association Law (EmscherGG) with regard to the impact of coal mining (§2 des EmscherGG). Subsidence resulting from coal mining has reduced the distance to the groundwater table over wide areas. However, groundwater levels are being maintained at a harmless level through the activities of the Emschergenossenschaft and the non-rehabilitated public and private sewers. Moreover, the sealing of sewers with their formerly drainage impact leads to an increase in groundwater.

4. Effects on treatment plants

The effects of infiltration water on purification performance and both the cost and energy efficiency of treatment plants were identified and evaluated on the basis of two concrete case examples (the Lake Starnberger sewage treatment plant and the Billerbeck sewage treatment plant); these were then compared with information from the relevant technical literature (cf. Section 6).

Investigations in the case example of the Lake Starnberger sewage treatment plant show that the extraneous water content of the sewage impacts on the operation of the wastewater discharge and purification processes and consequently also affects the economic efficiency of the treatment plant's operator, the Lake Starnberg Wastewater Association (Abwasserverband Starnberger See). The average infiltration water content at the Starnberg treatment plant in 2007 was approximately 42 %. The infiltration water which, as unsoiled water, is additionally discharged and treated, primarily results in increased energy consumption, the impact of which is not only directly discernable in terms of cost but also makes itself felt in all other operating costs. The main energy consumers directly affected by the extraneous water content are the pump and lifting systems. Moreover, the extraneous water content of the sewage also affects the purification performance of the Starnberg treatment plant. The higher the extraneous water content, the lower the purification efficiency. Apart from increasing direct costs, it also affects indirect costs such as depreciation, maintenance costs, personnel costs, residue disposal and sewage charges. Only by taking into account all the cost components attributable to extraneous water when calculating direct and indirect energy and operating costs will it be possible to gain a realistic overview and determine the possible savings potential. In the example case of Starnberg, a reduction in the infiltration water content of sewage can lead to considerable savings in energy costs.

As regards the Billerbeck sewage treatment plant, data relating to the infiltration water content in the sewer network was analysed before and after the rehabilitation of a section of the catchment area. The trend shows that once a section of a catchment area has been rehabilitated, the volume of infiltration water is reduced. Furthermore, the evaluated precipitation data for the Billerbeck region was compared with the infiltration water volume in the treatment plant, to enable the relationship between the precipitation events and the increased volume of infiltration water to be modelled. Observations made over a long period (2007 to 2012), point towards a relationship. The infiltration water content at the Billerbeck sewage treatment plant between 2007 and 2011 was on average 65 %.

Overall, annual electricity consumption and specific energy consumption of the Billerbeck sewage treatment plant are considerably lower than at Starnberg. This can be attributed to the differences in the structure, process engineering and modes of operation of the two treatment plants. An analysis of the measurement data shows that when the infiltration water content is higher, the degree of efficiency of COD and nitrogen elimination falls, due to the effects of dilution. In general, it can be stated that infiltration water has an effect on purification performance and energy consumption at the Billerbeck sewage treatment plant.

The potential energy savings resulting from reducing infiltration water essentially depends on the proportion of extraneous water and the general energy conditions as well as the size of the treatment facility. In general, specific electricity consumption drops significantly the larger the treatment plant is. With small to medium specific sewage volumes, the impact on electricity consumption is only slight (DWA, 2012, page 3). If the specific wastewater volume increases to more than 20 m^3/(EW*a), then there is a clear impact on electricity consumption. High specific wastewater volumes result from a larger volume of extraneous water and the stormwater run-off also treated in the combined system at the sewage treatment plants (DWA, 2012, pages 3-4). It is evident that the existing local marginal conditions at the treatment plants have an essential impact on electricity consumption. According to DWA (2012), pages 3-4, the effect of the mean load on electricity consumption in the treatment plants is proportional to its capacity. Considerably more electricity is required for lower plant loads than with higher loads. For a detailed consideration and evaluation of savings potentials in a sewage treatment plant, it is useful to conduct an energy analysis of the plant (cf. DWA-A 216 "Energiecheck und Energieanalyse – Instrumente zur Energieoptimierung von Abwasseranlagen" ("Energy check and energy analysis – instruments of energy optimisation in sewage treatment plants") (draft, April 2013)).

No representative statements can be made regarding the amount of energy that can be saved in specific components of the treatment plant, as the way in which extraneous water impacts on the productivity of sewage treatment plants can vary due to differences in marginal conditions. Accordingly, it is always necessary to consider individual cases for revealing interrelations between extraneous water and energy consumption.

The interrelations between extraneous water volume and energy consumption can be demonstrated quite explicitly on the basis of example calculations, however. In the project, energy consumption was determined on the basis of plant-specific calculation approaches pursuant to DWA-A 216. By determining ideal values specific to the plant, essential influence factors affecting energy consumption/generation could be quantitatively described and rendered transparent. The results of an example calculation for a model treatment plant (>100,000 PE, one-step activated sludge process with prior denitrification) clearly show that with the three selected components (air lift pump, recirculation unit, return activated sludge pump), electricity consumption increases as the extraneous water content increases. A tenfold increase in extraneous water content results in a doubling of electricity consumed by the air lift pump unit. If the extraneous water content rises from 14.3 % to 50 %, electricity consumption for the recirculation pump increases by more than one-and-a-half times. An increase in energy consumption can also be expected from the return activated sludge pump. If the extraneous water content roughly doubles from 33 % to 62.5 %, electricity consumption rises by approximately 35 %.

5. Effects on stormwater overflows

In the course of the joint project, a number of studies were conducted to ascertain the effects of various extraneous water situations on the relief structures in the combined sewer system (see Section 7).

First of all, the mathematical principles of the ATV worksheet (A 128 "Guidelines for the design and dimensioning of rainwater treatment plants in combined sewers") were described (see Section 7.1). These show that there must be an unambiguous correlation between the infiltration water load and the required tank volume in the catchment area of a sewage treatment plant. As the infiltration water load increases, so does the required nominal tank volume in the catch-ment area.

If the actual extraneous water inflow to the tank during operation is higher than the value taken for dimensioning, this can lead to higher overflows intervals (overflow duration T_{ue}) and volumes (overflow volume VQ_{ue}). Consequently, the increase in the overflow load (COD overflow load SF_{ue}) leads to an increase in water pollution at the feed-in points. This can at times lead to a higher water pollution than caused by the discharge from the sewage treatment plant.

A simulation of the filling and relief behaviour of a stormwater overflow tank was implemented with the sanitary sewage load calculation model KOSIM ("KOntinuierliches Langzeit- SIMulationsmodell" ("Continuous long-term simulation model")[2]) for an actual existing catchment area, based on the example of a district of the municipality of Schwanau (see Section 7.2). In the evaluation of the effects, a distinction was drawn between the effects on the dimensioning of the relief structures and the effects on the filling and relief behaviour of the relief structure implemented.

The necessary tank volume for a catchment area of the municipality of Schwanau was determined for various infiltration water loads and coordinated with the hydraulic performance of the existing treatment plant. By employing a thirty-year rainfall record, the system behaviour of the catchment area and stormwater overflow tank was investigated and analysed for various infiltration water loads.

This served as an example to demonstrate the relationship between increasing infiltration water load and the increase in the necessary tank volume on the one hand and increasing filling and relief durations in comparable precipitation conditions on the other.

It should be noted that in these observations, only the infiltration water load parameter was varied but not the other significant parameters, such as precipitation and sanitary sewage inflow.

In reality this is countered by constantly changing load situations with random combinations of sanitary, infiltration and stormwater inflows. For this reason, in the second case example for the town of Billerbeck, the results and interrelationships from the long-term simulation for the district of the municipality of Schwanau were verified on the basis of measurement data for an existing tank. The relationship between infiltration water load and filling/relief behaviour was identified by analysing available operational data from a stormwater overflow tank in the town of Billerbeck (see Section 7.3).

The town of Billerbeck performed infiltration water rehabilitation in the period between February and October 2008 in the catchment area of a stormwater overflow tank, accompanied by a measurement programme. This supplied data for the discharge of extraneous water to the sewage system for the period 2006 to 2011 and regarding the filling and relief behaviour of the overflow tank. No measurement data was available regarding overflow loads and concentrations.

The existing measurement data was subjected to statistical analysis. A correlation analysis and linear regression analysis were performed to assess and evaluate the relationship between infiltration water load and filling and relief parameters.

The evaluation showed that the relationship between infiltration water load and relief behaviour exists in the stormwater overflow tank in Billerbeck.

2 The "Kontinuierliche Langzeit-SIMulationsprogramm" is a software package from the Institut für technisch-wissenschaftliche Hydrologie GmbH (itwh) devised for the verification of structures used for stormwater treatment, management and retention.

The quantity of precipitation in a strong rainfall event has such a great effect on the stormwater discharge volume that influence of infiltration water load is superimposed. To counter this effect, six precipitation classes were introduced, ranging from < 25 mm/month to >150 mm/month.

This necessary classification serves to reduce the superimposition of the precipitation event on the infiltration water, but the number of available values within the individual classes is reduced as a result. Therefore it was not possible to sufficiently ascertain the effect and resultant interactions for all possible impact factors. Neither was it possible to consistently indicate the undoubted connection between increasing infiltration water load and increasing relief activity in the stormwater overflow tank for all precipitation classes. For individual investigation factors, however, it was possible to show a relationship with the increase in infiltration water load in certain precipitation classes, for example the increase in the number of filling events, the increase in the relief discharge volume or the total relief volume.

The following essential findings can be derived from the investigations of the effects of extraneous water on the behaviour of relief structures:

- In the dimensioning of stormwater overflow tanks, the required tank volume increases with increasing infiltration water load. The nominal tank volume required to comply with the generally accepted rules of engineering practice increases virtually with the infiltration water load. Due dimensioning of the stormwater relief tanks can only be done on the basis of a realistic record of actual infiltration water content and the distribution of infiltration water in the network.
- The increased inflow of infiltration water beyond the dimensioned value results in an increase in water pollution in the stormwater overflow tanks in the combined sewer system.
- To reduce water pollution in the stormwater overflow tanks, it is possible to either reduce the volume of infiltration water in the network, to increase the regulated flow to the treatment plant or to enlarge the size of the tank. The only sensible way to determine rehabilitation measures in sewer tunnels and pipelines is by weighing up all the technical and economic aspects and taking into consideration the sewage treatment plant. As when planning new systems, the realistic recording of infiltration water volume and its distribution in the network are necessary conditions of infiltration water rehabilitation. The effects of sewer seals on the local water balance should also be taken into account in deliberations.

6. Sewer rehabilitation: eco-efficiency and sustainability

The following section outlines the approach developed in the project for determining the eco-efficiency and sustainability of sewer rehabilitation techniques (see Section 8). This systematic approach consists of the following components:

- The environmental impact, comprising the ecobalance of the construction and other materials used and also comprising the determination and assessment of the environmental impact in the vicinity of the construction site.
- The product system value of the sewer rehabilitation techniques, which is determined on the basis of DIN EN ISO 14045 (cf. DIN EN ISO 14045, page 17), comprising the following components: value for stakeholder groups in the rehabilitation process, direct costs of sewer rehabilitation with respect to the average technical service life, usability of the rehabilitated sewer.

The eco-efficiency assessment comprises the environmental impacts and the product system value.

The additional aspect of sustainability is derived from the results of the eco-efficiency assessment based on abiotic depletion potential, direct costs, and benefit to stakeholder groups.

The evaluation of eco-efficiency is performed on the basis of four examples, representing four different rehabilitation techniques for a leaking DN 300 sanitary sewer (separate sewer system). The sewer requiring rehabilitation is located in the urban zone in the middle of a road lined with trees and residential buildings. It is also assumed that due to the existence of low permeability soils, no groundwater drainage is necessary.

Sewer rehabilitation techniques

Rehabilitation scenarios are as follows:

- Trenchless repair procedure: After high-pressure cleaning of the old sewer, a leak in the sewer in the vicinity of the house connection is given a preliminary seal using epoxy resin applied by robot equipment. The short liner subsequently applied with compressed air consists of silicate resin and glass fibres.
- Trenchless renovation procedure: After high-pressure cleaning of the old sewer, several leaks in the sewer in the vicinity of the house connection are given preliminary seals using epoxy resin applied by robot equipment. The short liner subsequently applied with compressed air consists of unsaturated polyester resin, glass fibres, and styrene as a solvent.
- Open repair procedure: After creating the small trench (depth 3 m, width 0.9 m, length 1 m), an external sleeve is placed around the leak in the old sewer, made of stainless steel with elastic sealing rings made of EPDM (ethylene propylene diene monomer). A connection piece is installed in the vicinity of the house connection made of PE-HD (high density polyethylene). After completing the repair work, the trench is filled with sand, gravel and chippings and the road surface renewed.
- Open replacement: After creating the trench (depth 3 m, width 0.9 m, length 50 m), the defective old sewer is dismantled. A new sanitary sewer is then constructed, made of stoneware pipes, connected by plug-in sleeves made of EPDM. Connection pieces made of PP (polypropylene) are installed in the vicinity of the house connections. After completing the replacement work, the trench is filled with sand, gravel and chippings and the road surface renewed.

Reference

The technically possible period of use or the expected technical service life (useful life) of rehabilitated sewer tunnels and pipelines are of considerable importance with respect to the factors of sustainability and eco-efficiency.

The average technical service life from the DWA study 2009 is applied to obtain the service life expected from these rehabilitation techniques (cf. Berger/Falk 2009, page 10). For the trenchless repair procedure, this is 17 years, for the open repair procedure 20 years, for the renovation procedure 46 years and for the replacement procedure 86 years.

To enable comparison of the various rehabilitation techniques under consideration, the following reference is used, to which the ensuing considerations will refer, assuming they are quantifiable:

- 1 metre construction length (e.g. 1 m pipe lining or 1 m stoneware pipe), and

- 1 year of use, calculated on the basis of the average technical service life of each rehabilitated sewer with respect to the sewer rehabilitation technique.

Input data and output data are normalized to the reference. The construction length is defined as functional unit. Furthermore the values are quantified, necessary to fulfil functions (reference flow). The values are referred to useful life.

Life-cycle assessment

The life-cycle assessment of the construction and other materials used in the sewer rehabilitation process takes into consideration the product life-cycle and associated ecological impacts. Material and energy turnovers are recorded on the basis of significant parameters and the resultant potential environmental impacts assessed.

Due to the scope of the possible processes and parameters, a life-cycle assessment requires demarcation on the basis of a suitable objective and framework definition. The aim of the eco-efficiency assessment approach developed here is for it be used to compare different sewer rehabilitation procedures. The selected scope of processes and parameters taken into consideration must be appropriate for this purpose. This means defining the processes observed and limiting the observation to the comparison of the different rehabilitation techniques performed here.

In the present context, Ökobau.dat 2011 is used for the life-cycle assessment. Ökobau.dat 2011 comprises hundreds of datasets relating to environmental indicators for construction materials and vehicles. It is based on the GaBi database, the standard database for environmental indicators used in the building and energy industries, among others. Ökobau.dat 2011 contains data relating to energy, waste, water consumption and impact categories, among others, but it does not contain data relating to sewage or airborne emissions.

The life-cycle assessment refers to the issues of energy, waste and water; it is applied in the interest of creating lead indicators. Sewage and airborne emissions are only included to the extent that these emissions are related to situation of energy, waste and water in Ökobau.dat 2011.

On the basis of the process descriptions for concrete case examples, the construction and other materials employed are categorised into relevant components for application in the life-cycle assessment:

- Upper road structure: asphalt paving, binder course, base layer, gravel, chippings and sand,
- Pipe liners made of polyester resin: polyester, styrene and glass fibres,
- Short liners made of silicate resin: silicate resin and glass fibres,
- Stoneware piping: stoneware pipe and plug-in sleeves,
- Outer sleeve: stainless steel sleeve and sealing ring made of EPDM.

An essential component of a life-cycle assessment is an appropriate life-cycle inventory. Environmentally relevant inputs and outputs are compiled for this purpose. For the life-cycle inventory in the current procedure, significant inputs and outputs, based on Ökobau.dat 2011, are considered to the manufacture of construction materials and their transportation to the building site, the work on the building site, the transport away from the site, and the recycling of waste and residual materials.

Significant issues are considered enabling a comparison to be made of different rehabilitation scenarios.

The following input parameters are considered in the life-cycle inventory:

- Primary and secondary energy costs,
- Water consumption in the production of building and other materials.

The following output parameters are considered in the life-cycle inventory:

- Waste occurring in the production of building and other materials and on the building site.

For the impact assessment, potential environmental impacts are assessed on the basis of the life-cycle inventory. The output categories considered are the greenhouse effect, the depletion of ozone in the stratosphere, the formation of photochemical oxidants, acidification and eutrophication. Human toxicity and ecotoxicity cannot be quantified and are not used in the impact assessment determined here.

On the basis of the life-cycle inventory, trenchless procedures have benefits in comparison to open procedures in terms of energy, water and waste balance factors. This is due to the lower frequency of truck transport and the absence of trenches and shafts in the road with all the accompanying wastes and residues.

This is confirmed in the impact assessment: transport processes have a strong effect on five of the six impact categories.

Environmental impacts in the immediate vicinity

The criteria catalogue for selecting building methods for the rehabilitation of drain and sewer pipes (cf. GSTT 2000, pages 7-35) published by the German Society for Trenchless Technology e.V. (GSTT) is used to determine and assess possible environmental impacts in the immediate vicinity of a sewer rehabilitation procedure and the protected goods allocated in accordance with the Environmental Impact Assessment Act (UVPG 1990, § 2).

Potential impairments of protected goods occur in the rehabilitation phase. No appreciable impairment of protected goods is expected in the utilisation phase for the assumed marginal conditions.

However, there may be subsequent after-effects resulting from the building activity that impact on protected goods such as plants (e.g. sustained change to soil water and nutrient balance) and cultural and other physical goods (e.g. ongoing subsidence after conclusion of the rehabilitation measures).

Product system value

The product system value of sewer rehabilitation measures is formulated as a tabular summary of the results of the components described in the following: value of sewer rehabilitation to stakeholder groups, direct costs per year of sewer rehabilitation (in comparison: cost savings), service life and usability of the rehabilitated sewer. It is assessed by means of verbal argumentation.

According to DIN EN ISO 14045:2012 (cf. DIN EN ISO 14045, page 14), the stakeholder groups are groups who have an immediate benefit from the sewer rehabilitation. With reference to the repair of sewers, five stakeholder groups are defined as follows along with their main objectives, after Orth (cf. Orth/Lange 2008, page 52):

- Connectees/fee payers: functioning sewage disposal, long-term cost stability,
- Regulatory and supervisory bodies: compliance with legal regulations, in particular with reference to water conservation,

- Sewer network operator/owner of sewer network: preservation of infrastructure value, long-term economic sewer operation, secure working environment for employees,
- Sewage treatment plant operators: low level of impairment of sewage purification from extraneous water,
- Local government policy: long-term fee stability, financeability.

In individual cases, the benefits to the stakeholder groups are determined by means of surveys and votes in meetings. The respective benefit types are recorded and discussed with respect to the concrete marginal conditions prevailing at the site.

In the case examples investigated, trenchless procedures lead to a higher benefit to the stakeholder groups than do open procedures.

The costs incurred in sewer rehabilitation measures are divided into direct and indirect costs and – if used – applied to 1 m construction length and 1 year service life (useful life).

Examples of direct costs are:

- Direct costs of the rehabilitation process,
- Costs of maintaining the drainage during the rehabilitation,
- Costs of renewing the road surface following sewer rehabilitation using the open construction method.

Examples of indirect costs are:

- Costs of removing tree damage as a consequence of building work,
- Costs accruing to road users due to diversions,
- Costs of lost turnover to retail traders.

In the present context, only direct costs are applied. The data basis in the case example is tender evaluation for sewer rehabilitation of the Arbeitshilfen Abwassser (see BMVBS/BMVG 2011, Arbeitsblatt A-6.4). In individual cases, indirect costs must also be applied.

The usability of rehabilitated sewage tunnels is assessed on the basis of literature evaluations regarding the extent to which recycling, energy recovery and backfilling are already possible today.

The product system value for trenchless rehabilitation and open replacement differ more strongly than with repair processes. The case examples considered here show clearly that trenchless rehabilitation has advantages in terms of the benefits to stakeholder groups and cost factors. Open replacement has benefits in terms of reusability.

Eco-efficiency and sustainability

In the overall assessment of eco-efficiency and sustainability, the findings regarding the environmental impact and product system value of sewer rehabilitation techniques are summarised in a table and subjected to evaluation on the basis of verbal argumentation. The more benefits a rehabilitation technique has with regard to its environmental impact and product system value compared to other rehabilitation techniques, the more eco-efficient it is.

The evaluation of sustainability is also performed on the basis of verbal argumentation. Abiotic resource consumption, benefits to stakeholder groups and direct costs are presented in a table and evaluated. The eco-efficiency assessment is summarised in a table in the form of profiles for the rehabilitation techniques investigated in the separation system (see Section 8.3.1.4).

7. Effects on the local water balance

In the course of the research project, the effects on the local water balance of groundwater infiltrating sanitary and combined sewers were investigated (see Section 9). Of particular interest here were the effects of sealing measures on sanitary and combined sewers on the groundwater table and the possible consequences for buildings and vegetation.

A national survey was conducted among sewer network operators and water boards to obtain an overview of damage to buildings and vegetation resulting from changes to the groundwater location as a consequence of sewer sealing. The findings show clearly that damage from rising groundwater levels occurs particularly frequently following sewer rehabilitation measures.

These investigations are able to show that moisture damage often has a long prehistory. Damaged sewage systems can result in improper drainage of settlement areas. When new buildings are planned and constructed, they are often based on these artificially created groundwater levels. When the natural groundwater level is restored following a rehabilitation measure, damage often results.

In three case studies, the effects of extensive sewer rehabilitation measures on the local water balance were investigated in detail.

The first case study refers to an area in an urban space with parallel streets. The effects of a variety of rehabilitation scenarios on the groundwater table were simulated using the calculation program FEFLOW (cf. Diersch 2009, page 13). It was evident that the haphazard sealing of individual leaks hardly had any effect on the volume of extraneous water. In such cases, the groundwater simply enters the sewer through neighbouring leaks. Moreover, the results of the simulation show that when all leaks in the sewer tunnels and pipelines (full sealing) in the area under investigation are sealed, infiltration water emanating from the groundwater was prevented. On the other hand, this can also lead to the groundwater rising to a critical level due to the loss of the drainage effect of the sewage tunnels and pipelines, with the result that buildings and vegetation are impaired (moisture in buildings, degradation).

The results of the investigation clearly show that by taking a methodical and modified approach when sealing sewer tunnels and pipelines (partial sealing) – and taking into account the local groundwater conditions – it would be possible to achieve an appreciable reduction in infiltration water volume, without the groundwater table reaching a level that could be critical for the surrounding buildings.

When developing an overall rehabilitation concept for an area with several leaking sewers, the chronological sequence of the rehabilitation measures and in turn the temporary effects of the individual measures should be taken into consideration.

In the case example under consideration, it would be possible to effect a reduction of approximately 57% in the groundwater (Infiltration water) entering the sewer without encroaching on the surrounding buildings or vegetation. If further sealing were to be carried out, it would be necessary to perform countermeasures to prevent damage to buildings and vegetation, such as constructing substitute systems for diverting drainage water.

In another case study, settlement areas were examined on slopes that were under particular danger from stratum water. In the case example under investigation, this groundwater, which is discharged in the hydraulic gradient, rises sharply with respect to the ground moisture and the initial position of the groundwater table, in particular after heavy precipitation. Disconnecting domestic drains from the public sewage system causes more precipitation water to seep into the ground where it can result in a rising water level. Moreover, in this example, sewer sections are sealed, also removing the drainage effect for the stratum water. As a result of these measures, stratum water can rise sharply following precipitation. As a consequence, there is an increased risk of moisture in cellars of surrounding buildings.

In the third case study, the effects of changes to groundwater levels on soil characteristics were investigated. On the basis of a theoretical example, incidences of subsidence were determined with respect to groundwater levels for different types of soil. The results of these investigations showed that there is a great risk of subsidence and heave associated with cohesive, inhomogeneous soils, when groundwater levels change.

All in all, the results of the investigations show that sewer rehabilitation measures under corresponding hydrogeological marginal conditions can have a great effect on groundwater balance and soil characteristics. This applies both to rehabilitation measures performed on sewers in the groundwater or groundwater fluctuation zone and to such measures conducted in areas in which stratum water plays a role (on slopes). For this reason, the possible effects of a rehabilitation measure on the groundwater balance should be estimated in advance of the measure and, where necessary, appropriate countermeasures taken (e.g. construction of drainage channels). Moreover, it is possible to considerably reduce the incidence of extraneous water in a first step by adopting a modified approach to rehabilitating sewer tunnels and pipelines (e.g. partial sealing, setting of chronological priorities), without a rise in groundwater encroaching on the existing buildings and vegetation. In a second step, full sealing of the sewer tunnels and pipelines can be performed in conjunction with the construction of drainage systems.

8. Conclusions

The following core conclusions can be drawn from the investigations made in the project, relating to the situation with infiltration water in Germany and its causes (See Section 2.2) and regarding legal regulations concerned with the handling of infiltration water (See Section 2.3):

- It cannot currently be reliably demonstrated on the basis of statistical evaluations exactly how large the proportion of leaking sewage tunnels and pipelines in the groundwater or groundwater-fluctuation zone are and how much infiltration water enters the drainage system. The large volume of infiltration-related damage (approx. 62% of damage determined) with a simultaneous high incidence of infiltration water (23% of total water volume) points to the conclusion that a considerable proportion of extraneous water is attributable to groundwater infiltration.
- Concrete examples from practice clearly show that seals in the sewer network can bring about a considerable reduction in the volume of extraneous water (cf. Schlüter 2009, page 71).
- Legislation currently provides little backing or orientation to local councils for handling rising groundwater levels in the wake of rehabilitation measures (See Section 2.7). On the other hand, this increases the pressure to act as far as possible towards preventing infiltration water occurring through leaks in sewers, for example through the qualitative and quantitative specifications of the EWFD, the working aid for implementing the EWFD (cf. LAWA 2003, Annex 1), through the dilution ban set out in AbwV (cf. AbwV 2004, Annex 1), and through the obligation to "avoid leaks" in some state regulations. Moreover, there is a risk of water pollution in the event that leaking sewers are known about (criminal offence pursuant to § 324 StGB). This gives rise to a conflict in that functionality and operational safety of the overall system is required without impairing public well-being (in virtually all state water legislation). A rise in groundwater level following sewer rehabilitation can, however, lead to moisture in buildings as well as subsidence.

- The responsibility for resolving this conflict remains undecided, since groundwater control in settlement areas for the purpose of avoiding damage to buildings and vegetation has only been the subject of legal regulation in a few cases. The Emschergenossenschaft ('Emscher Association') has been assigned to perform this task on the basis of the Emscher Association Law (EmscherGG) (§ 2 des EmscherGG). However, in this region, the main cause of the reduction in the groundwater table distance is coal mining, because it is not the groundwater that rises but the land surface that falls.

With regard to the effects – i.e. the possible benefits and potential risks – of sewer sealing on sewage treatment plants (See Section 2.4) and stormwater overflows (See Section 2.5) as well as on the local water balance (See Section 2.7), the following conclusions can be drawn:

- The higher the proportion of infiltration water in the inflow to the sewage treatment plant, the lower the purification performance, especially because of the effect of dilution. In general, no decisive impact of temperature can be demonstrated in practice. In the interests of water protection, the investigation of pollutant load is preferable to monitoring concentrations (as in Austria for example).
- Increased volumes of infiltration water cause additional costs in the treatment plant. A realistic savings potential can only be determined by considering all components together: dimensioning basis, operating statuses, operating hours, energy costs, maintenance and repair, operating resources, residue disposal, and sewage fees.
- Energy savings brought about by infiltration water reduction measures require detailed recording, presentation and assessment of energy consumption levels, in particular with respect to hydraulically affected plant components (cf. 'Energiecheck & Energieanalyse' after DWA-A 216).
- Regarding the economic effectiveness of a sewage treatment plant, it is possible to conduct a success check or demonstrate that infiltration water reduction measures have been successfully performed in the course of a process benchmark procedure (energy control).
- In the dimensioning of stormwater overflow tanks, the required tank volume increases as infiltration water load rises. The nominal tank volume required to comply with the generally accepted rules of engineering practice increases virtually with the infiltration water load. Due dimensioning of stormwater relief tanks can only be done on the basis of a realistic record of actual infiltration water content and the distribution of infiltration water in the network.
- The increased inflow of infiltration water beyond the dimensioned value results in an increase in water pollution in stormwater overflow tanks in the combined sewer system.
- To reduce water pollution in stormwater overflow tanks, it is possible to either reduce the volume of infiltration water in the network, to increase the regulated flow to the treatment plant or to enlarge the size of the tank. The only sensible way to determine rehabilitation measures in sewer tunnels and pipelines is by weighing up all the technical and economic aspects and taking into consideration the sewage treatment plant. As when planning new systems, the realistic recording of infiltration water volume and its distribution in the network are necessary conditions of infiltration water rehabilitation. The effects of sewer seals on the local water balance should also be taken into account in deliberations.
- Sewers embedded in the groundwater can have severe effects on the groundwater level due to infiltration. If the leaks are sealed in a rehabilitation measure, the groundwater

level can rise as a result, resulting in interactions with buildings (moist cellars, impaired structural stability) and vegetation. This applies both in flatlands and in sloping areas (stratum and percolating water).

- For this reason, rehabilitation measures should always be preceded by a holistic consideration of the effects, taking into account hydrological and geological conditions, especially for sewers located in the groundwater. Holistic means with respect to the effects on building structures and vegetation, but also in conjunction with several (public and private) sewers that interact with each other through the groundwater.
- If it is expected that the rise in groundwater can result in conflict following sewer rehabilitation, an attempt should be made to counter it by drawing up chronological priori-ties within the sealing measures and/or making alternative measures for diverting the groundwater (e.g. a separate drainage system connected to a suitable receiving water course).
- Groundwater fluctuations that exceed the natural breadth of fluctuation caused by precipitation – as can happen when rehabilitating sewers that formerly had a drainage effect – can have varying effects depending on the adjacent soil. Subsidence in buildings or subsidence cracks in roadways can occur with cohesive soils.
- The interactions between groundwater and the drainage effect of leaking sewers/the effects of rehabilitation measures on the local groundwater level are discussed in the DWA pamphlet DWA-M 182, pages 54 to 56. Possible conflicts of interest are pointed out and reference made to the need for a holistic consideration.

With regard to sealing sewer tunnels and pipelines, it is not just the benefits and risks that are of interest but also the expenditures and emissions incurred when employing certain rehabilitation techniques (see Section 2.6). For precisely this purpose, an eco-efficiency assessment was developed for sewer rehabilitation techniques that was applied to specific examples with defined types of damage, rehabilitation techniques and marginal conditions (e.g. inner city area). Evaluation of the case examples (1: comparison of trenchless repair comprising injection, pressing, and short liners on the one hand with repair in open construction based on exchanging the component and outer sleeve by means of a small trench on the other, 2: comparison of trenchless renovation using pipe lining and replacement in open construction) leads to the following conclusions:

- Taking the life-cycle assessment into account, the trenchless repair method in the case example displays benefits compared to the open method. This is particularly apparent in terms of energy and water requirements in the manufacture of the building materials used. Except for the ozone depletion potential, the environmental effects considered in the individual impact categories are smaller with trenchless procedures than with the open method.
- With regard to environmental effects in the direct vicinity of the building site in the case examples, the possible impairments resulting from the trenchless methods considered are lower (number of protected goods affected and intensity of possible impairments) than with open procedures.
- Concerning product system value, the case example of the open repair procedure displays slight advantages over the trenchless repair method. The trenchless renovation method looked at has benefits over open replacement in terms of product system value.
- Despite its disadvantages in terms of product system value, the eco-efficiency of the trenchless repair method in the case example displays advantages (lower values in the life-cycle inventory and impact assessment, benefits in terms of environmental effects in

the immediate vicinity) over the open repair procedure and achieves a higher level of eco-efficiency. The eco-efficiency of the trenchless renovation method in the case example displays advantages in the life-cycle assessment, in the environmental effects in the immediate vicinity and in product system value, and is therefore ascribed a higher eco-efficiency than the open replacement method.

- Regarding sustainability, the case example of the trenchless repair method displays a smaller abiotic resource potential than the open repair method as well as slightly higher acceptance on the part of the stakeholder groups and slightly higher costs. Against this background, the trenchless repair method is assessed as more sustainable than the open repair process, despite its disadvantages in terms of product system value. Regarding sustainability, the case example of the trenchless rehabilitation method displays a smaller abiotic resource potential than the open replacement method, as well as higher acceptance on the part of the stakeholder groups and lower costs. Against this background, the trenchless renovation method is in this case assessed as more sustainable than the open replacement process.
- Sewers must be operationally safe, structurally stable, and leakproof over their entire planned service life. The construction and rehabilitation methods offered contribute to the fulfilment of these performance goals in different ways. Since the emphasis in this project is on the effects that sewer sealing has on infiltration, the eco-efficiency assessment described (see above) refers solely to the case of restoring a sewer's leak integrity. This assumes marginal conditions that enable the use of rehabilitation and repair procedures. In particular, it assumes that there will be no changes to the requirements of the network structure in the long term. It is further assumed that measures will only be performed by a single network operator.
- Should the open construction method result in synergies, such as the replacement of gas and water supply lines or the replacement of the road surface, these should be taken into ac-count in the eco-efficiency assessment. Considerable potential for reducing environ-mental impacts emerges from the simultaneous laying or replacement of supply and disposal pipelines, similarly resulting in improved eco-efficiency. Another reason why replacement is frequently chosen by sewer network operators is that – unlike with closed methods (rehabilitation and repair) – the result is a sewer that can fully (i.e. also hydrau-lically) comply with current requirements. Moreover certain damage scenarios barely al-low any alternatives to replacement, such as defects in the pipe-soil system (soil caving and adverse soil changes, pipe sag, hollows). It should be borne in mind in practice when selecting a rehabilitation method that in addition to the actual sealing effect, it is also necessary to consider other performance goals in the decision making process, such as the restoration of structural stability and, if applicable, improving hydraulic performance.
- Cost-effectiveness is in turn largely determined by the planning horizon that the rehabilitated system can attain, which can also be affected by demographic developments and the possible consequences of climate change. Again, the open construction method may offer additional flexibility with regard to network expansion or reduction, and it can be expected that this will be accompanied by a higher product system value and eco-efficiency.
- The results of the eco-efficiency assessment only apply to the case examples considered here. It would be incorrect to generalise these results as they only ever refer to the specific marginal conditions at the respective site. For this reason, it is necessary to ascertain the eco-efficiency for each sewer rehabilitation case separately. In individual

cases, a transparent, understandable weighting of the product system value factors is absolutely essential.

In the course of assessing eco-efficiency and sustainability, research was also conducted into the environmental compatibility of sewer rehabilitation resources. The results of this research clearly show that pollutant materials are used in the rehabilitation process, which vary depending on the construction method employed (e.g. styrene, bisphenol A, toluol diisocyanate). Since styrene and toluol diisocyanate are present at times in only low concentrations and/or are biodegradable, the environmental impact is classified as slight. No scientific findings on the release of bisphenol A from rehabilitation materials are so far available. It should in general be possible to conduct sewer rehabilitation measures in a due and proper manner such that impacts on the environment can be minimised.

In conclusion, the following **recommendations** can be derived from the findings of the project:

- <u>Legal framework</u>
  Legislation currently gives little backing or orientation to local councils for handling rising groundwater levels in the wake of rehabilitation measures. It would be desirable if a legal basis were to be created and orientation aids devised by which to implement expedient, holistic solutions with the aim of being better able to appraise in advance the effects of sewer rehabilitation on rising groundwater and using this as a basis for the subsequent procedures.

- <u>Infiltration from sewer leaks: non-action leads to problems</u>
  Infiltrations through leaking sewer tunnels and pipelines that discharge groundwater by virtue of their drainage function can have extensive effects on sewage treatment plants, stormwater retention tanks and the local groundwater balance:

  - Infiltration water impairs the performance of sewage treatment plants (reduced purification performance resulting from dilution) as well as their cost-effectiveness (cost and energy efficiency).

  - In a combined sewer system, the increased inflow of infiltration water into stormwater retention tanks, and in particular stormwater overflow basins, results in increased water pollution.

  - The local drop in the groundwater table results in risks to the soil, buildings and vegetation, such as the flushing of soil material from the pipeline zone even to the road surface (resulting in the formation of hollows and altered bedding conditions), building subsidence caused by changes to soil characteristics (altered density, 'shrinking process'), and loss of the natural groundwater connection to deep-rooted vegetation, such as trees.

☐ ⇒ Measures need to be taken!

<u>But: performing sewer rehabilitation without taking a holistic view can create new problems</u>

If leaks in sewer pipes and tunnels are sealed by way of rehabilitation measures, the result can be a rise in the groundwater level (i.e. a change to the status quo) including interactions with the soil, buildings and vegetation (see Section 2.7). This applies both to flatlands and to sloping areas (stratum and percolating water), by way of:

- Mobilisation (resolution) of inherited waste, soil liquefaction, buoyancy of soil and underground infrastructures (soil),

- Moistening of buildings, flooding, uplift of buildings caused by changes in soil characteristics (moisture expansion) (buildings),

- Damage to trees from continuous saturation of the soil, ponding (vegetation).

- Effects of large-scale rehabilitation to be estimated in advance
Before commencing large-scale rehabilitation measures, a holistic consideration of the effects of the measure should always be undertaken, taking into account hydrological and geological conditions; holistic means with respect to the effects on building structures and vegetation but also in conjunction with several (public and private) sewers that interact with each through the ground water.

  After undertaking a holistic consideration, it is only possible to derive realistic savings potentials in the treatment plant by recording, presenting and assessing in detail the energy consumptions of all plant components affected by infiltration water.

  It is recommended, to use the effluent load from the sewage treatment plant as an official monitoring value rather than the concentration of effluent.

  With stormwater retention tanks, it is necessary to weigh up the effects of possible measures for handling infiltration water against each other: increasing the regulated flow to the treatment plant, modifying the size of the tank or, preferably, reducing the inflow of infiltration water.

- Handling infiltration water: additional recommendations for rehabilitation concepts
For efficient sewer rehabilitation, it is necessary to recognise the sources of the extraneous water and their distribution.

  In the interest of a holistic consideration, the expenditures involved in sewer sealing are also important: eco-efficiency assessments can be seen as an important orientation aid when selecting a rehabilitation method. This includes a consideration of:

  - Life-cycle assessment of used materials and construction process
  - Environmental effects,
  - Product system value.

  Prior to conducting large-scale sewer rehabilitation measures, the possible consequences on the groundwater balance should be estimated. Corresponding damage to buildings and vegetation should be expected as a consequence of the rise in groundwater level. Should a holistic approach be taken in the rehabilitation procedure, immediate measures can be taken that lead to buildings remaining undamaged but still create a considerable reduction in infiltration water. Full sealing of the sewer tunnels and pipelines is only advisable in this case when conducted in conjunction with the construction of a drainage system.

- Responsibility for groundwater management should be clarified
According to current legislation, many of those responsible are under pressure to minimise infiltration water (see Section 2.3, e.g. EWFD requirements, ban on dilution pursuant to AbwV, criminal offence according to StGB if there is knowledge of a leak). Legal and technical regulations leave a certain amount of room for interpretation but give no concrete specifications. In particular, this concerns both the question of who is responsible for groundwater management as well as the legal situation as regards the diversion of infiltrating groundwater to avoid negative consequences of sewer sealing (e.g. wetness in buildings caused by a rise in the groundwater). In areas where water management is problematic, it might make sense under defined marginal conditions to incorporate drainage water in the obligation to dispose of sewage.

  The control of groundwater to avoid damaging buildings and vegetation in settlement areas has only been enacted in special cases in Germany. One example of this is the

Emscher region. The Emschergenossenschaft ('Emscher Association') has been assigned to perform this task on the basis of the Emscher Association Law (EmscherGG) with regard to the impact of coal mining (§2 des EmscherGG). As already described above, subsidence resulting from coal mining has reduced the distance to the groundwater table over wide areas. However, groundwater levels are being maintained at a harmless level through the activities of the Emschergenossenschaft and the non-rehabilitated public and private sewers. Moreover, the sealing of sewers with their formerly drainage impact leads to an increase in groundwater.

The possible negative consequences of a reduced groundwater table distance are moisture in buildings and damage to vegetation.

Overall it can be determined that in the event of leaking sewer tunnels and pipelines, both action and non-action can have an immense impact. With regard to a holistic approach to infiltration water rehabilitation, there is a great deal of knowledge available, but the question of responsibility and jurisdiction must still be clarified. Moreover, in this context, the financing also has to be secured.

While the exfiltration of sanitary sewage is a local problem, the question of infiltration of groundwater into sewage pipes and tunnels represents an entire systemic problem, since the effects are so diverse (e.g. effects on the operation of sewage treatment plants and discharge structures, effects on the local water balance). This should be taken into consideration when assigning responsibility and formulating requirements.