How "Tight" is our Sewer System?

Urban sewer systems are subjected to constant stress by traffic and soil movement. Combined with natural fatigue of materials, these conditions lead to damage to underground pipes, causing exfiltration of sewage into the ground water as well as infiltration of ground water into the sewer pipes. EAWAG is currently developing a new method to quantify these processes by using both natural and artificial tracers, which will help us in planning more efficient remedial action.

Although urban sewer networks are built for longevity, damage occurs over time and systems inevitably develop leaks. If such leaks are situated below the groundwater table, clean ground water may infiltrate sewer pipes; but if the leak lies above the groundwater table, raw sewage may exfiltrate into the surrounding soil.

Exfiltration of raw sewage from leaking sewer pipes is considered to be a serious threat to humans and the environment since it can directly impact drinking water [1]. Infiltration of ground water is a problem as well, since sewage is diluted and wastewater treatment plants receive an unnecessarily large hydraulic load. Neither situation is normally recognized until they reach rather serious proportions. This is mainly due to the fact that sewer pipes are located underground and that these processes are, for all practical purposes, invisible. Traditional monitoring techniques are very labor-intensive and yield rather imprecise results (see box).

Traditional Measurement Methods

The amount of exfiltration is typically assessed in leak tests using water or air [3]. Such tests are expensive and only provide information about certain problem spots; extrapolation over an entire sewage system is too uncertain. Using classic methods for a comprehensive assessment of the amount of exfiltration, which would be needed to develop efficient remediation plans, is therefore impractical.

Traditionally, infiltration of ground water is determined simply by measuring runoff volumes [4]. The assumption is that during periods of low flow (usually Sunday night until Monday morning), the sewage component is practically zero, and the flow consists exclusively of infiltrated ground water. This assumption is becoming more and more problematic, however, as even private households run machines that use water during the night in order to reduce operating costs. Sewage systems are also growing with expanding agglomerations. In some sections of the sewage system, there may be sewage flow at any time of the day because it arrives with varying delays from different parts of the system.

For this reason, EAWAG is developing new methods for the measurement of water infiltration and exfiltration. This project is part of a larger European research project, APUSS (Assessment of the Performance of Urban Sewer Systems) which was initiated in 2001 and aims to assess the condition of urban sewer systems based on infiltration and exfiltration of water. Methods developed as part of this project will aid in designing more efficient remediation plans for urban sewer systems.

The new methods use both natural and artificial tracers (see box on p. 30); by measuring increases or decreases in the amount of a given tracer, we can calculate the amount of water entering and leaving the sewer system.

Exfiltration Measurements with Artificial Tracers

Exfiltration is measured by employing artificial tracers that are added to the sewage (see box on p. 30). If the sewer system is leaking, part of the added tracer will be lost with the leaking sewage. This loss is directly linked to exfiltration; for example, if 10% of the tracer is lost, it can be concluded that 10% of the sewage is leaving the pipe in that particular section of the sewage system [2]. The operating principles of this method are summarized as follows (Fig. 1):

- The tracer is added at two points: at the beginning (indicator signal) and at the end (reference signal) of the section to be tested. The indicator signal is attenuated by exfiltration, indicating whether or not water is leaving the pipe. The reference signal is not affected by exfiltration; it merely serves to quantify the diminution of the indicator signal. It is important in making these measurements that the tracer and the sewage are completely mixed.
- If the tracer is dosed in slugs, a single tracer compound may be used. At the measuring point, pulse-shaped concentration curves are observed (Fig. 2). Measurements are taken directly in the sewage stream with so-called in-line probes, which provide high temporal resolution. This approach allows for differentiation between the indicator pulse, the reference pulse and the natural background. For continuous tracer addition, two different tracer compounds would have to be used, and the measurement would yield twice the measurement error of a pulsed tracer addition.
- The tracer addition at the reference site is delayed relative to the addition at the indicator site. In this way, both pulses overlap at the measurement point (Fig. 2). This

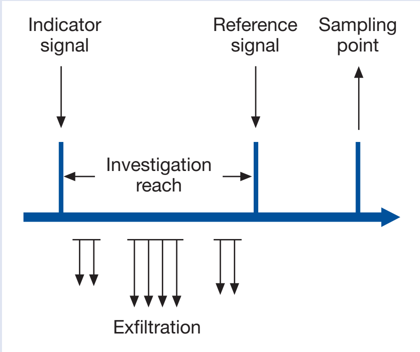

Fig. 1: Schematic representation of an experiment for quantifying exfiltration.

Artificial and Natural Tracers

Artificial Tracers, **e.g., simple or fluorescent dyes, particles, chloride in the form of sodium chloride or lithium in the form of lithium chloride, are compounds that are added to the sewage stream at a particular location and measured at a second location. They must meet the following requirements:**

- **low natural abundance,**
- **low detection limit,**
- **no interactions with other compounds,**
- **no toxicity,**
- **good solubility and mixing characteristics in water,**
- **inexpensive.**

Natural Tracers **are specific properties of a local drinking water, ground water or sewage water, such as their stable isotope composition, which can be used to distinguish different types of water.**

method has the advantage that potential measurement errors (e.g., changes in sewage composition, error or drift in the probe signal) affect both tracer signals equally and so are cancelled out.

■ Since the amount of added tracer at the indicator site is known, the peak area may be used as the reference signal to estimate how large the indicator signal should be if no exfiltration would occur. The difference between this estimate and the measured indicator signal tells us whether or not the sewage pipe in that particular test section is leaking.

Exfiltration experiment: addition of NaCl solution as a reference signal.

NaCl as a Tracer for Exfiltration

Figure 2 shows a typical experiment in which NaCl is used as a salt tracer. The probes used are conductivity probes, which indirectly measure NaCl concentrations in the water stream. In the experiment shown here, the test section was 285 m long, the average runoff volume during dry weather was 25 l/s, and the average natural background conductivity was 0.8 mS/cm; generally, it is preferable to measure longer test sections (up to several kilometers), since this would maximize the number of leakage points identified in one test. Before conducting the actual measurement, runoff volume and conductivity should be measured for approximately two days. Based on these background parameters, we can calculate how much NaCl should be added at the indicator and reference points. In this case, 1.9 kg of NaCl was added at the indicator point, and three additions of 0.4 kg NaCl were made at the reference point approximately 10 minutes later. The results of this experiment indicate that there were no leaks present in this test section.

Infiltration Measurements with Natural Tracers

Infiltration cannot be measured using artificial tracers. Homogenous distribution of tracers throughout an entire aquifer is neither feasible nor desirable for environmental reasons. Rather, specific natural characteristics of the local drinking water, ground water and sewage have to be used as natural indicators of mixing and dilution processes (see box).

It is rare to find a direct natural tracer since sewage typically contains a vast number of different compounds. These compounds usually exhibit large daily fluctuations and so obscure the natural tracer signal. An example of a suitable tracer system, however, would be the isotopic composition of water. It is predominantly determined by the topographic elevation of the region where ground water and surface water are recharged by the local precipitation (altitude effect). This method can be used when a town uses drinking water from a watershed that is situated significantly higher or lower than the urbanized area. In such a situation, significant differences in the isotopic compositions of the drinking water, the waste water and the ground water can be expected, allowing for quantification of the various mixing ratios.

For more general situations, however, another method appears to be promising: the fraction of infiltrating water can be determined by comparing the time series for pollutant concentrations and discharge volume. A suitable lump-sum parameter representing pollutant concentration is, for example, the chemical oxygen demand (COD). This parameter indicates how much oxygen is required for complete oxidation of the organic and inorganic pollutants contained in the sewage stream. Modern in-line probes are able to determine COD equivalents directly by measuring light absorption in the UV range (Fig. 3). These probes record the signal with high temporal resolution, thus providing the basis for a detailed data and error analysis.

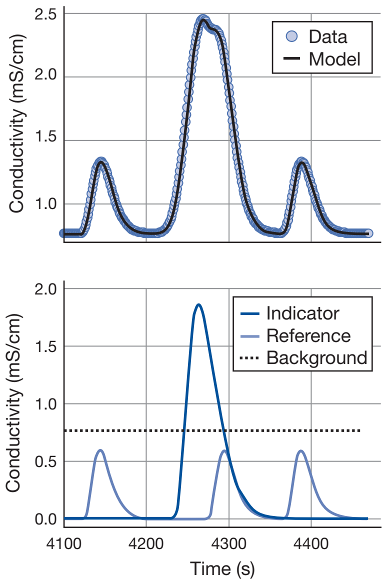

Fig. 2: Results of an experiment measuring exfiltration. NaCl was used as an artificial tracer.
Top: measured and calculated tracer signal.
Bottom: separation of the measured signal into the indicator and reference signals with subtraction of the natural background.

Pollutants as Infiltration Tracers

Figure 3 shows the results of a measurement campaign that was conducted in the winter of 2002–03 at the influent of a cooperative wastewater treatment plant which serves approximately 23 500 people. The COD equivalents and the wastewater volume were registered with a temporal resolution of 3 minutes. Data processing was performed with a mixing model using the data for the two measured parameters. This required additional assumptions which were made based on external information. The COD value for infiltrating water was assumed to be negligible. The volume of infiltrating water consists of two components: a constant base flow and an exponentially decreasing interflow. In the simplified case illustrated here, we also assumed that the COD concentration of the actual foul sewage component was approximately constant. The total variation of the COD concentration in the waste water is therefore determined by the diurnal hydrograph of the sewage flow (24 hr rhythm) and the slowly fluctuating amount of infiltrating water (exponential decline after long rainy periods). A short rain event on 26 December 2002 (sharp increase in wastewater volume at mid-day) was not caught by the model.

Are these Methods Usable in their Practical Application?

We are currently developing a general methodical guide that will allow the user to measure exfiltration in any sewage system. The guide helps the users choose the best combination of tracer, measuring method and dosage protocol for their particular situation. Analysis of our field experiments conducted thus far indicates that the detection limit for exfiltration is about 10%. Since typical losses are rather low (below 5%), the quantification methods will have to become more accurate in order to be useful in real applications.

Whether or not our method for measuring infiltration will be an improvement over traditional methods will depend on the reliability of the model assumptions that have to be made. Furthermore, pollutant concentrations and runoff volume will have to be measured with high accuracy in order to achieve an overall accuracy of 10 to 20% for infiltration values. We will use the stable isotope methods to further validate our new approach. Both methods are currently being tested in different countries and in a variety of sewage systems as part of the APUSS project.

Exfiltration und Infiltration as "Benchmarking" Tools

If exfiltration and infiltration could be established nationally or internationally as indicators, these parameters could be used to "benchmark" sewage systems. A comparative evaluation of the structural integrity of different sewer systems is currently very difficult to make. It normally takes years to collect data for an entire sewage system by the traditional method using a mobile camera (CCTV). In addition, damage classification varies with both the technique and operator, which makes overall comparisons problematic. An objective comparison of different sewage systems or operating strategies will only be possible if we have assessment tools that yield reproducible results in a useful time frame. Whether our methods will prove to be such tools will depend on whether or not we can achieve the necessary measurement accuracy.

Jörg Rieckermann, engineer, is working on his doctoral thesis in the department of "Environmental Engineering" where he is developing a method for the measurement of exfiltration with artificial tracers.

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[1] Bishop P.K., Misstear B.D., White M., Harding N.J. (1998): Impacts of sewers on groundwater quality. Journal of the Chartered Institution of Water and Environment Management *12,* 216–223.

[2] Rieckermann J., Gujer W. (2002): Quantifying exfiltration from leaky sewers with artificial tracers. Proceedings of the International Conference on "Sewer Operation and Maintenance 2002». Bradford, UK.

[3] Stein D. (1999): Instandhaltung von Kanalisationen. Ernst & Sohn, Berlin, 948 S.

[4] Schweizer Bundesamt für Umweltschutz (1984): Methoden zur Bestimmung der Fremdwassermenge in Kanalisationen und Kläranlagen. Bundesamt für Umweltschutz, Bern, 51 S.

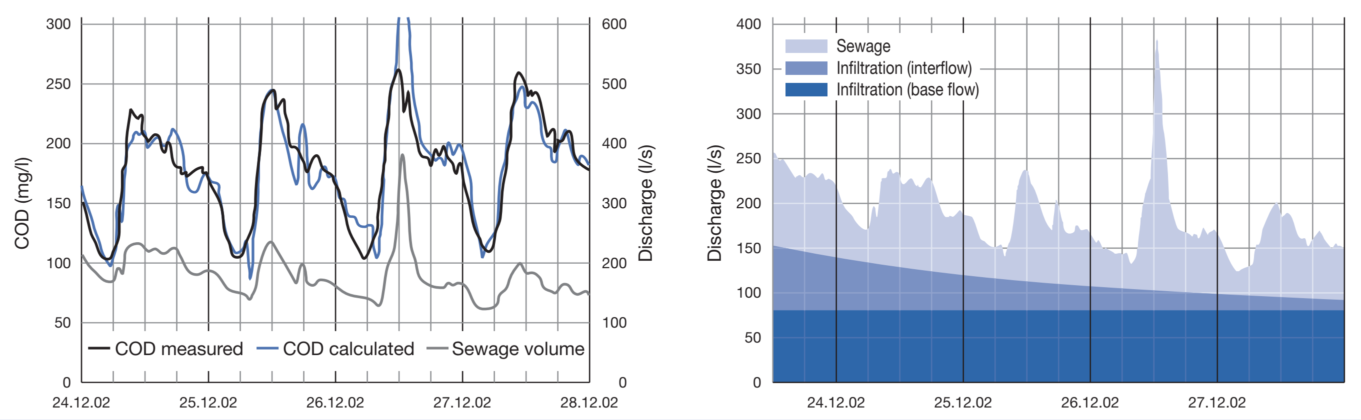

Fig. 3: Results of a measurement campaign determining infiltration. Chemical oxygen demand (COD) was used as the natural tracer. Left: comparison of COD measurements with model calculations. Right: identification of different water components. In this test section, "foreign" water accounted for an average of 60% of the total runoff.