Chalmers University of Technology
Department of Sanitary Engineering

Infiltration / Inflow in Separate Sewer Systems

Some Aspects on Sources and a Methodology for Localization and Quantification of Infiltration into Sanitary Sewers caused by Leaking Storm Sewers

by

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This thesis is based on the work contained in the following 8 publications.

1. Hans Bäckman
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2. Hans Bäckman
AVLOPPSLEDNINGAR I SVENSKA TÄTORTER - En översiktlig historik. (Development of Sewer Systems in Sweden) VATTEN, Vol 40, No. 2, p 177-187, 1984. (In Swedish, English abstract) (10 fig., 25 ref., 11 pp)

3. Hans Bäckman and Gilbert Svensson
FLÖDESMÄTNING I AVLOPPSNÄT MED PORTABLA UTRUSTNINGAR - Mätnoggrannhet under kontrollerade förhållanden i en 225 mm:s betongledning. (Flow Measurements in Sewers using Portable Equipment - Measurement Accuracy in a Laboratory Concrete Pipe of the Diameter 225 mm.) Urban Geohydrology Research Group, Report No. 69, Chalmers University of Technology, Göteborg, 1983. (In Swedish) (30 fig., 9 ref., 49 pp)

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ACCURACY OF FLOW MEASUREMENTS IN SMALL SEWERS - A Laboratory Investigation. Accepted for presentation at an International Conference of Flow Measurements in the Water Industry, Glasgow, April 1983. The conference was however cancelled. Submitted for publication elsewhere. (18 fig., 4 ref., 22 pp)

5. Hans Bäckman and Gilbert Svensson
UTVÄRDERING AV KALIBRERINGSPUNKTER VID FLÖDESMÄTNING I ÖPPEN LEDNING - Presentation av en metod och ett datorprogram för ABC80. (Flow Measurements in Open Channels - A Method and a Computer Program för Evaluation of Calibration Data). Dept. of Sanitary Engineering, Internal Report Series No. 2:83, Chalmers University of Technology, Göteborg, 1983. (In Swedish) (2 fig., 4 ref., 24 pp)

6 Hans Bäckman
ÖVERLÄCKNING FRÅN DAG- TILL SPILLVATTENLEDNINGAR - Metoder för att påvisa och kvantifiera överläckning samt redovisning av mätresultat från kommunala avloppsnät. (Infiltration into Separate Sanitary Sewers caused by Leaking Storm Sewers - Methods for Localization and Quantification and a Presentation of Field Investigation Results.) Urban Geohydrology Research Group, Report No. 77, Chalmers University of Technology, Göteborg, 1985. (In Swedish) (63 fig., 4 tab., 37 ref., 97 pp)

7 Hans Bäckman and Börje Sjölander
AVLOPPSPERISKOP - ett enkelt och billigt hjälpmedel vid undersökningar i avloppsnät. (The Sewer Periscope - a Simple and Inexpensive Tool in Sewer Surveys) VATTEN, Vol 40, No. 2, p 188-192, 1984 (In Swedish, English abstract) (4 fig., 5 pp)

8 Hans Bäckman
UNDERSÖKNINGAR FÖR ATT BESTÄMMA LEDNINGARS FUNKTION (Assessing the Hydraulic Performance of Separate Sanitary Sewers) Presented at a Nordic Seminar on the Strategic Planning and the Rehabilitation of Sewer Systems, Chalmers University of Technology, 13-14 Nov. 1984. Also published at the Dept. of Sanitary Engineering, Internal Report Series No. 4:84, Chalmers University of Technology, Göteborg, 1984. (In Swedish) (8 fig., 11 ref., 16 pp)

INFILTRATION/INFLOW IN SEPARATE SEWER SYSTEMS

Some Aspects on Sources and a Methodology for Localization and Quantification of Infiltration into Sanitary Sewers Caused by Leaking Storm Sewers.

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ABSTRACT

A very important task in Sanitary Engineering today is the management of sewer systems. Sewer systems have been built in Sweden for over 100 years but the median sewer pipe age is less than 20 years. The construction conditions at different periods influence sewer quality but other parameters, such as workmanship and geohydrological conditions, are also important.

Flow measurements have a central role in many sewer surveys. The available methods require certain hydraulic conditions which are not often met in sewers. This can result in flow measurement errors. Flow measurement methods used in sewer manholes and pipes have been studied in a laboratory sewer line and the sensitivity and accuracy of the methods are discussed.

Infiltration/inflow into separate sewer systems causes problems in the transport and treatment of wastewater. One source of infiltration, infiltration due to leaking storm sewers, has been studied. Investigation methods have been developed and aspects are given on the strategic planning of these investigations. Field studies of several older separate sewer systems were made in three towns. Over 5 km of sewers were examined. The infiltration was measured, in several sewer lines, to be between 20% and 90% of the simulated stormwater flow. The time for water transport between the pipe systems was very short. This indicates that in flow surveys made during wet weather conditions such "cross-leakage" between storm and sanitary sewers cannot be separated from connected impermeable area runoff.

Neither the age of the sewer pipe nor other simple parameters can be used for predicting the occurance of this "cross-leakage". In many of the examined sanitary sewers no detectable infiltration was found despite what often appeared to be deteriorated conditions.

Keywords: Separate sewer systems, sewer survey, flow measurements, strategy, infiltration, inflow, sources.

PREFACE

Sewerage is an important part of the urban infrastructure. Its proper function is essential for sanitary as well as environmental aspects. Problems dealing with sewer systems have, for a long time, been considered mostly a matter for the operation and maintenance department of the local communities.

There was an increasing awareness during the 1970's that the poor performance of many separate sewer systems influenced the pollution load to receiving waters. In combined sewer systems this was a direct consequense of their design. Estimations of replacement costs of combined sewer systems with separate systems also emphasised that the sewer systems were a very large asset.

The Swedish Council for Building Research (BFR) recognized that the sewer systems would be a significant future problem area. In order to promote development within this field, BFR considered it essential to stimulate research on sewerage at the technical universities.

At this time there was also an increasing interest at Chalmers University of Technology (CTH) for investigating the operation and maintenance of sewer systems. This was met with interest by BFR and the profession.

The main reason why sewerage has been a neglected area in academic research is probably that this very applied subject is difficult to penetrate using traditional research methodologies. Often many parameters cannot be controlled when working in sewers due to a lack of available instruments, unacceptable investigation costs and lack of knowledge of the actual conditions for subsurface utilities.

The first approaches at the Department of Sanitary Engineering in 1978 were very broad. After some initial studies the author was given the opportunity to be the secretary of a working party, set up by BFR, to evaluate the need for research and development in water distribution and sewage collection systems.

The results of this investigation were presented in September 1981 at a seminar in Göteborg with representatives from local communities, consultants, contractors, manufacturers, environmental authorities and research organisations. This investigation and the following seminar (Balmér et al, 1982), became somewhat of a starting point and the activities increased at different locations.

In 1981 a group was formed, within the Urban Geohydrological Research Group at CTH, to deal with the operation and maintenance of sewer systems. It was felt that the first projects should have a very applied approach. By this approach it is very important to be aware of the borderline between academic work and practical work carried out by engineers at consulting firms ~~or~~ local communities. If this is not considered then it is easy to carry out work within a research project that should be done on a commercial basis or that the investigations lead to results which are difficult to generalize.

It was decided that different current problems should be studied at a more detailed level than was at that time possible on a commercial basis and be carried out in close contact with experienced sanitary engineers. Furthermore, the development and evaluation of modern, efficient survey techniques was considered important.

This project was entitled " Deficiencies in Existing Sewer Systems and their Consequences". The title covers a very wide field and the first target was therefore to limit the scope to a more tangible extent. Since the environmental aspects of sewer system deficiencies were being discussed at that time in Sweden, this project was planned to deal mainly with infiltration/inflow problems.

The project was divided into three parts:

1) A historical review of the development of sewer systems in Sweden. Initially it was believed that by a historical review, it would be possible to sort out a number of "typical sewer trenches" that could then be examined. The results might then be generalized. This was, with our present knowledge, a bit naive. Even if this intention failed as the complexity of important parameters became obvious, it is still considered that this background was essential for the further work.

   A better understanding of sewer construction conditions during different periods can be very useful to provide an insight into how sewer deficiences might occur. The historical review is based on the available literature and is supplemented with comments from various experienced sanitary engineers.

2) Flow measurement accuracy. It was recognized early that flow measurements would be an essential tool in many sewer projects. It was therefore decided to carry out this part as a more independent study than was initially intended.

   The study aimed to increase the understanding of total flow measurement accuracy when using portable measurement equipment in manholes. This investigation had to be carried out under controlled conditions and an experimental sewer line was built in the laboratory.

   The experimental sewer line was also used to calibrate the flow measurement equipment for the third part of the project.

3) Infiltration into sanitary sewers caused by leaking storm sewers. In part three, which was the most time-consuming part, one source of infiltration was studied. This infiltration is a result of deficiencies in the sewer pipes such as untight joints and defective manhole connections.

The work included developing a methodology which could detect and quantify this infiltration and recommendations are given for the strategic planning of this type of sewer investigation.

This thesis focuses on sewer problems in Sweden and most of the reports and papers are published in Swedish. This English summary is intended to make these results more available.

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The enthusiasm and help given by Börje Sjölander has been indispensable when developing the equipment required for this project. I am also very grateful for all the pleasant memories I share with Börje Sjölander from the field measurements.

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Göteborg in April 1985

Hans Bäckman

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GLOSSARY

Background flow:	Sanitary wastewater plus dry weather infiltration/inflow.
CCTV-inspection:	Closed Circuit Television inspection.
Combined sewer systems:	Sewer systems for the removal of sanitary wastewater, urban stormwater and drainagewater in a single pipe system.
Cross connections:	Pipe connections between two separate systems which may or may not be intentional.
Cross-leakage:	Rapid infiltration of stormwater into sanitary sewers due to leaking storm sewers.
Exfiltration:	Water leaving a sewer into the ground.
Infiltration:	Water entering a sewer through the ground.
Inflow:	Water discharged directly into a sewer from connected roof leaders, foundation drains, cross connections or through manhole covers.
Infiltration/inflow:	The total quantity of water from both infiltration and inflow without distinguishing the source.
Manhole distance:	The distance between two consecutive manholes.
Rainfall-induced infiltration/inflow:	An increase in infiltration/inflow related to rainfall.

Sanitary sewer:	The pipe transporting sanitary wastewater in a separate sewer system.
Sanitary wastewater:	Wastewater from households, offices, restaurants and schools
Separate sewer system:	Sewer systems for the removal of sanitary wastewater and stormwater in separate pipe systems
Specific survey costs:	The total survey costs divided by the total surveyed sewer length.

ACRONYMS

BFR:	Statens råd för byggnadsforskning (Swedish Council for Building Research)
CTH:	Chalmers Tekniska Högskola (Chalmers University of Technology)
EPA:	United States Environmental Protection Agency
SKTF:	Svenska Kommunal-Tekniska Föreningen (The Swedish Association of Municipal Technici)
SNV:	Statens Naturvårdsverk (National Swedish Environment Protection Board)
TNC:	Tekniska nomenklaturcentralen (Swedish Centre of Technical Terminology)
VAV:	Svenska Vatten- och Avloppsverksföreningen (Swedish Water and Waste Water Works Association)
WPCF:	Water Pollution Control Federation, USA
WRC:	Water Research Centre, England

1 BACKGROUND - SWEDEN'S SEWER HERITAGE

An understanding of what has been thought to constitute sewers of high quality over the last century is useful when dealing with different problems in sewer systems. It is not possible to predict the status of a specific sewer just based on historical data since the quality is dependent on many parameters such as workmanship, pipe and joint material usage, construction methods and geohydrological conditions. Many of these parameters are often poorly known. Chapter 1 is based on publications no. 1 and no. 2.

1.1 Development of Sewerage in Sweden

Sewer systems have been constructed for more than 100 years and the objectives for their construction have gradually changed. Sanitation was the first main objective for sewerage and later also environmental problems, caused by the increasing urbanization, had to be solved. At present, the management of these utilities is emphasized.

The Sanitary Objective

The sanitary standards during the 19th century were very poor in the towns and cities. Wastes were transported in gutters, ducts and ditches during storm events to the nearest receiving waters. Actions to improve the poor sanitary standards became more acute as urbanization increased during the second half of the 19th century. Figure 1.1 shows the increase in urban population since 1800.

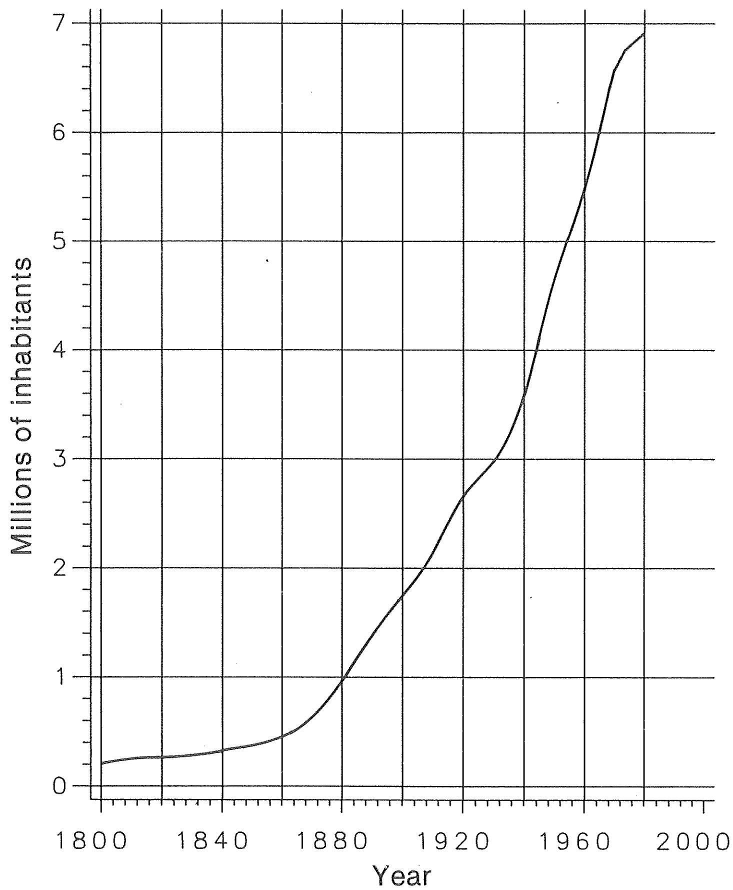

Figure 1.1 Millions of inhabitants in densely populated areas in Sweden, 1800-1980.

At this time serious efforts were made to improve the sanitary standard. Amongst the several important actions taken were the construction of water mains and sewage collection systems. The first underground sewers in the modern sense were built during the 1860's and by 1905 there were underground sewers in 80 Swedish towns. The public health slowly improved and mortality gradually decreased, as seen in Figure 1.2.

Increased urbanization created a need for planned urban storm-water drainage of the cities. A collection system for domestic wastewater was also needed where water distribution systems were planned. This was solved by constructing combined sewer systems. Latrines were collected separately. The low standard of these first sewer systems and the closeness to receiving waters did not permit a frequent installation of flush–toilets until the early 20th century by which time the sewer systems had improved.

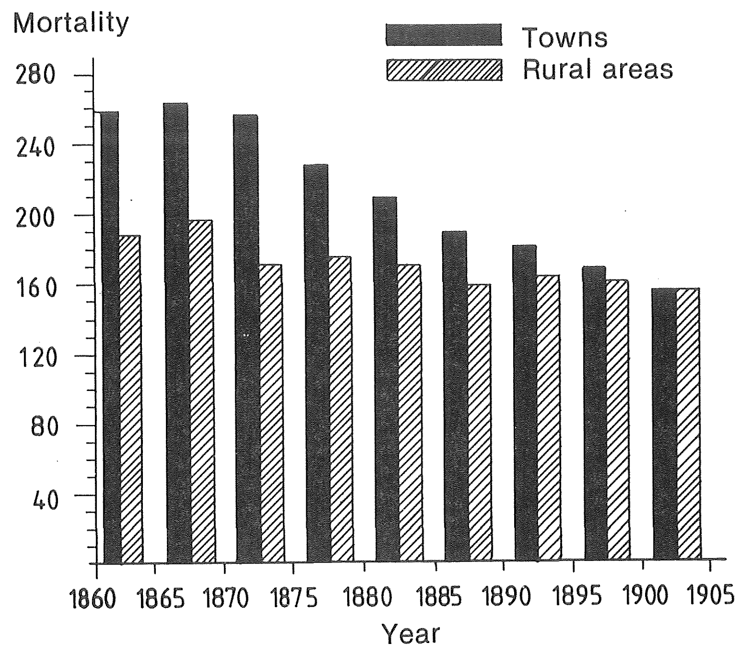

Figure 1.2 Mortality in Swedish towns and rural areas, expressed in number of deaths per 10 000 inhabitants and year (Lindman 1908).

The increasing population in the urban areas and the more general use of flush-toilets gradually caused pollution problems in the receiving waters. The inconvenience of basement floodings also increased as more flush-toilets were connected to the sewer systems. Combined sewer systems were so predominant that by 1942 they were the only constructed systems in 98 of 132 local communities.

The Environmental Objective

During the 1950's the negative environmental effects on many receiving waters were severe. Construction of treatment plants started with more plants expected in the future and therefore a sewage flow, without storm water dilution, was preferred. The benefits of using the separate systems would be less variations in sewage flow and reduced pumping costs. From the 1950's an increasing share of new sewer systems were therefore constructed with separate storm sewers.

The separate sewer systems were built in one trench with the sanitary sewer at the bottom and the storm sewer at a higher elevation. The stormwater was discharged into the nearest receiving water.

Cronström (1954) stated that very tight sewers, both municipal and private, were required to achieve the full benefit of separate sewer systems. This was difficult to achieve with the joint materials available at that time. Furthermore there was no satisfactory solution for the connection of foundation drains, especially in flat areas. Usually these drains were connected to the sanitary sewer, otherwise deeper sewer trenches were required. This exemplifies one of the compromises that were made when new separate sewer systems were constructed.

Intensive building schemes during the 1960's and the 1970's caused a dramatic increase in the yearly constructed sewer length. The increase is also a result of the change in practice from the 1950's onwards when mostly separate sewers were constructed, in principle doubling the length of pipes laid.

To solve the environmental problems treatment plants were intensively constructed during the 1960's and 1970's (Figure 1.3). The construction of treatment plants was stimulated by generous government grants.

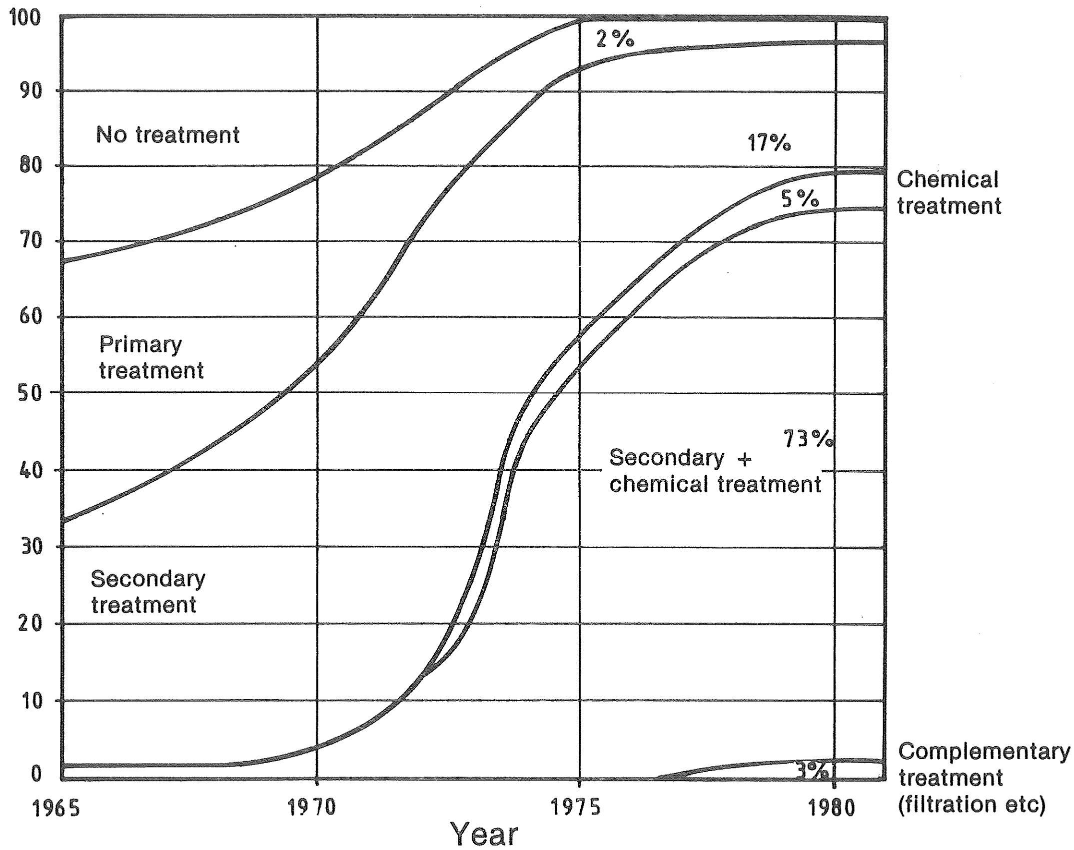

Figure 1.3 Percentage of population in urban areas connected to various types of treatment plants, 1965-1982. (SNV 1984)

The Emphasis on Management

The construction of sewers decreased as housing construction declined in the late 1970's and early 1980's. The construction of treatment plants also decreased as all municipal sewers in urban areas were connected to treatment plants. Management of these facilities then became a major undertaking.

The cumulative length of municipal sewers over the last 120 years is shown in Figure 1.4. The median age of the sewers in

Sweden is less than 20 years. If replaced sewers are not considered then about 75% of all municipal sewers were built after 1960 and about 50% after 1967.

In 1983 the total length of all municipal sewers (combined, sanitary and storm sewers) was about 74 200 km. The average length of sewers per connected person was 10.4 meters (VAV 1984). It was estimated in 1980 that 14% of all municipal sewers in Sweden were combined sewers, 49% were sanitary sewers and 37% were storm sewers (SNV 1983).

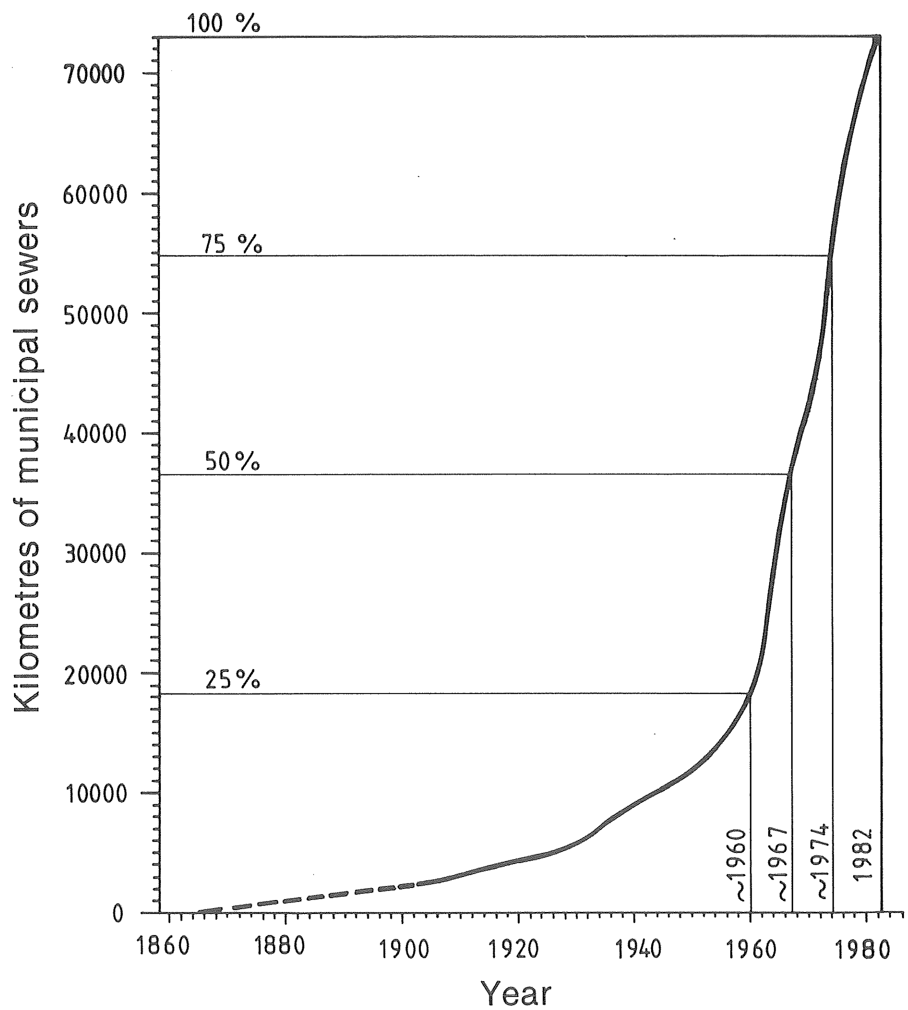

Figure 1.4 Cumulative length of municipal sewers in Sweden over the last 120 years.

The approximate age distribution of sewers, shown in Figure 1.4, can be somewhat misleading if the length of sewers are preferred to be seen as the length of sewer trenches. The figure shows the total length of pipes laid, which is in principle twice the length of the sewer trench for the separate sewer systems.

1.2 Parameters Influencing Sewer Quality

As mentioned earlier, no general assessments based on a historical review can be made on the quality of sewers. Several important parameters which have influenced the quality of sewers do appear. These include pipe material, jointing methods and leakage control.

Pipe Material

Sewers constructed during the 19th century were mainly made of clay. The manufacturing of concrete pipes started in the 1870's. Figure 1.5 illustrates the manufacturing process in the 1890's. Larger diameter sewers were at that time brick.

By 1900, the pipe material distribution of the 100 km sewer system in Göteborg was about 75% vitrified clay, 18% concrete and 6% brick.

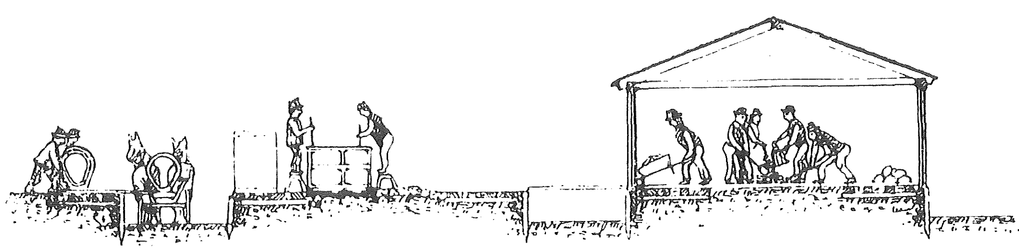

Figure 1.5 Manufacturing concrete pipes during the 1890's.

During the 20th century concrete soon became the dominant pipe material. The first concrete sewer pipe standards were adopted in 1923 and were extended and revised in 1931, 1949, 1968, and 1977. Despite the adoption of concrete sewer pipe standards many manufacturers earlier did not use them. In the early 1950's there were about 1000 concrete pipe manufacturers but only about 20% were members of organizations that enforced impartial quality control checks.

Pipe material in sewer systems was estimated, in the beginning of the 1960's, to be about 94% concrete and about 5% vitrified clay.

PVC-pipes were introduced for use in municipal sewers in the late 1960's and during the 1970's gradually captured nearly 30% of the market. Concrete, however, still dominates with a market share of about 65%. An estimation of pipe material distribution in sewer systems in 1982 is shown in Figure 1.6.

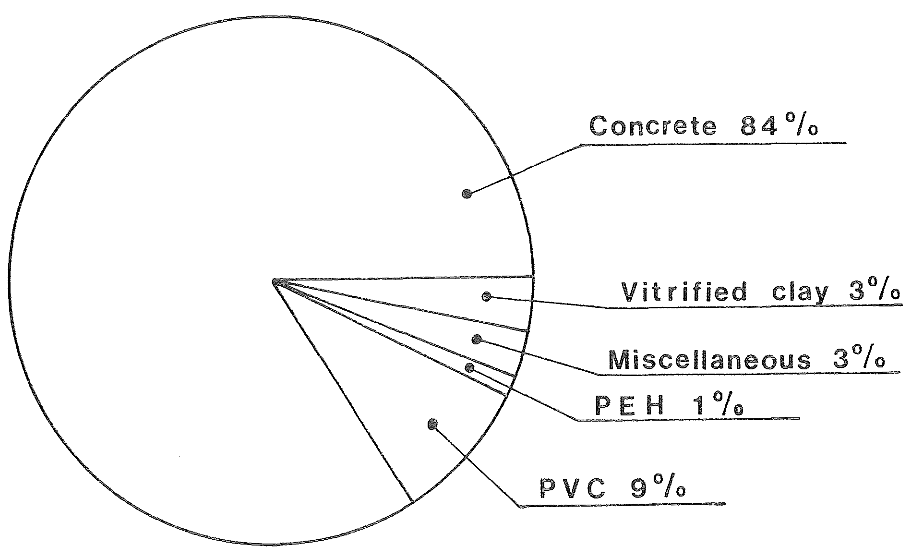

Figure 1.6 Pipe material distribution of Swedish municipal sewers in 1982. Calculation based on statistics from VAV.

Sewer Pipe Jointing Methods

Several methods for pipe jointing have been used during different periods and it is difficult to give a simple description of their development. Some methods used in Sweden will be described.

Before the rubber ring was commonly used and fully developed it was difficult to make a tight joint. Tightness was to a great extent dependent on the skill of the craftsmen. It is probable that for many of the sewer lines constructed at that time infiltration is highly related to the permeability of the soil surrounding the pipes and other geohydrological parameters.

Early jointing methods often used a tarred oakum packing. The tarred oakum helped to centre the pipe and prevented the sealing material from entering the sewer. Several sealing materials have been used.

In the earliest sewers, clay was used as a sealing material. Later cement mortar was used and by the 1930's it was considered the dominant sealing material. The joints were stiff and thus sensitive to ground movements.

Asphalt became a popular sealing material during the 1940's since it, to some extent, provided a more flexible joint. The asphalt could be applied in different ways, either poured as a liquid or rolled out and pressed into the socket. Cement mortar was applied to fill out the remaining space in the socket, as illustrated in Figure 1.7.

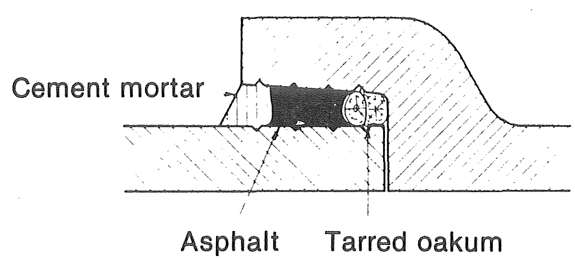

Figure 1.7 Sewer joint of tarred oakum combined with asphalt and mortar, 1948.

In 1947 it was recommended in a manual of practice produced by SKTF, that cement mortar should be used as a sealing material for sewers built on solid ground and asphalt should be used if the ground was less stable.

The introduction of mechanical excavators, around 1950, brought about a significant change in sewer construction methods. Earlier trenches had been to a great extent excavated by hand and were usually backfilled with the excavated material. When excavators and trucks were used, the costs for excavation of sewer trenches dropped dramatically and it was easier to exchange the backfill material. This could be done if, for instance, the excavated materials were difficult to compact. Exchanging the backfill material for a more permeable material may have worsened conditions for exfiltration/infiltration through untight joints.

The interest for tighter joints, due to the planned treatment plant expansion during the 1950's, resulted in several new jointing methods. One of them, a plastic ring, was not successful since it soon lost its elasticity and became pinched at the bottom of the pipe with leakage resulting at the top.

The rubber ring joint, shown in Figure 1.8, was introduced at the end of the 1950's. A rubber ring joint required closer socket tolerances than was allowed in the concrete sewer pipe standards from 1949. Thus several "special pipes" were introduced by different manufacturers where the concrete pipes were manufactured to closer tolerances.

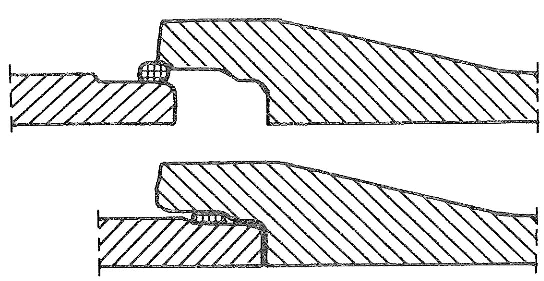

Figure 1.8 Rubber ring jointed concrete pipes, 1963.

It was not until 1968 that new concrete sewer pipe standards were adopted and tight rubber ring joints could be achieved with standardized concrete pipes. The development of the rubber ring jointing method has continued.

Leakage Control

In 1931 the first method for testing leakage was included in the concrete sewer pipe standards. The pipe was raised at one end, filled with water and the sinking rate of the water surface measured. This method only measured leakage through the pipe walls.

This leak-test was adopted to reduce the risk for structural deterioration when acidic groundwaters infiltrated through the concrete. At that time leakage control dealt primarily with structural aspects and not with problems caused by increased sewage flows due to infiltration.

The same method for a sewer pipe leakage test was also included in the concrete sewer pipe standards adopted in 1949, Figure 1.9.

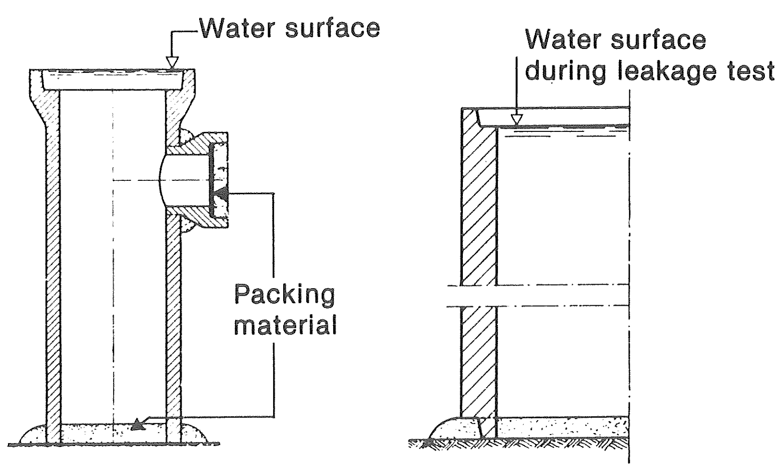

Figure 1.9 Pipe wall leakage test from 1949. Test made by measuring the sinking rate of the water surface in an upright, water filled pipe.

Leakage control of sewer pipes and sewer joints together was for a long time a neglected area. In the 1950's there were several methods for leakage control but no standardized ones, although better methods were sought.

Unofficial guidelines for leakage control of constructed sewers were used during the 1960's. The VAV established guidelines for water and air leakage tests of rubber ring jointed concrete sewer pipes in 1968. Three years later corresponding guidelines for PVC-pipes were also established and these included control of pipe deformation.

Even though joint and pipe materials have improved, the quality of the constructed sewer is still highly dependent on the skill of the craftsmen.

Interest in leakage control testing was in many cases low even in the 1970's. This is illustrated by a survey carried out by VAV in 1973 where only 44% of the local communities stated that they performed leakage control tests when sanitary sewers were built using internal resources. If contractors were used it was stated that most sanitary sewers were tested for leakage. Interest in leakage control of storm sewers was much less than for sanitary sewers.

Standardized descriptions for sewer construction in Sweden were published in VA AMA (1966). This includes several type drawings and detailed installation instructions. Extended and revised versions were published in 1972 and 1983.

1.3 Swedish Sewer Systems - Current Issues

Sewer systems represent a tremendous investment. As the intensive construction activity during the 1960's and the 1970's gradually subsided it was discussed more and more how to improve the operation and how to increase the life expectancy for the sewer systems. At the end of the 1970's many sanitary engineers in Sweden considered that the management of sewers would be an important part of the future economy of the water and sewage utilities.

Despite the relatively young age of Swedish sewers it is obvious that they often do not perform satisfactorily. Many sewer surveys have now been initiated with the intention of improving the knowledge of the sewer systems or highlighting operational aspects. The objectives vary but some common ones are:

* Reduction of infiltration/inflow in separate sewer systems

* Reduce pollution loadings from combined sewer systems without an expensive replacement with separate sewers

* Prediction of overload frequencies in combined sewer systems

The structural aspects have been highlighted less. This can be explained by the rather low average age of the sewer systems and that no increase in sewer collapses has been found in the reported statistics. The lack of a simple method for the reliable evaluation of structural defects has also been a limiting factor.

2 INFILTRATION/INFLOW IN SEPARATE SEWER SYSTEMS - APPROACHING THE PROBLEM

A substantial intrusion of groundwater or stormwater into the separate sanitary sewer system causes problems in both the transport and the treatment of wastewater. Problems may occur as heavy peak flows for limited periods of time or as a more sustained flow increase over a longer time period.

Higher peak flows often result in environmental loadings due to a reduction of treatment efficiency. In addition when overflow occurs the untreated wastewater is discharged directly into the receiving water. Sanitary problems also occur if peak flows result in basement floodings.

Sustained but more moderate flow increases over long periods result in large volumes of water which have to be transported and treated. This results in increased pumping costs and increased chemical costs in treatment plants with chemical treatment assuming that the chemicals in the treatment plant are dosed relative to the incoming flow. Very large investments are needed if the remaining capacity of the sewer collection system or of the treatment plant are low and new areas are planned to be connected to the sewer systems. A very expensive extension of the capacity may then be required.

The intrusion of groundwater and stormwater may also lead to increased loadings of discharged pollutants from the wastewater treatment plants. This is thoroughly discussed by Jacobsen (1979).

Subsidences can occur in developed areas built upon sensitive clays if the groundwater table is lowered. This can be caused by many factors, one of them being groundwater drainage due to leaking sewers.

Many investigations have studied groundwater or stormwater intrusion into separate sewer systems in Sweden. Still there is surprisingly no national compilation of the magnitude of the problem.

2.1 Terminology

There are many different expressions and definitions which can be used for the description of groundwater or stormwater intrusion into separate sanitary sewers. The definitions used in Sweden do not always correspond to those used in other countries. Furthermore, in Sweden there are many different definitions and expressions used by different companies or organizations.

This confusion can be explained by the different approaches, views and levels used when studying these problems. There appears to be no general concensus about the definition of terms in this field.

The following is an attempt to explain the approaches which lead to the different expressions. The discussion does not claim to be complete.

Definitions can be derived from or related to:

a) the sources: Definitions can vary greatly. A clear example of this is the definition of "infiltration" and its distinction from "inflow".

Swedish hydrologists, according to Nordic Glossary of Hydrology (1984), define infiltration both as "Penetration of water from the soil surface into the soil" and "Flow from a porous medium into a channel, drain reservoir or conduit".

According to TNC (1977) sanitary engineers in Sweden should define infiltration, in Swedish, as the intrusion of liquid into a porous material, e.g. the intrusion of water into the ground. TNC then recommends the Swedish word for leakage for the entry or loss of water due to leaking sewers and this is often used in combination with the direction of the flow i.e. in or out.

On the other hand WRC defines infiltration as "entry of groundwater into sewer" (WRC 1983), while the American literature (WPCF, 1983) separates infiltration, as the water entering from the ground and inflow, as the water discharged directly to the sewers.

Other more straightforward descriptions of the sources, which can also be found in the literature, include surface water, drainage water and water from roofs.

b) <ins>the time scale</ins> Definitions can also be related to a time scale. There are two major types of time dependent definition, firstly the response time related to rainfall and secondly long term groundwater table fluctuations.

The first type of time dependent definition is used when evaluating flow measurements in a sanitary sewer system during a rainy period. There is a rapid response of rainfall runoff, typically due to connected surface areas. There can also be a more delayed response due to the transport of water through the ground before its intrusion through untight joints. Expressions used to define these include rainfall-induced infiltration/inflow and indirect or direct inflow.

The intrusion of groundwater is an example of the second type of time dependent definition which shows seasonal variations. These variations can be expressed as for example the "dry weather minimum night flow" in the sanitary sewer during periods of a high or low groundwater table.

Other expressions are often used to give a summarized description (some of them are translated directly from Swedish) and include unwanted water, irrelevant water, extraneous water or, as summarized in the earlier discussed expressions, total infiltration/inflow. Words like baseflow are often used in the literature with different meanings.

The expressions described here are often used rather indistinctly. As this thesis is written in English the expressions are those commonly used in the English written literature. Since this subject has been extensively covered in the United States the definitions of infiltration/inflow used in this summary are as described in WPCF (1983). However, when strictly examining the definitions used throughout this publication one finds several different definitions in conflict with the definition of infiltration/inflow initially stated.

Problems arise when trying to combine different approaches. An example is if infiltration and inflow (as described above) are used assuming the infiltration always has a much longer time lag than inflow. This is not the case for the intrusion of stormwater which has leaked out of the storm sewer, been transported through the backfill and finally intruded into the sanitary sewer, as is described in Chapter 3. The timelag here is about the same as that for connected roofs. As a combined expression for this type of flow it has been proposed that "Rainfall-induced infiltration" should be used (WPCF 1983, Glasgow 1985). The following definition of rainfall-induced infiltration can be found in WPCF (1983): "Rainfall-induced infiltration, a category between infiltration and inflow, is an increase in infiltration caused by rainfall-induced changes in subsurface conditions".

However, rainfall-induced infiltration is a summarized description of different types of infiltration and furthermore the flow described in Chapter 3 may also exist during dry weather periods if a flow in the stormwater pipe is generated by snow melting or drainage water.

Since this thesis deals, to a great extent, with this specific infiltration problem with a rather high flow and a very short time lag, no short and suitably well defined expression could be found. Therefore a more specific expression, "cross-leakage flow" is introduced and sections in the sewer trenches where cross-leakage flows occur are called "cross-leakage sections". The expressions "infiltration" and "inflow" are used for water entering the sewer from the ground and water discharged directly into the sewer respectively. The term "infiltration/inflow" is the total quantity where the sources are not distinguished.

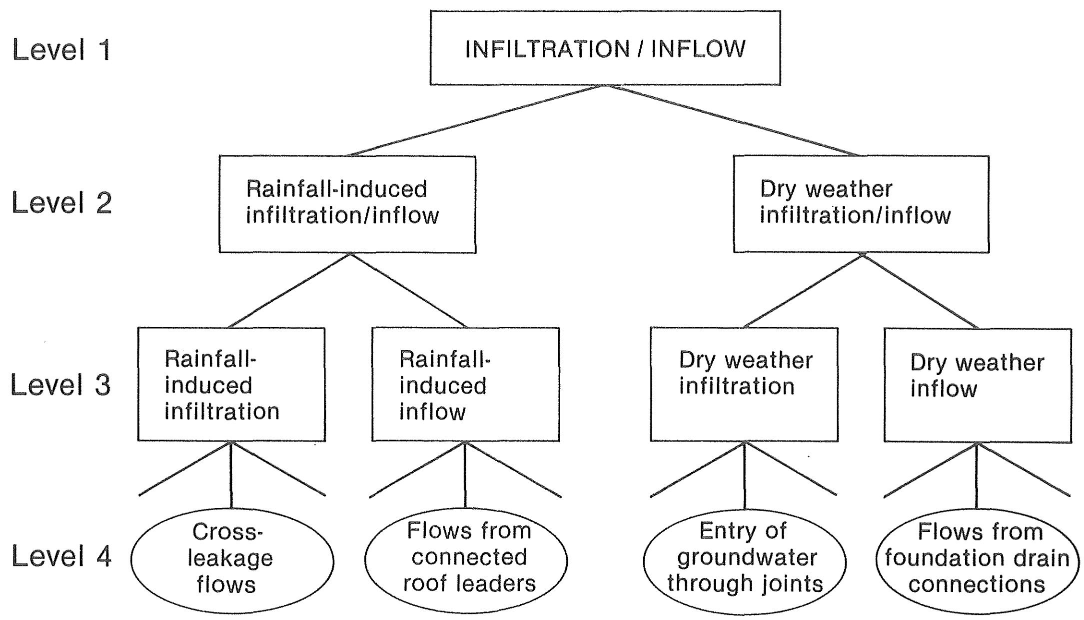

Figure 2.1 The relationship between different infiltration/inflow expressions.

In Figure 2.1 a scheme of the different expressions used in this thesis on infiltration/inflow are presented where the relative positions of different expressions are shown. The scheme can be used as a logical approach to identifying the actual problem source. As the level number increases the definitions become more specific.

The fourth level in Figure 2.1 shows examples of possible sources. However, cross-leakage flow may also occur at level 4 for dry weather infiltration, as mentioned earlier, if the storm sewer systems are loaded with long term groundwater flows which, during dry weather conditions, can then enter the sanitary sewer through cross-leakage sections.

Several terms are also defined in the Glossary.

2.2 Strategy for Infiltration/Inflow Surveys

In Sweden, many sewer system surveys have been initiated in order to assess the magnitude of infiltration/inflow problems. Survey techniques are well described in the literature (WPCF 1983, Peterson 1984).

Flow measurements are a first requirement during infiltration/inflow studies. Infiltration/inflow in the sanitary sewer can be disclosed by an increase in flow during storm events, a high groundwater table or snow melt. The total flow increase is the result of all upstream sources. A strategy of efficient stepwise localization of these sources aids their identification. Most of the efforts can then be concentrated to the parts of the sewer system where the dominating infiltration/ inflow sources exist.

When working with sewer systems it is easy to recognize three major limitations:

* Long total sewer length, both on public and private property.

* Underground utilities, such as sewer systems are difficult to inspect.

* Weather dependent investigations are difficult to schedule.

The sources of infiltration/inflow can be widespread throughout the whole sewer system but the consequences may only become obvious at the treatment plant.

If there are no parts of the sewer systems which are a priori suspected of containing major infiltration/inflow sources, the first step in the flow survey should be flow measurements in the major sewer line branches. Substantial parts of the sewer system can then be declared either containing or not containing major infiltration/ inflow sources. The specific survey cost, i.e. survey cost per meter of surveyed sewer network, is relatively low.

The results of the flow survey provide the base for more intensive flow measurements in the most suspected sewer line branches. As flow measurements are carried out further upstream in the sewer network, considerably less sewer length is included in each measurement and therefore the specific survey cost increases.

When the infiltration/inflow survey has reached the stage where the different specific sources can be localized, the specific survey cost increases dramatically. Methods for the precisely locating of infiltration/inflow sources include CCTV-inspections, roof leader control and small scale flow measurement setups in one or a few manhole distances. Some variations on the last method are discussed in Chapter 3.

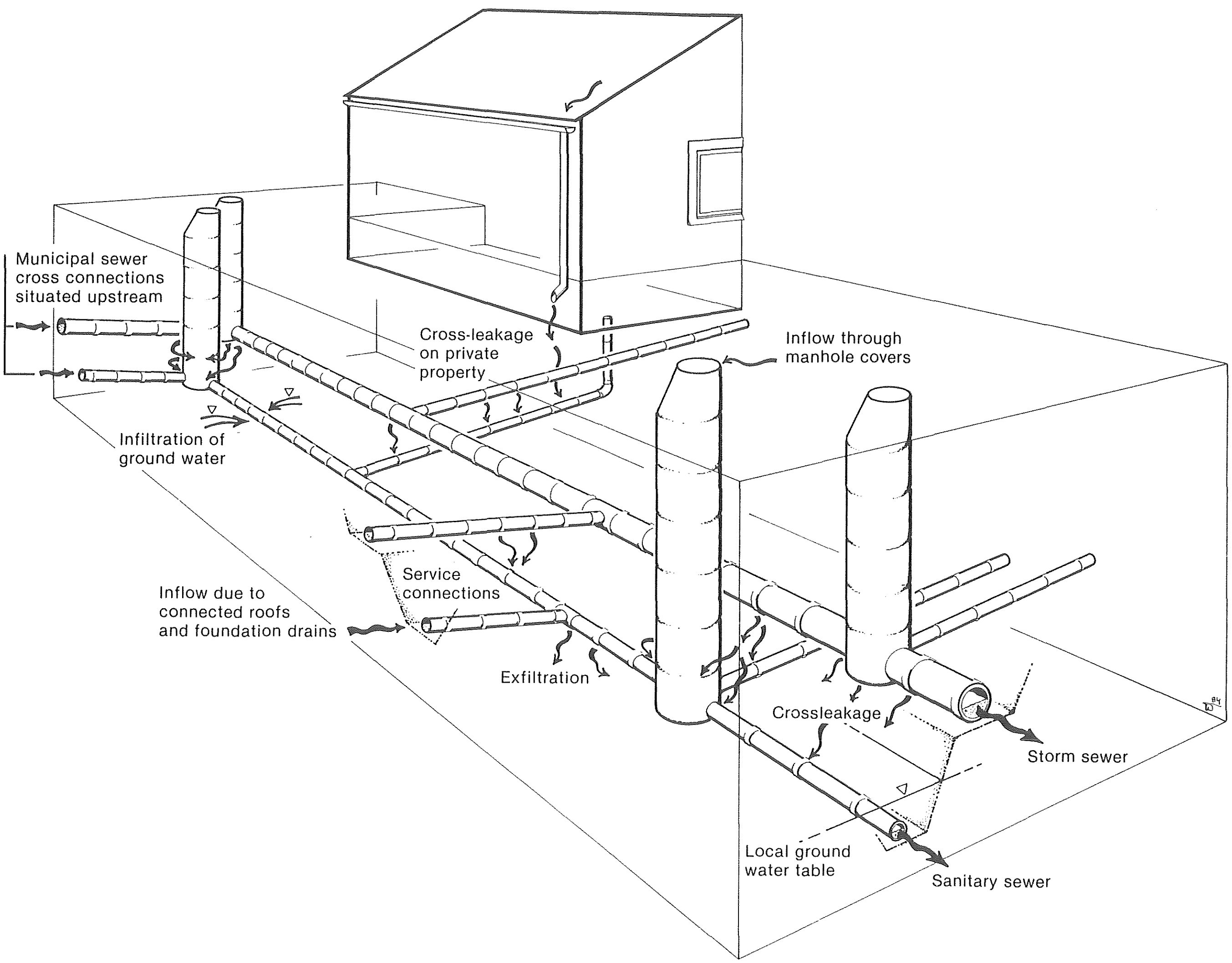

Figure 2.2 Possible infiltration/inflow sources into a typical Swedish sanitary sewer.

Potential infiltration/inflow sources of stormwater or groundwater entering a separate sanitary sewer are shown in Figure 2.2. All of these do not necessarily occur within the same sewer line. In Swedish sewer trenches, the water main is situated above the sanitary sewer and leaking drinking water may also percolate through the backfill and intrude into the sanitary sewer.

The existence and magnitude of different infiltration/inflow sources, as shown in Figure 2.2, are dependent on many parameters which are normally very poorly known. The importance and relevance of the different parameters depends on the type of infiltration/inflow source. Some of the important parameters are:

* local geohydrological conditions (soil material, groundwater table)

* type of sewer trench construction

* sewer pipe material quality

* sewer pipe jointing methods

* workmanship

* connected impermeable surfaces.

When looking at all possible sources of infiltration/inflow it is important to keep in mind the normal lack of knowledge about the real conditions in the sewer trenches. Thus a reduction of infiltration/inflow requires a thorough localization and identification of the sources which contribute the most. It is important that the infiltration/inflow survey be sufficiently thorough if the results are to be used as a base for choosing the proper measures. Large sums of money can be wasted if, for instance, sewer renovation is carried out in the wrong part of the sewer system or if inappropriate rehabilitation methods are chosen.

The specific survey costs, even for the most expensive survey techniques, normally represent only a minor fraction of the total specific cost of measures for the reduction of infiltration/inflow problems.

2.3 Flow Measurements - An Important Tool in Infiltration/Inflow Surveys

Flow measurements are commonly used in both general sewer surveys and in more specialized surveys such as those investigating infiltration/inflow problems. Many instruments have been developed around the few available flow measurement principles.

Hydraulic flow measurement theory and flow measurement methods are well known (DHL 1976, Ven Te Chow 1959). Some sewer line flow measurement methods are also briefly outlined in publication 8.

There are several potential sources of error for flow measurements in sanitary sewers. These include:

* Using a flow measurement method based on a hydraulic theory which is only valid for specific hydraulic conditions. These conditions are often not met in a sewer system.

* Inaccurate instrument installation, sensor signal interpretation and conversion of the measured parameter into a flow.

* Maintaining high accuracy over the whole instrument range.

Each flow measurement method has its own limitations and sensitivity to deviations from ideal hydraulic conditions. Therefore knowing the sensitivity of a specific flow measurement method in a specific sewer, combined with practical experience, is essential if reliable measurements are to be made.

There is, however, surprisingly little written on the total flow measurement accuracy for the different flow measurement methods when they are used in sewer manholes.

A very interesting and revealing study on the measurement accuracy of flow measurement equipment installed in sewage treatment plants has been carried out by Vedum (1981) in Norway. Some of his findings were that the total relative error was less than +/-50% at only 4 of the 15 treatment plants investigated. In one treatment plant using a v-notch weir the relative error was as high as +186%.

A higher demand for flow measurement accuracy also implies a higher measurement cost if more expensive instrumentation has to be chosen. Therefore it is important to carefully examine the purpose of the flow survey and thereafter decide on the required accuracy. A higher absolute accuracy can result in fewer flow surveys if only a fixed sum of money is available (Figure 2.3).

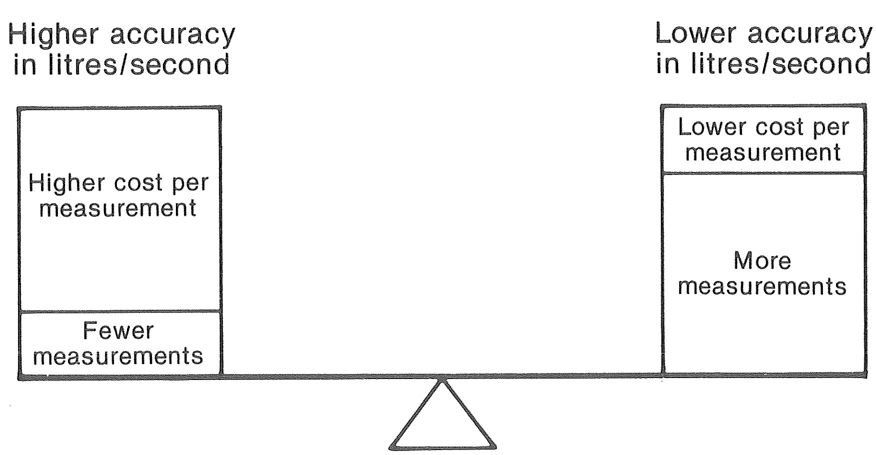

Figure 2.3 The "benefit balance" weighing many low accuracy measurements with a low unit cost against a few accurate measurements with a high unit cost.

It is also important to document, together with the flow measurement result, the flow measurement procedure and all assumptions made when calculating the flow. Otherwise it is very difficult afterwards to estimate the flow measurement accuracy or, if repeated measurements are carried out, to compare the results.

A study of flow measurement accuracy was carried out, within this project, under controlled conditions in a 24 m long, 225 mm diameter laboratory concrete sewer line. The three measurement methods studied were:

* level sensing at normal depth, i.e. flow measurements in open channels by water level gauging

* level sensing of water depth in a small Palmer-Bowlus flume

* simultaneous measurements of velocity and depth.

The results and many detailed aspects on the flow measurement accuracy of these methods are discussed in publications 3, 4 and 5). Figure 2.4 is a typical example of the complexity and multiple error sources which can occur when gauging the water level in an open channel and converting the measured water level into a flow.

The method shown in Figure 2.4 is commonly used because of its simplicity. However, it is very sensitive to deviations from the required hydraulic conditions at the measurement site. For example subsidences just upstream of the manhole cause a water depth which cannot be the assumed "normal" by definition and therefore the equation used is not applicable. In practice, even with a rather constant slope, it is difficult to estimate the roughness coefficient and the in situ slope.

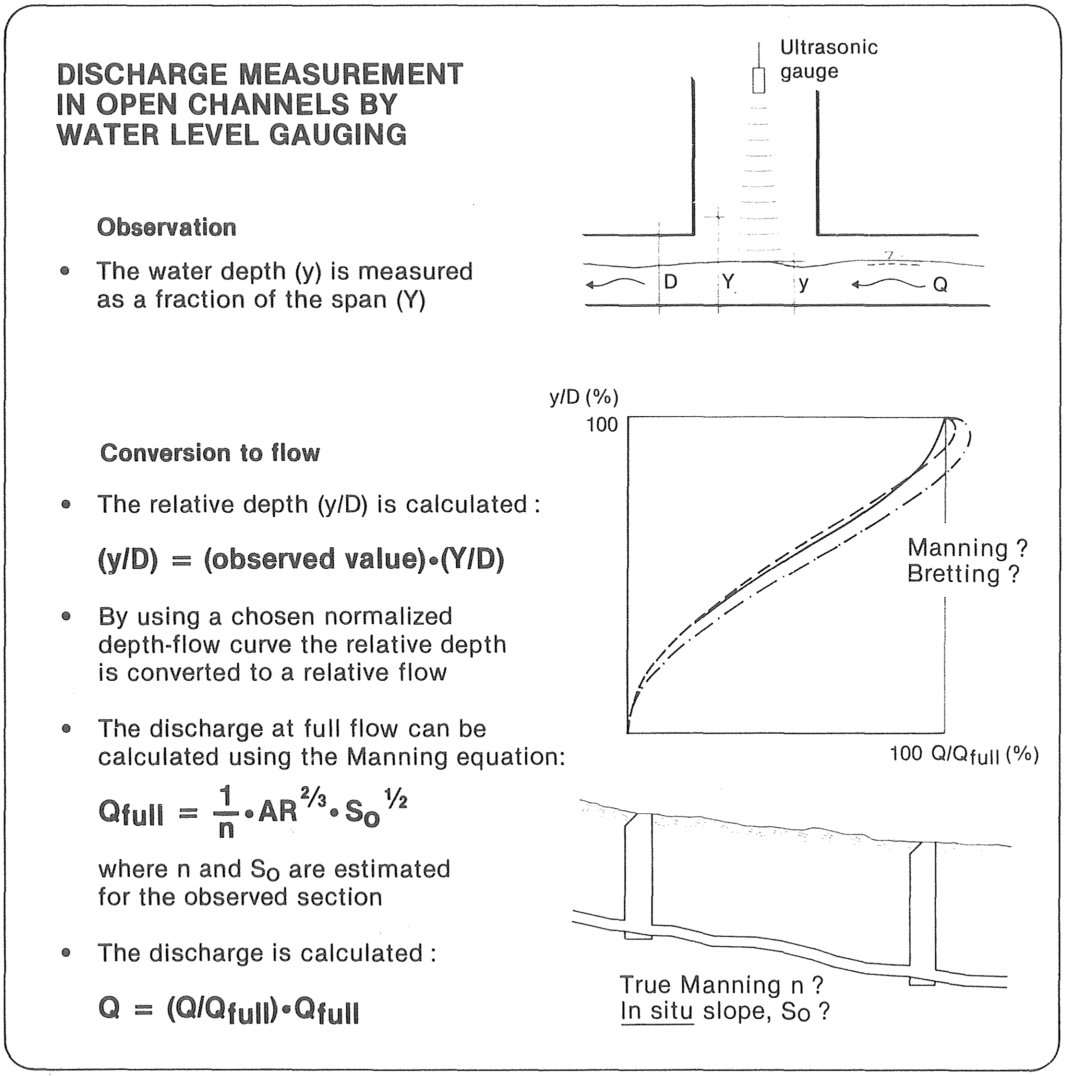

Figure 2.4 Outline of a discharge measurement procedure for open channels by water level gauging.

Even in this "ideal" constructed sewer line, the total flow measurement error for "level sensing at normal depth" was found to be very high. In Figure 2.5 the relative error is shown for two different ultrasonic measurement devices. The total error varies from about +/-25% to +/-50% depending on the flow.

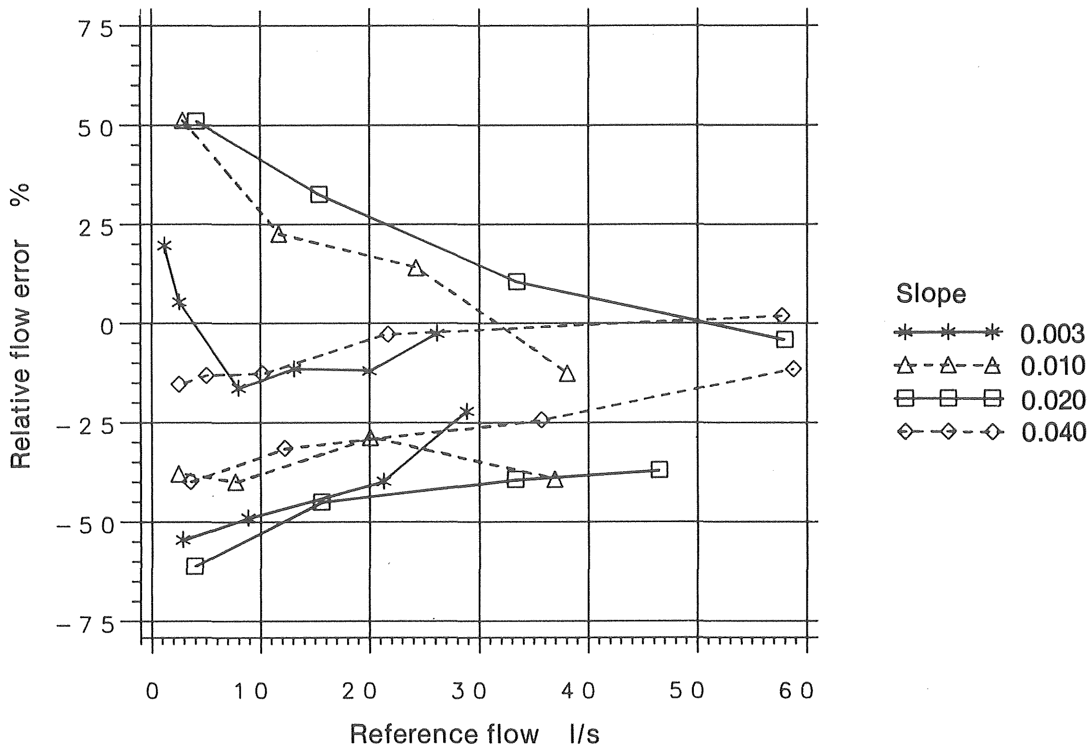

Figure 2.5 Example of relative errors for discharge measurements by level gauging at normal depth without calibration of the measurement section. Level gauging by ultrasonic devices.

The poor measurement accuracy in this "ideal" concrete sewer line may at first be surprising but it is easier to understand if all different sources of errors, as shown in Figure 2.4, are considered.

The influence on accuracy due to an erroneous determination of water depth can be examined. This error is the cumulative error due to instrument installation, small variations in water depth, interpretation of a disturbed water surface by the measurement instrument and recording of the result.

The error due to erroneous water depth determination is shown in Figure 2.6. The figure is theoretically constructed by gradually displacing the normalized depth-flow curve. The water depth measurement error is expressed as a percentage of the pipe diameter. For example water depth measurement errors of 5 mm and 10 mm in a 225 mm diameter sewer pipe result in flow errors close to the +/-2.5 and +/-5 lines respectively in Figure 2.6.

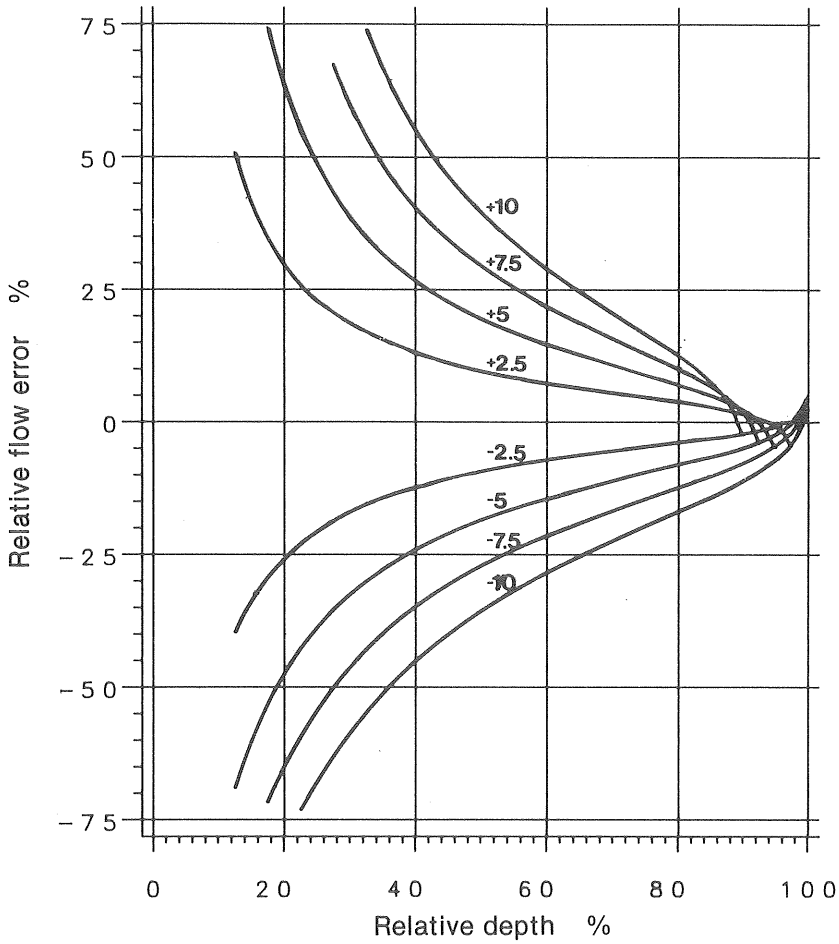

Figure 2.6 Relative discharge error caused by erroneous level gauging as a function of relative depth. The error of the level gauging (+10, +7.5, ..., -10) is expressed as a percentage of the pipe diameter.

It is very useful when estimating the obtainable accuracy in practice to firstly test or estimate the error in measured water depth. Thereafter the flow accuracy can be estimated for different water depths. Other sources of error must be added to this estimate.

3 INFILTRATION INTO SANITARY SEWERS CAUSED BY LEAKING STORM SEWERS

In this chapter infiltration into sanitary sewers caused by leaking storm sewers will be considered. The infiltration discussed here is characterized by a very short response time such as those of roof drain connections and potentially high flows. Infiltration of this nature will be called "cross-leakage" between storm and sanitary sewers. (See Chapter 2.1.)

It is important to stress that only cross-leakage problems are discussed in this chapter. The order in which one should investigate different types of infiltration/inflow sources is not included either.

3.1 A Methodology for the Localization and Quantification of Cross-leakage Flows

There is a potential risk of cross-leakage in the separate sewer systems in Sweden since sanitary sewers are normally constructed at a lower elevation than storm sewers (Figure 3.1).

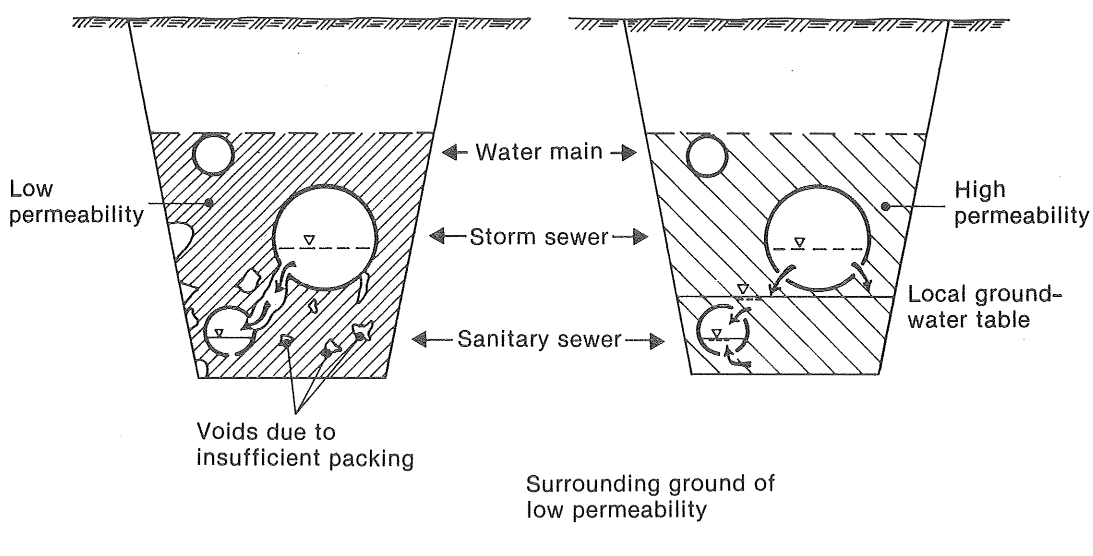

Figure 3.1 Cross-leakage sections in typical Swedish trenches.

If the sewer pipes or joints are not tight then cross-leakage flow between the two sewer systems is dependent on either relatively high permeability in the trench backfill or the formation of small channels due to washout in low permeable backfill material. A low permeability in the material outside the sewer trench prevents exfiltrated stormwater from percolating down to the groundwater table and therefore increases the likelihood of heavy cross-leakage flow.

Many types of cross-leakage sections can be found. In Figure 3.2, seven different types of cross-leakage sections are shown. Types 1-5 are situated in the municipal sewer system and types 6 and 7 on private property. Cross-leakage on private property is not considered here.

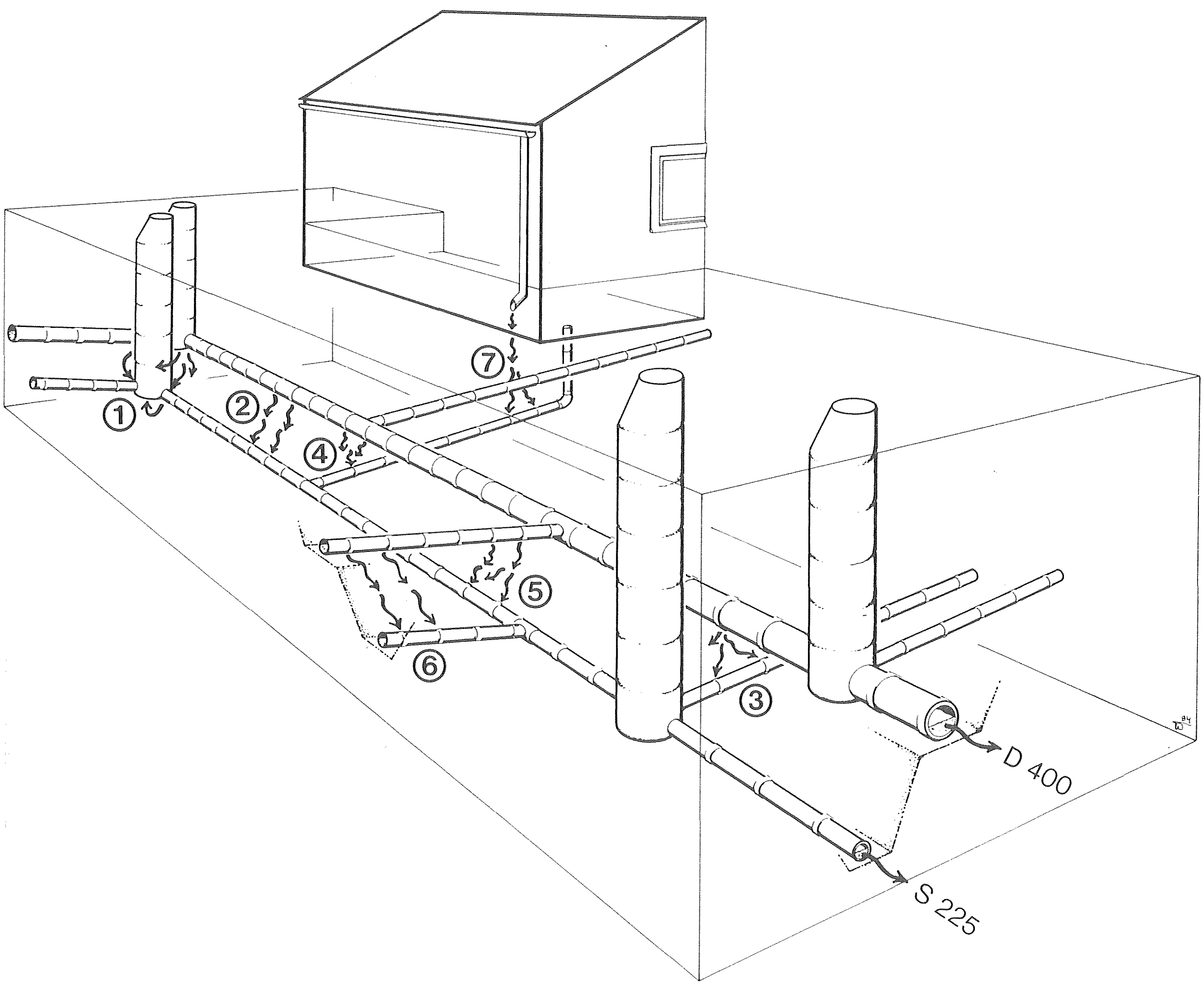

Figure 3.2 Different cross-leakage sections in separate sewer systems.

If cross-leakage flows are found and actions are planned to reduce the cross-leakage flows, such as joint sealing techniques, it is important to determine the location and the type of the cross-leakage section. Large sums of money would otherwise be wasted if the measures are carried out in the wrong part of the sewer. This is the case, for instance, when only the municipal sanitary sewer is being renovated by joint-sealing but the dominant cross-leakage sections are similar to type 4 (Figure 3.2).

The cross-leakage sections can, depending on the local conditions, either be concentrated around one or a few joints or be more evenly distributed along the sewer line.

In Sweden the cross-leakage problems were discussed during the 1950's (Cronström, 1954) when separate sewer systems became more common and the available jointing methods did not always result in joints of high tightness. Cross-leakage problems have also been described by Peterson et al (1978), VAV (1978, 1979) and Peterson (1984). Reference can also be found in the American literature, EPA (1970, 1971, 1975, 1977) and WPCF (1983).

Many methods for cross-leakage measurements are listed in the literature. Detailed descriptions and critical evaluations are generally not found. Very little can be found on the practical limitations of carrying out a cross-leakage survey, on the possibilities for further evaluating results using different methods or on the estimation of survey costs.

Each method described in the literature for disclosing cross-leakage sections can be, in general, divided into two parts, stormwater simulation and cross-leakage flow detection.

1) Stormwater simulation

   Simulation of stormwater by flushing the storm sewer with water from a fire hydrant. Tank trucks may be used if fire hydrants are not available as a water source. The flow in the storm sewer can be a free flow. If plugs are used, a greater water depth in the storm sewer can be achieved. If necessary a dye or a radioactive tracer can be added to the hydrant water.

2) Cross-leakage flow detection

   Cross-leakage sections can be disclosed through visual manhole inspections, CCTV-inspections, flow measurements or detectors if using radioactive tracers.

The purpose of the survey will determine which method should be used. The method chosen may also depend on the availability of personnel, equipment and economic resources. The methods described here have been developed with respect to the purposes of this research project, i.e. to accurately quantify cross-leakage flows.

For the investigations summarized in this thesis the three cross-leakage survey techniques used are:

1) Measurements of exfiltration from storm sewers.

2) Measurements of cross-leakage flow using free flowing stormwater and continuous flow measurements in the sanitary sewer.

3) Measurement of cross-leakage flow by plugging the stormwater sewer and filling it up with hydrant water combined with continuous flow measurements in the sanitary sewer.

The above order also represents a gradual increase in specific survey cost (Publication no. 6). Several reservations concerning the estimation of sewer survey costs must be made and this order for specific survey cost is only valid when the different methods are used as described hereafter.

The dominant costs, excluding travel costs, for these surveys are time costs for the staff, including time for installation, performing and closing down the survey. The measurement time depends on the chosen method, performance and ambitions for the survey and skill of the personnel. The major factor influencing the specific survey cost is the chosen length of the examined sewer. The longer the length the lower the specific costs.

Before presenting these methods in the given order, it is important to stress that an economic and sensible use of survey resources should normally start with flow measurements according to the strategic plan of action discussed in Chapter 2.1. High specific cost methods for detecting cross-leakage flows can normally only be justified when the sewer system to be examined is known to receive large flows of rainfall-induced infiltration/inflow.

In practice it is often difficult to strictly follow a specific order. In many instances the most suitable combination of methods can only be decided after a site inspection.

Method 1: Measurements of Exfiltration from Storm Sewers

If no specific parts of the sewer system are especially suspected of containing cross-leakage sections, yet the whole system suffers from rainfall-induced infiltration/inflow, it can be useful to start with an exfiltration test. If there is no exfiltration from the storm sewers, no cross-leakage flow can exist. Exfiltration indicates a potential risk for cross-leakage flow.

It is important to choose a relatively long storm sewer length for the exfiltration test, typically 10-15 manhole distances, if a low specific survey cost is to be achieved. The exfiltration method is outlined in Figure 3.3. The hydrant water flow is measured by a water meter situated at the fire hydrant. The remaining stormwater flow in the downstream storm sewer manhole is measured by a calibrated weir and a point gauge (accurate mechanical level gauging instrument).

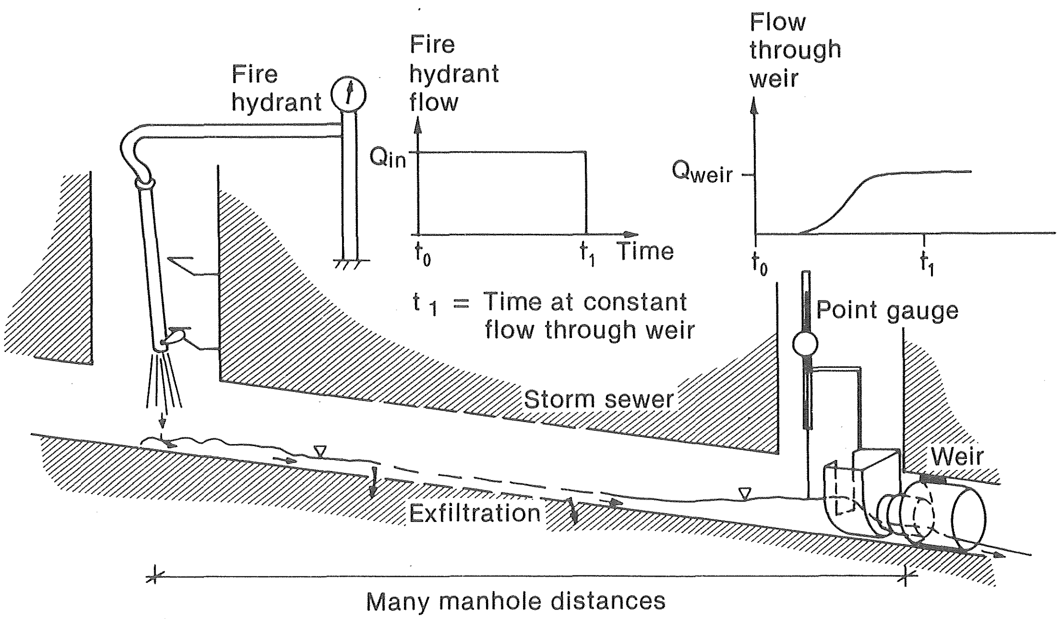

Figure 3.3 Measuring exfiltration from a storm sewer.

If no significant loss of the stormwater flow is found no further action is required in this sewer line. On the other hand, a significant loss of stormwater indicates the possibility of cross-leakage. If a substantial increase of flow in the downstream sanitary sewer can be visually estimated, the need for further investigations is even more obvious. At this stage it is important to exclude parts of the sewer line not containing cross-leakage sections. This can be done by a visual inspection of the intermediate sanitary sewer manholes.

The visual inspection should reveal between which two consecutive manholes the flow increases and this increase in flow cannot be explained by anything other than cross-leakage flow.

A limited visual inspection into sewer pipes can also be made using a sewer periscope (Figure 3.4). The sewer periscope, consisting of a halogen spotlight and a mirror mounted on a PVC-pipe is described in publication no. 7. In an unobstructed 225 mm sewer pipe at least 10 m of the pipe can often be inspected using the sewer periscope. The inspection length possible is also dependent on the size of the object to be observed.

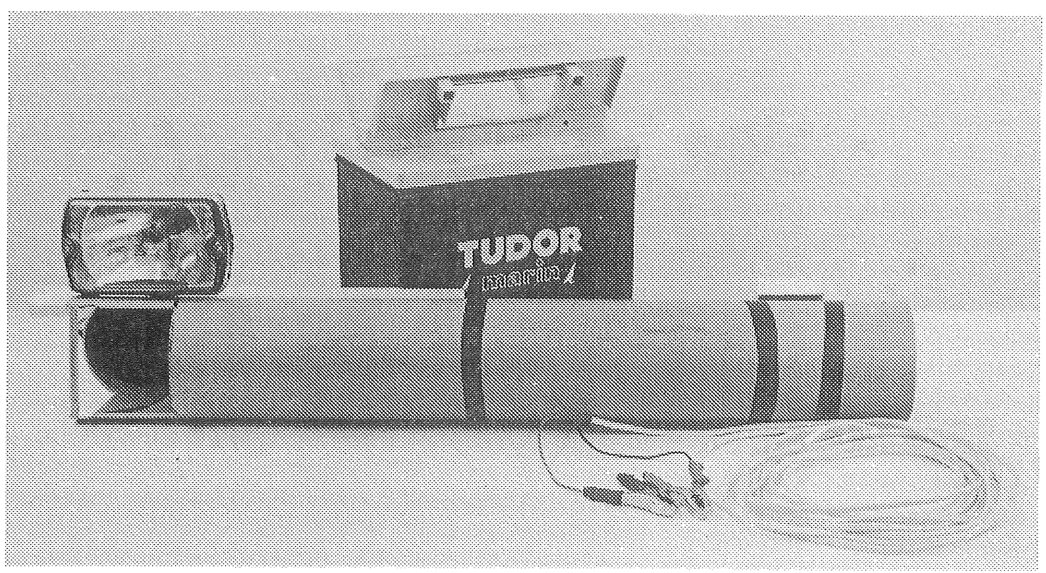

Figure 3.4 The sewer periscope (Photo: Thomas Eriksson).

Depending on where the cross-leakage sections are situated the cross-leakage flow may be seen from the manholes. In Figure 3.5 the intrusion of cross-leakage flows into the sanitary sewer is concentrated to a leaky manhole connection and in Figure 3.6 to some untight joints in the sanitary sewer pipe.

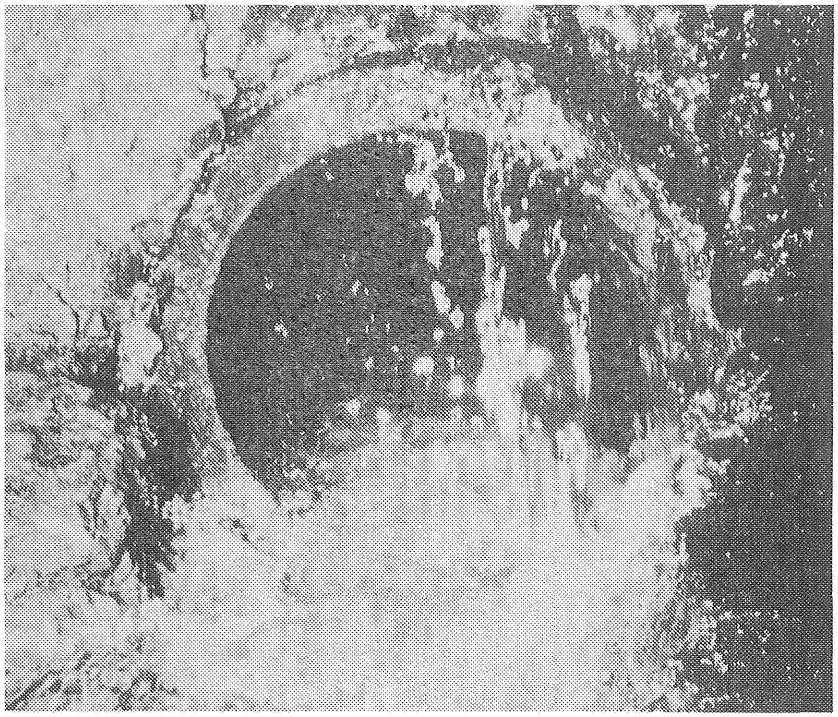

Figure 3.5 Intrusion of cross-leakage flow through deficient manhole connections.

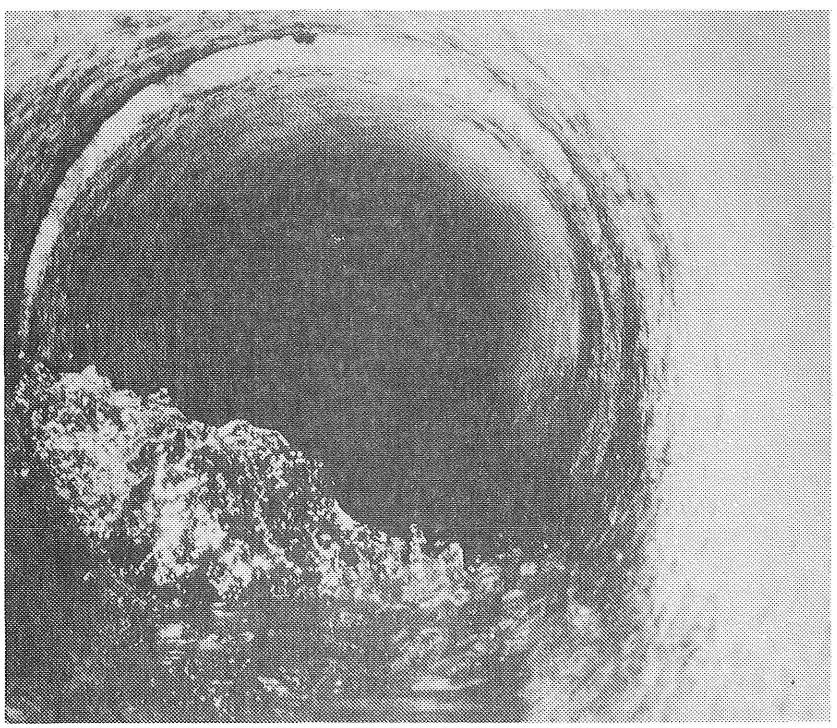

Figure 3.6 Intrusion of cross-leakage flow through defective pipe joints.

If no accurate quantification is required then sufficient information may already have been gathered. A CCTV-inspection of the sanitary sewer while running hydrant flow into the storm sewer can locate other cross-leakage sections if it is felt that the visual inspection of manholes did not give enough information. When a quantification of cross-leakage flows is needed it can be achieved by the second method.

Method 2: Measurements of Cross-leakage Flows Using Free Flowing Hydrant Water in the Storm Sewer.

The cross-leakage flow is quantified as the change in flow in the sanitary sewer due to a flushing of fire hydrant water into the storm sewer. Continuous flow measurements are carried out in the sanitary sewer during the cross-leakage test (Figure 3.7).

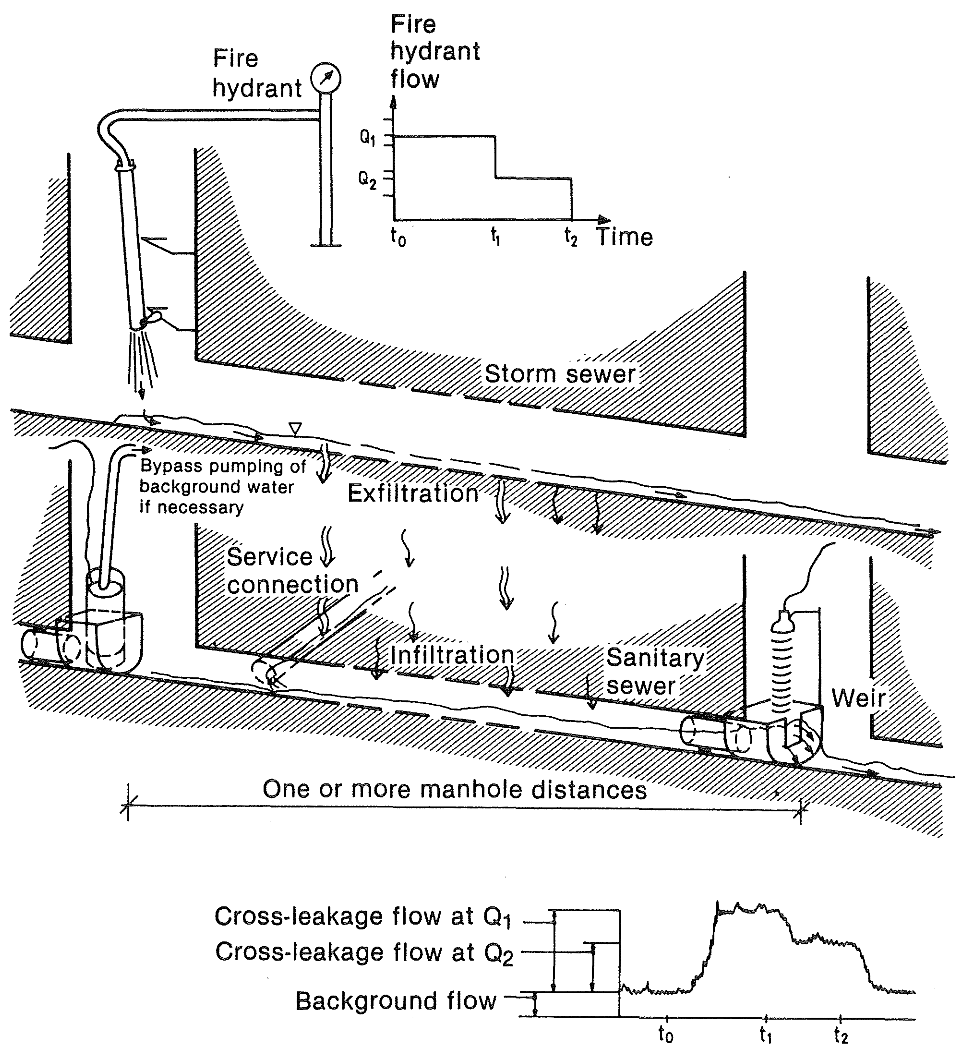

Figure 3.7 Sketch over instrumentation setup for quantification of cross-leakage flows.

A convenient sewer length for this type of survey is 1-5 manhole distances. A longer sewer length reduces the specific survey cost but it makes it harder to isolate different cross-leakage sections.

Stormwater is simulated as in Method 1 and the maximum fire hydrant flow available is directed into the storm sewer. A small weir is installed in the downstream manhole and the water level is measured using an ultrasonic device. To achieve accurate flow measurement it is important to choose a suitable flow measuring interval according to the expected flows. A weir with an unsuitable capacity or design will not be sensitive to small changes in flow.

A suitable weir capacity is hard to predict. Therefore it is convenient to use a weir with an interchangeable front (Figure 3.8). By changing the front with another weir-form it is easy to obtain a more suitable measurement interval and thereby achieve a higher flow measurement accuracy.

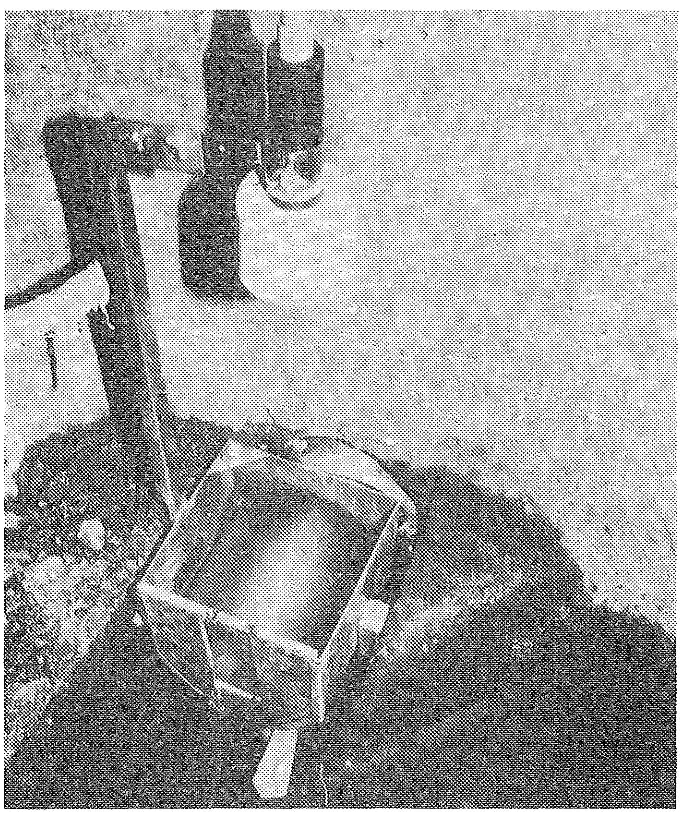

Figure 3.8 Flow measurement in a sanitary sewer manhole using a small weir with an interchangeable front and a ultrasonic device.

If a cross-leakage section is located and the results of the survey are to be used for rough estimates of, for instance, the yearly quantities of cross-leakage water, then it is useful to examine the cross-leakage flow at different stormwater flow rates. The fire hydrant flow can then be reduced to about half capacity. Any fire hydrant changes must be noted on the recorder chart to allow easier evaluation.

The cross-leakage flow is the difference between the sanitary flow while running hydrant water into the storm sewer and the background flow measured before and, preferably, after running the hydrant flow.

If the sewer line is situated far up in the sewer system the background flow does not usually cause any severe problem. If the background flow is the dominant flow then it can be hard to separate out the increase in flow caused by cross-leakage sections. Upstream flows should then, if possible, be bypassed to reduce the background flow. Otherwise other methods, e.g. tracers, must be chosen.

Method 3: Measurements of Cross-leakage Flow by Plugging the Storm Sewer and Filling it up with Hydrant Water

The available fire hydrant flow is usually about 10-15 litres/second which results in a rather small water depth, especially in a large diameter storm sewer. If the storm sewer is plugged and filled with hydrant water, cross-leakage flows at higher stormwater depth can be measured. The flow in the sanitary sewer is measured as in Method 2.

Normally this method can only be used to examine short distances, depending on the slope of the storm sewer and the maximum allowable backwater level. If a water level in the storm sewer is allowed to reach the crown of the pipe just upstream of the plug, only 80 m and 40 m will be examined in a 400 mm storm sewer, for a slope of 0.005 and 0.010 respectively. Since the specific survey cost is sensitive to the surveyed sewer length, a high specific survey cost will result if only short distances can be included in one measurement. Additional problems arise when evaluating the results since the water depth varies in the storm sewer along the examined sewer length. This is discussed in more detail in publication no. 6.

If high specific survey costs are expected, the plugging method should only be carried out after using Method 2. In any case it is likely that cross-leakage sections of importance would have already been revealed by Method 2.

The use of plugs can be useful in low gradient and large diameter storm sewers where a hydrant flow achieves a very low water depth relative to the pipe diameter. It is very important to ensure that no hazardous working conditions exist downstream from the plug.

3.2 Measured Cross-leakage Flows

Cross-leakage flows have been studied in 35 different sewer lines. The examined sewer lines have been mainly chosen amongst separate systems constructed in the early 1960's or earlier. The total length of the examined sewer lines is slightly more than 5 km. Investigation sites were situated in Göteborg, Borås and Växjö, Figure 3.9.

Figure 3.9 Map of southern Scandinavia showing the cities of Göteborg, Borås and Växjö.

The results are briefly outlined in Table 3.1. If several fire hydrant flows were used in the same sewer line only the results using the highest hydrant flow are included in Table 3.1. A comprehensive presentation of the results is given in publication no. 6.

In general the results can be summarized as follows:

* The presence and distribution of cross-leakage sections has been found to be very unpredictable and irregular. Cross-leakage sections in some of the sewer lines were concentrated to a limited part or to a limited number of joints while in others the sections were more scattered.

* In several sewer lines, consisting of one or a few manhole distances, cross-leakage flows of up to 8 litres/second could be measured when the hydrant flow in the storm sewer was of the order 8-20 l/s.

* In sewer lines containing cross-leakage sections between 20 and 90% of the hydrant flow flushed into the storm sewer could be found in the sanitary sewer.

* All the cross-leakage flows found in this study had a very short response time when starting up the test, when changing hydrant flows and when closing down the test. These cross-leakage sections could not, in flow surveys made during wet weather conditions, be separated from connected contributing areas like roofs and parking lots.

* In many sewer lines no cross-leakage flows could be found despite visually observed deficiencies such as subsidences and signs of infiltration such as iron precipitation around untight joints.

* The age of the sewer is not a good criterion for suspecting the presence of cross-leakage sections, although when poor jointing techniques have been used in older sewers the probability of cross-leakage flows increases. The cross-leakage flows are then highly dependent on the geohydrological conditions.

* Even in sewer trenches likely backfilled with low permeable materials cross-leakage flows could be found. The cross-leakage sections were then often concentrated to a few joints. Intensive cross-leakage flows, in this case, can be explained by small channels being washed out between the sewers.

The irregular and therefore unpredictable presence of cross-leakage sections is not surprising. Many different parameters affect the occurrence of cross-leakage sections. Since the important parameters like geohydrological conditions, backfill material, degree of backfill compaction, jointing methods, sewer pipe quality and workmanship are often poorly known, it is not surprising that the occurrence of cross-leakage sections is hard to predict.

The information presented in this report on backfill material, jointing methods etc. has been obtained from experienced sanitary engineers in the local communities and were if possible compared with information from the sewer files.

In the following, measurement results will be presented for three examples chosen from the examined sewer systems. The examples are sewer lines no. 111-114 (Göteborg), no. 201-203 (Borås) and no. 321-323 (Växjö).

Very heavy cross-leakage flows were found in sewer lines no. 102-107, which are situated in Högsbo, Göteborg (Table 3.1). In this summary these sewer lines are not used as an example since this sewer system was already known to contain severe cross-leakage sections. This sewer system was therefore used early in the project to test different cross-leakage measuring methods. All other sewer lines presented in this report were not known, before this study, to contain cross-leakage sections.

Table 3.1 A compilation of results from the cross-leakage studies.

Sewer line Number	Length [1] metres	Number of manhole distances [1]	Year of construction	Fire hydrant flow l/s	Cross-leakage flow [2] l/s	Cross-leakage flow [2] %	Comments
Göteborg :							
102	72	1	1950 - 51	13	7.5	57	
103	26	2	1950 - 51	12	0.2	2	Part of No. 104
104	109	4	1950 - 51	20	8.0	40	
105	86	1	1950 - 51	1.8	1.3	72	
106	53	2	1950 - 51	12	4.1	34	
107	55	2	1950 - 51	16	1.9	12	
111	131	4	1950 - 51	9.3	2.1	23	
112	25	1	1950 - 51	6.1	4.1	67	
113	118	4	1950 - 51	7.8	2.3	29	
114	37	2	1950 - 51	8.3	0.3	4	
121	184	4	1965	19	0	0	
122	ca. 7	2	1965	20	0 [3]	0	
123	ca. 30	2	1965	plugged storm sewer	0	0	
131	ca. 50	2	1971	plugged storm sewer	0	0	
Borås :							
201	257	4	1938	13	3.9	30	
202	226	5	1938	15	1.3	9	
203	181	2	1938	11	0	0	
204	306	4	1944	12.6	0	0	
211	233	6	1957	9.6	0	0	
212	121	2	1957	12	0	0	
213	96	2	1957	9.5	1.9	20	
214	153	3	1957	11	0.3	3	
221	332	9	1960 - 63	11	0	0	
222	126	2	1960 - 63	8.8	0	0	
223	295	6	1960 - 63	10	0	0	
231	186	2	1946	14	0	0	
232	308	4	1946	11	0	0	
241	179	3	1975	12	0	0	
Växjö :							
301	214	3	1948	5.5	0	0	
311	162	4	1930	14	0	0	
321	369	10	1952	15	1.2	8	
322	169	2	1952	14	0	0	Cross-leakage flow visually estimated
323	ca. 1	—	1952	15	3	20	Cross-leakage flow visually estimated
324	222	5	1956	13	0	0	Cross-leakage flow visually estimated
331	201	3	1968	13	0	0	
	Σ ca. 5300 m						

[1] Length of the sanitary sewer.

[2] A cross-leakage flow of 0 means not detectable or measurable.

[3] During an extra test with plugged storm sewer ca. 0.5 l/s cross-leakage flow was found.

Example 1: Järnbrott, Göteborg

The sewers in this part of Järnbrott were constructed around 1950-51 and the surrounding material is clay.

This sewer system was one of the first in Göteborg constructed using mechanical excavators. The excavators excavated down to a level about 0.2-0.3 m above the bottom of the trench. The last layer was excavated by hand and was then thrown around the constructed sewer and was packed by foot-tamping. This procedure was used to stabilize the sewers before the trench was mechanically backfilled. The excavated clay was used as the backfilling material. Both the storm sewer and the sanitary sewer were jointed by tarred oakum.

In a flow survey carried out by the Gothenburg Water and Sewage Works this sewer system was found to receive large amounts of rainfall-induced infiltration/inflow. The sources of these flows had not been investigated.

Four sewer lines were chosen randomly within the area (Figure 3.10).

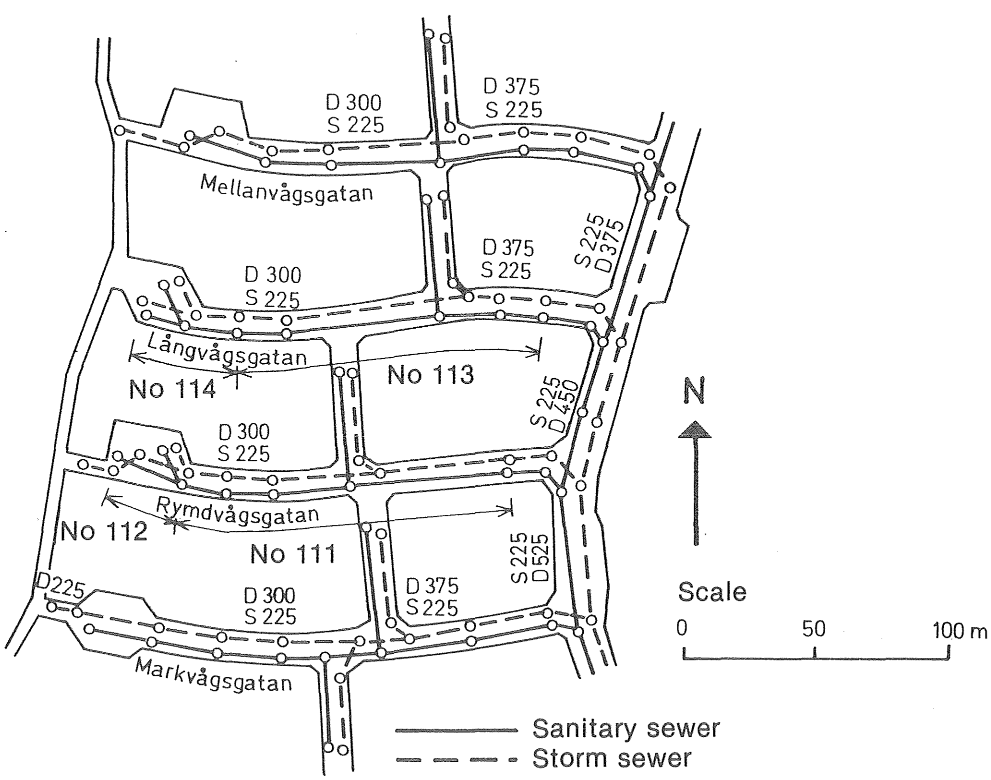

Figure 3.10 Sketch of the examined sewer lines in Järnbrott, Göteborg.

The results from the measurements are shown in Figures 3.11 and 3.12. Visual inspections made during the measurements revealed that many joints did not receive cross-leakage flows despite the impression of a deteriorated condition. The cross-leakage sections were found to be concentrated to limited sections of either one or two joints (see also Figure 3.6, sewer line no. 111), or between a pair of manholes.

In sewer line no. 112 (test 1) about 90% of the hydrant flow flushed into the storm sewer could already be found in the sanitary sewer after about 25 m. Here the exfiltration from the storm sewers was concentrated to sections around two of the storm water manholes. Holes up to 10 cm^2 could be found in the middle of the manhole.

The rapid response time of the cross-leakage flows is illustrated in Figure 3.13, where the ultrasonic level chart height has been converted into flow. The delays in response time can be explained by the time for transport along the sewer line and the time for the filling up and emptying of backwater masses upstream from the low capacity weir, installed in the sanitary sewer.

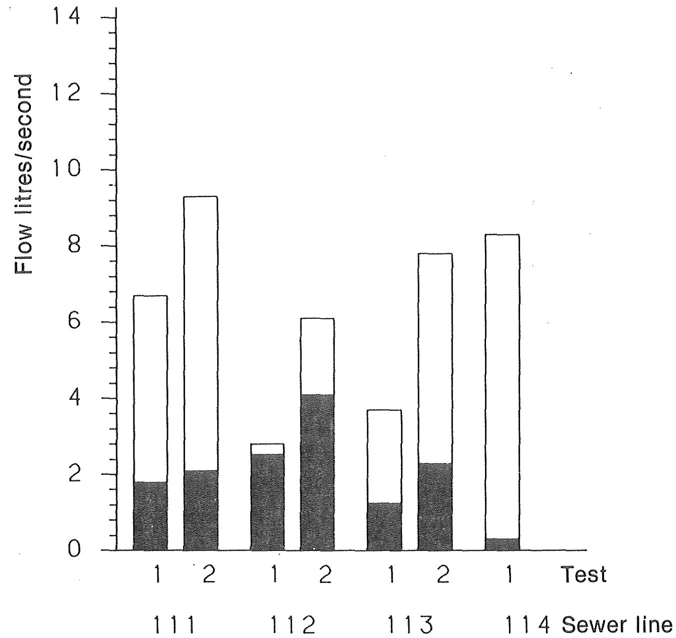

Figure 3.11 Bar chart showing the fire hydrant flow flushed into the storm sewer during the cross-leakage tests (the whole bar) and the measured cross-leakage flow (shaded bar) for Järnbrott in Göteborg.

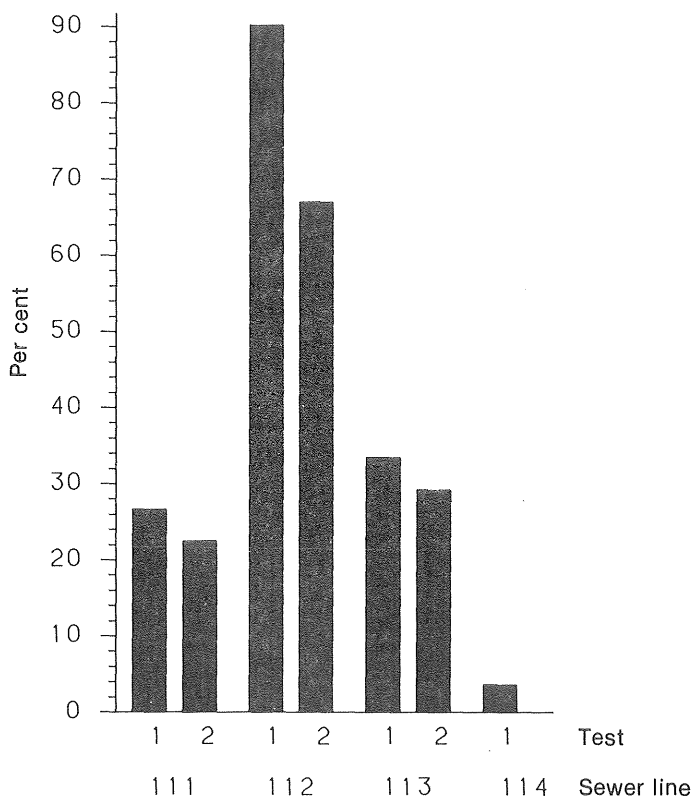

Figure 3.12 Cross-leakage flows measured in the sanitary sewer expressed as a percentage of the fire hydrant flow into the storm sewer for Järnbrott in Göteborg.

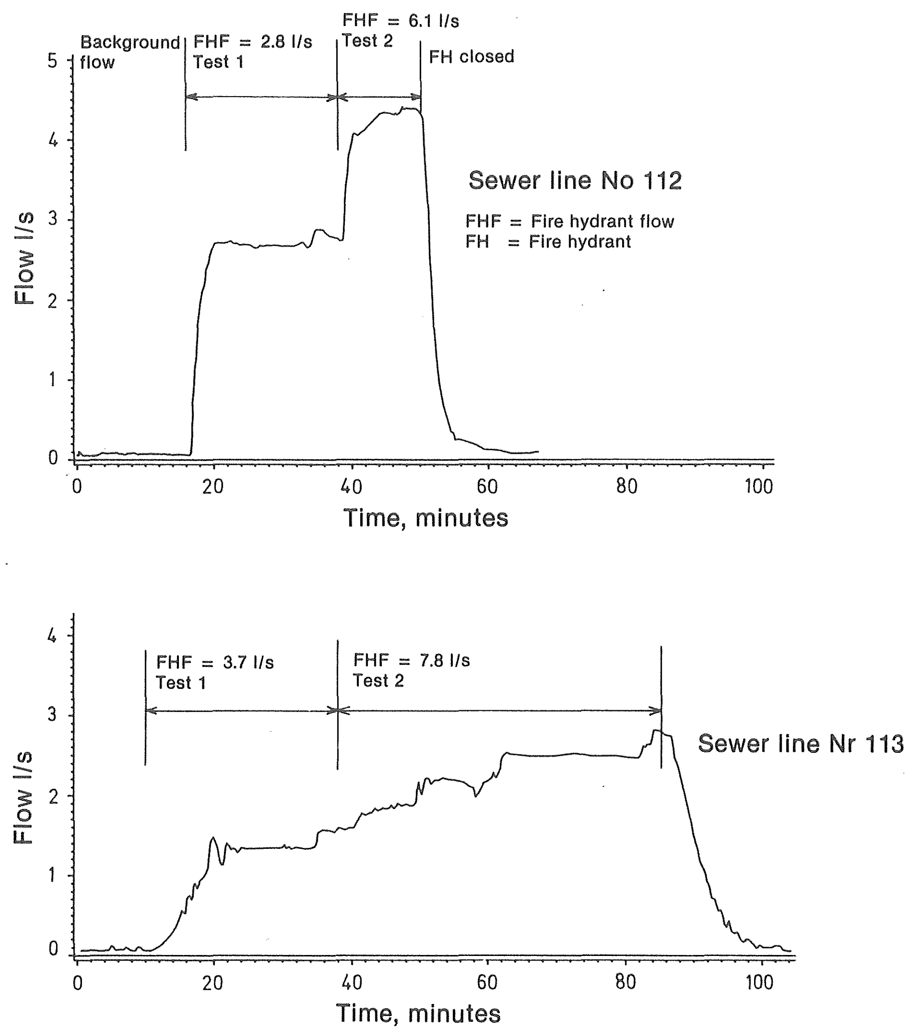

Figure 3.13 Measured flow in the sanitary sewers during the cross-leakage tests in sewer line no. 112 (25 m) and no. 113 (118 m) for Järnbrott in Göteborg.

Example 2: Sjöbo, Borås

The separate sanitary sewer system in Sjöbo had earlier been reported being overloaded during heavy storm events. This had resulted in basement floodings which is a very obvious indication of rainfall-induced infiltration/inflow problems. The sources had not been investigated.

In this study only a very small part of the sewer system was examined but the results are quite interesting.

The three sewer lines no. 201-203, all constructed around 1938 (Figure 3.14), were chosen without any specific suspicion of them being more defective than other sewer lines. The soil material in this area is predominately moraine and in some parts possibly mixed with rocks. The excavated material was probably used for backfill in the trench.

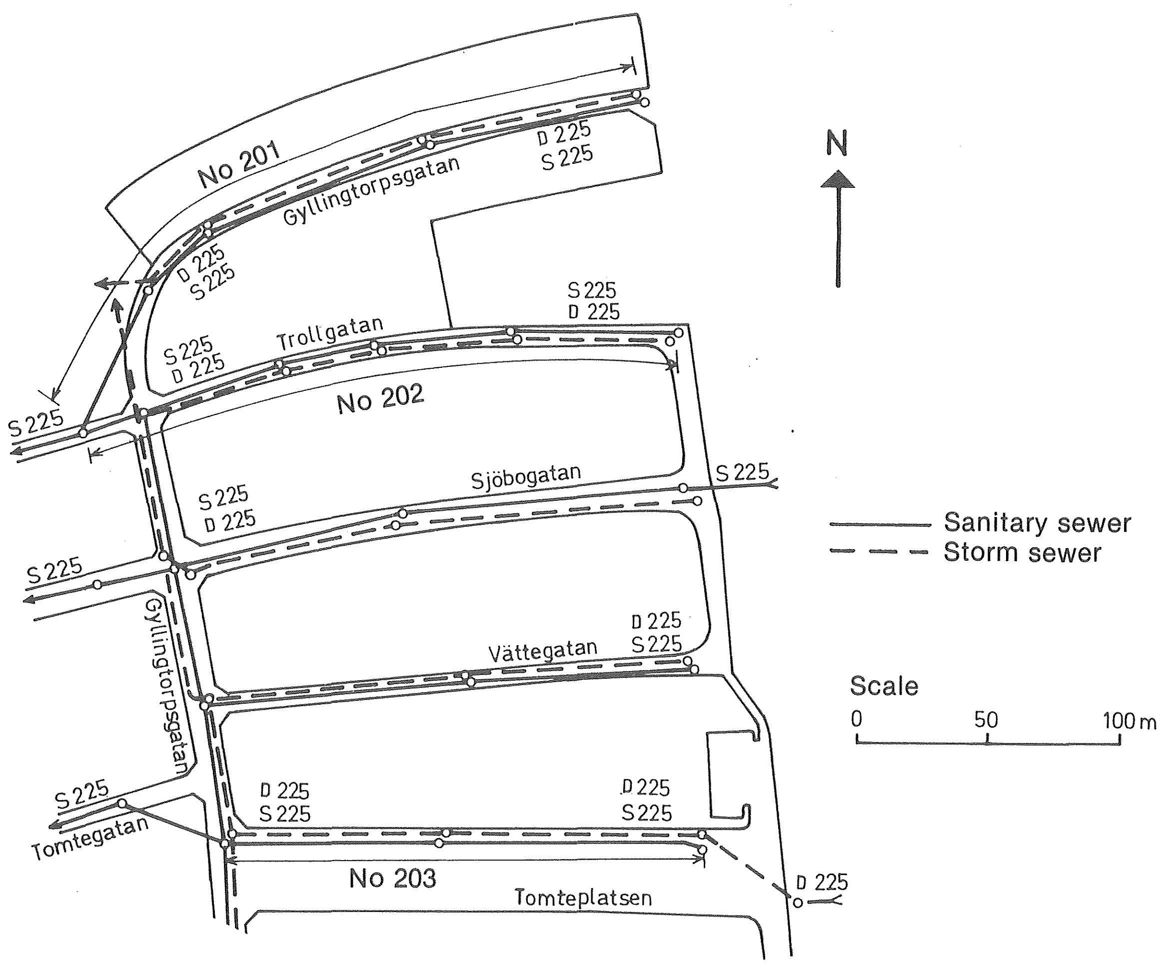

Figure 3.14 Sketch of the examined sewer lines in Sjöbo, Borås.

The measurement results are presented in figure 3.15 where the ultrasonic level charts have been converted into flows. The cross-leakage flows in these apparently equal sewer lines were found to be heavy, relatively moderate and non-existent respectively. The results are also presented in Figures 3.16 and 3.17.

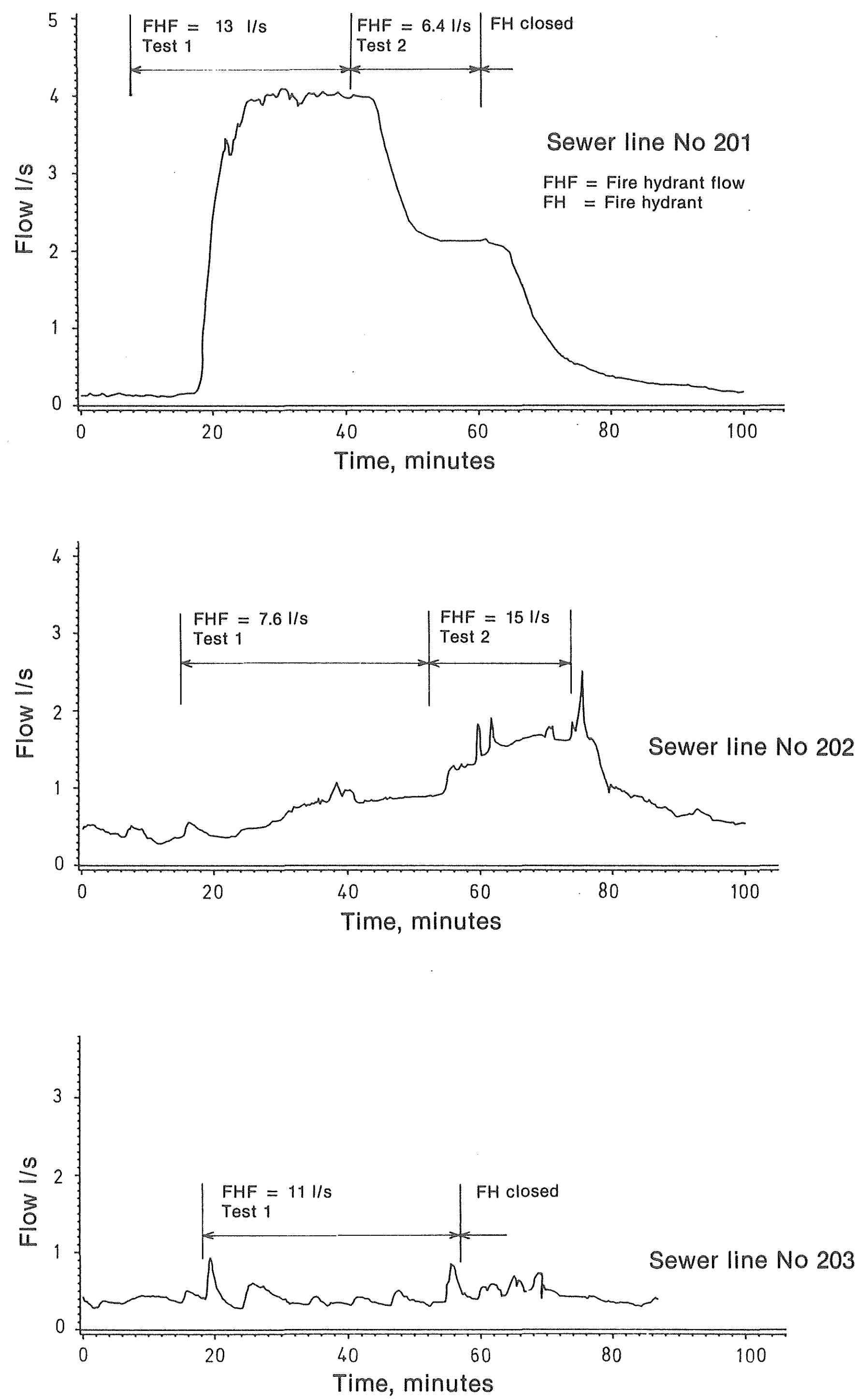

Figure 3.15 Measured flow in the sanitary sewers during the cross-leakage test in sewer lines no. 201 (257 m), no. 202 (226 m) and no. 203 (181 m) for Sjöbo in Borås.

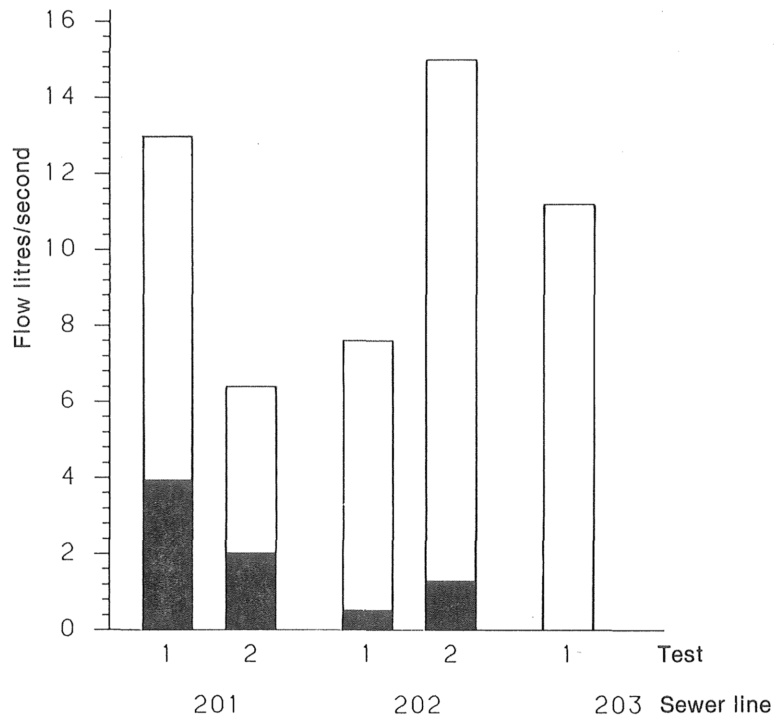

Figure 3.16 Bar chart showing the fire hydrant flow flushed into the storm sewer during the cross-leakage tests (the whole bar) and the measured cross-leakage flow (the shaded bar) for Sjöbo in Borås.

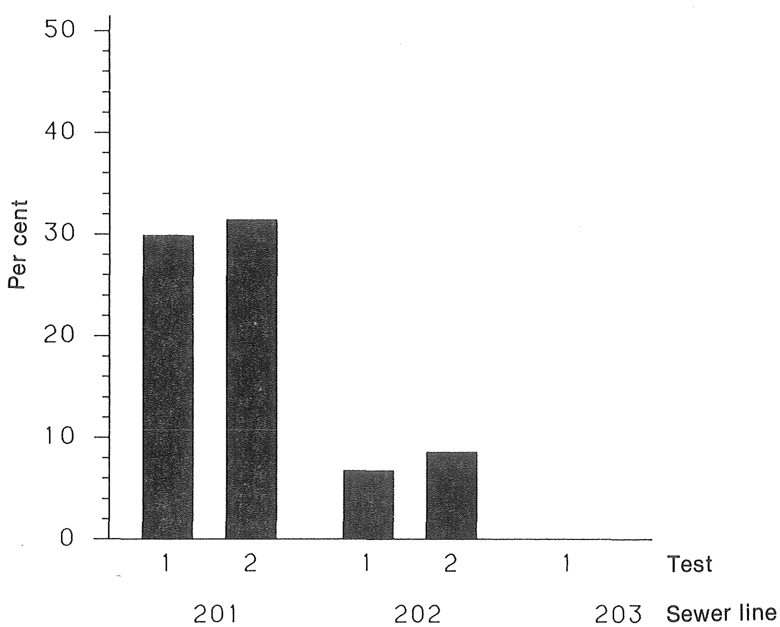

Figure 3.17 Cross-leakage flows measured in the sanitary sewers expressed as a percentage of the fire hydrant flow flushed into the storm sewers for Sjöbo in Borås.

The measurement results are presented in figure 3.15 where the ultrasonic level charts have been converted into flows. The cross-leakage flows in these apparently equal sewer lines were found to be heavy, relatively moderate and non-existent respectively. The results are also presented in Figures 3.16 and 3.17.

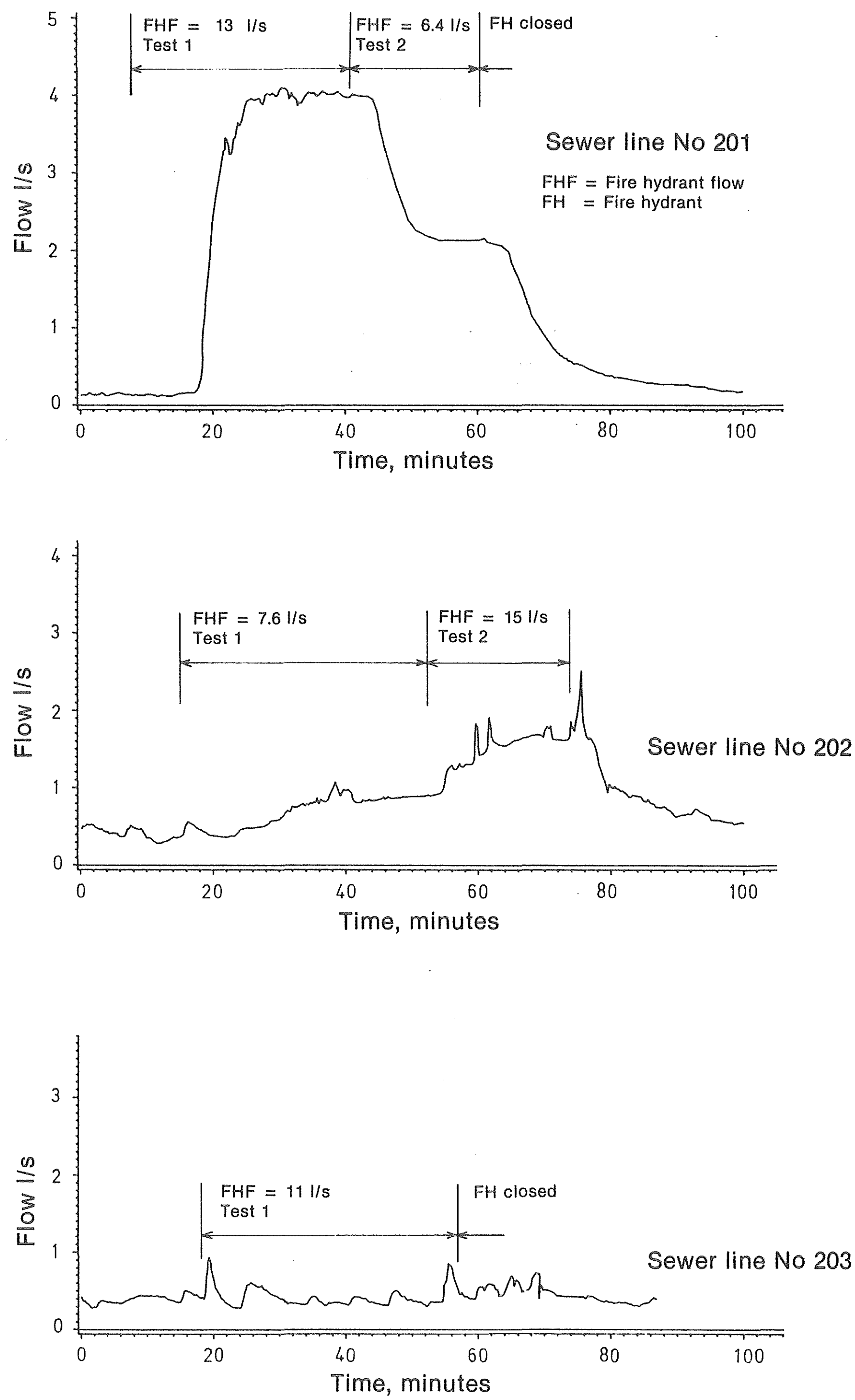

Figure 3.15 Measured flow in the sanitary sewers during the cross-leakage test in sewer lines no. 201 (257 m), no. 202 (226 m) and no. 203 (181 m) for Sjöbo in Borås.

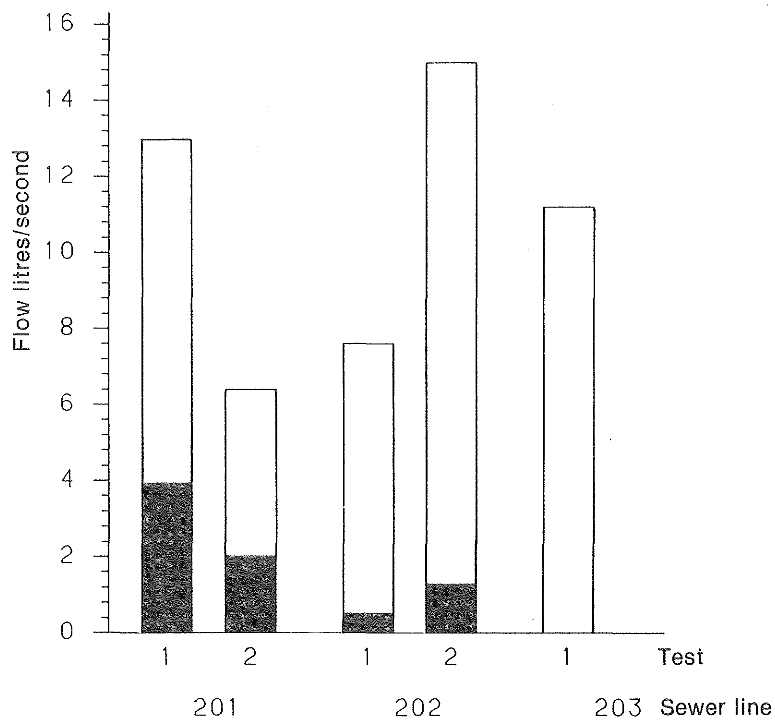

Figure 3.16 Bar chart showing the fire hydrant flow flushed into the storm sewer during the cross-leakage tests (the whole bar) and the measured cross-leakage flow (the shaded bar) for Sjöbo in Borås.

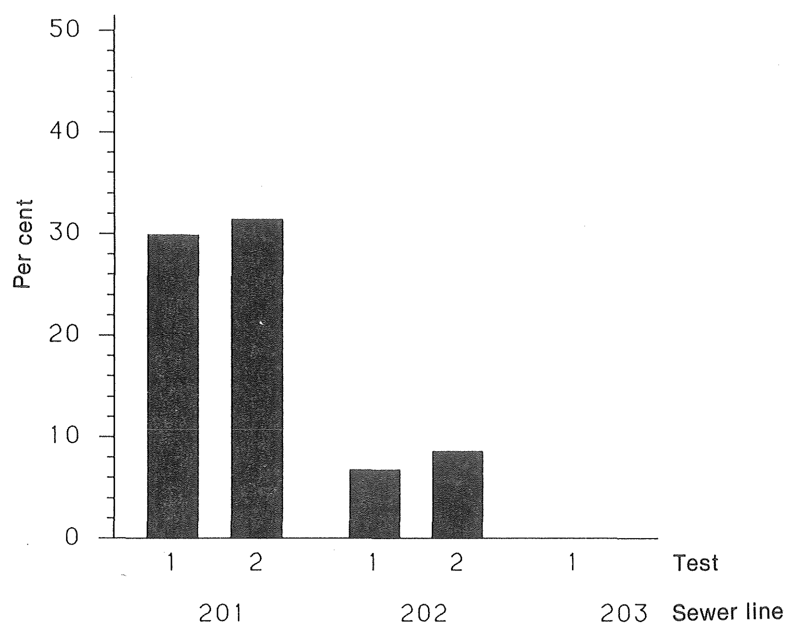

Figure 3.17 Cross-leakage flows measured in the sanitary sewers expressed as a percentage of the fire hydrant flow flushed into the storm sewers for Sjöbo in Borås.

The results for Sjöbo illustrate the difficulty of finding a general relationship between different functional problems in existing sewer and parameters such as age and material. Figure 3.15 also shows that the accuracy in the measured cross-leakage flows is very dependent on the variation and intensity of the background flow. The conditions for accurate determination of the cross-leakage flows are better for sewer line no. 201 than for no. 202. However, there can be no doubt about the existance of cross-leakage flows in both the sewer lines.

Example 3: Växjö

Sewer lines no. 321-323, Figure 3.18, in Växjö were chosen randomly from a sewer system which had been found to have high flows (>150 litres/24 hours/metre) of groundwater infiltration during periods of high groundwater level under dry weather conditions. No measurements had been carried out to investigate rainfall-induced infiltration/inflow.

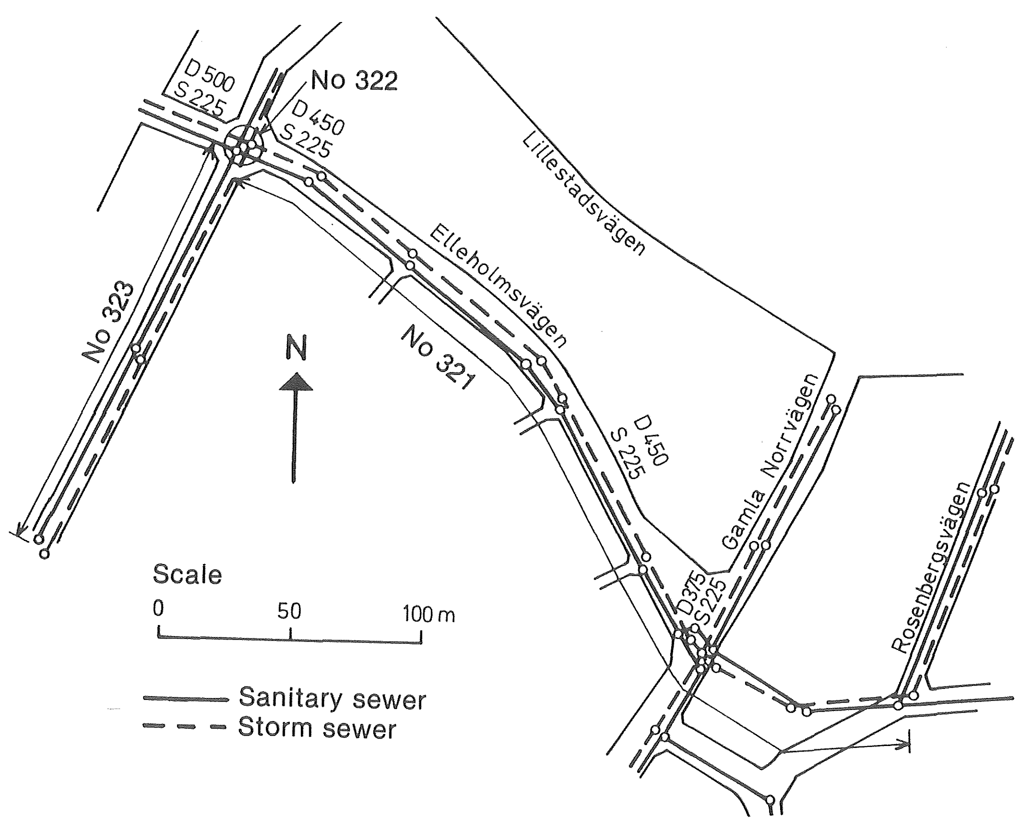

Figure 3.18 Sketch of the sewer lines no. 321, 322 and 323 in Växjö.

The sewers were constructed in 1952 and the surrounding material is probably moraine of low permeability. The sewer pipes are likely jointed with cement mortar and the trench backfilled with the excavated material.

A rather extensive cross-leakage section was found in the common downstream manhole for the sewer lines no. 321 and 322. The intrusion of the exfiltrated stormwater was mainly concentrated to untight sanitary manhole connections.

Since the sanitary flow during the cross-leakage tests for the two sewer lines no. 321 and no. 322 were measured using a weir installed in the incoming sewer pipes this cross-leakage flow from the manhole was not included in the flow measurements. This cross-leakage flow was visually estimated to be about 3 l/s when the fire hydrant flow was 15 l/s. This limited cross-leakage section between the storm sewer manhole and the sanitary sewer manhole is called no. 323. Parts of this cross-leakage flow were photographed and are shown in Figure 3.5.

A cross-leakage flow of 1.2 l/s was also measured in no. 321. By visual inspection no significant increase in flow during the cross-leakage test in no. 321 could be seen in the upstream sanitary manholes.

It is also interesting to note that no cross-leakage flow could be measured in sewer line 322 despite the very heavy cross-leakage flow in no. 323, just a few decimetres downstream the installed weir in no. 322. This indicates that the cross-leakage section here must be very localized.

These cross-leakage flows were the only ones found in Växjö even though more than 1.3 km of sewers were examined.

3.3 Consequences of Cross-leakage Flows

Three consequences of cross-leakage-flows can be identified:

* high yearly quantities of water to the treatment plant
* higher peak flows during heavy storm events
* risk for erosion of the backfilling material.

Cross-leakage sections and the resulting cross-leakage flows must be considered together with other sources of infiltration/ inflow in the specific sewer systems. Nevertheless it is interesting to discuss the isolated consequences of cross-leakage flows. Thereafter it is possible to compare these consequences with those resulting from other sources.

The yearly quantity of cross-leakage water depends on the magnitude and duration of cross-leakage flow during different stormwater flows.

Cross-leakage flow can be measured by the previously discussed methods. Stormwater flows can then be simulated up to the available fire hydrant flow. True stormwater flows are, however, generated by:

* stormwater runoff with high, rapid flow variations

* snow melt and drainage water, with low, sustained flow variations

It is therefore very difficult to estimate the duration time for the different stormwater flows in a specific storm sewer.

The storm events that generate most of the yearly quantities of cross-leakage water are those with high yearly volumes. These are also the most frequent storm events and are characterized by low intensities and long duration times.

As a calculation example presented in publication no. 6, the yearly cross-leakage volume resulting only from storm runoff was estimated for sewer line no. 113. The impermeable area connected to the storm sewer system for that sewer line was roughly estimated to be 3800 m^2. Despite the rather small connected area and resulting low stormwater runoff flow the cross-leakage volume was calculated to be about 750-800 m^3/year into the sanitary sewer. (No consideration is taken to the runoff detention time.)

The cross-leakage water volume caused by stormwater flow generated by snow melt and drainage water are not included here and are very difficult to estimate. These volumes might be very high if the storm sewers are receiving snow melt and drainage water over long periods of time which can then enter the sanitary sewer through the cross-leakage section. Information about the magnitude and duration time for flows in the storm sewer caused by snow melt and drainage are usually not available.

In comparison, a 100 m^2 house roof connected directly to the sanitary sewer will generate a yearly water volume of nearly 60 m^3 for a yearly rainfall of 600 mm.

When peak flow problems cause basement floodings or overflows, the cross-leakage flows must be considered together with flows coming from other sources of infiltration/inflow.

Chapter 3.2 cross-leakage flows of up to 8 litres/second had been noted despite rather small stormwater flows, usually 8-20 l/s, simulated from the fire hydrants. This can be compared to that a 100 m^2 house roof in the Göteborg area, connected to a sanitary sewer results in a momentaneous peak flow of slightly more than 1 l/s for a storm event with a 2-year return period and 15 minutes duration time (an intensity of about 41 mm/h (Arnell, 1982)). This shows that a major cross-leakage section can result in peak flows equivalent to a great number of house roofs connected to a sanitary sewer.

An erosion of the backfill material can result in the formation of voids and the undermining of the above lying services, such as the storm sewer, the water main and the roadway. Washout of backfill material may be possible if the sewer trench backfill consists of easily eroded material and the flow through the backfill is high enough.

Since the number of sewer collapses in Sweden is rather low, the structural problems are less emphasized. Little work has been done to investigate the risk of water exfiltrating from the storm sewer or the water main and being transported down through the backfill into the sanitary sewer. Only recently have research activities concerning these potential problems begun in Sweden.

4 CONCLUDING REMARKS

This thesis discusses only a small part of the subject of management of municipal water distribution and sewage collection systems. Even when studying this limited subject the importance of a thorough understanding is apparent for efficiently dealing with these types of problems.

Other problems of the management of water distribution and sewage collection systems, also have their own specific needs for detailed understanding. Therefore the relative importance of different problems must be thoroughly discussed and the conclusions expressed in a strategic plan.

It is important that discussions on the management of water distribution and sewage collection systems include a balance between the degree of investigations needed for determining the cause of the problems and the measures required for solving them. It is also important to discuss the least acceptable level of funding needed to maintain or improve the sanitary standard and reduce the negative environmental effects in the receiving waters.

Highly competent Sanitary Engineers are needed to manage the water distribution and sewage collection systems and ambitiously working in this field can be regarded as a challenge.

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