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Project Summary

Exfiltration in Sewer Systems

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Many municipalities throughout the United States have sewerage systems (separate and combined) that may experience exfiltration of untreated wastewater from both sanitary and combined sewers. This study was conducted to focus on the estimation of the magnitude of leakage of sanitary and industrial sewage from sanitary sewer pipes on a national basis.

The method for estimating exfiltration amounts utilized ground-water table information to identify areas of the country where the hydraulic gradients of the sewage are typically positive, i.e., the sewage flow surface (within pipelines) is above the groundwater table. An examination of groundwater table elevations on a national basis reveals that the contiguous United States is comprised of groundwater regions (established by the U.S. Geological Survey) which are markedly different. Much of the northeastern, southeastern, and midwestern United States has relatively high groundwater tables that are higher than the sewage flow surface, resulting in inflow or infiltration. Conversely, a combination of relatively low groundwater tables and shallow sewers creates the potential for widespread exfiltration in communities located in the western United States.

This study provides information on typical sewer systems, identifies and assesses the factors that cause or probably cause exfiltration, presents commonly used and advanced corrective measures and their costs for dealing with exfiltration, identifies technology gaps, and recommends associated research needs and priorities. This report also examines urban exfiltration, including a case study of Albuquerque, New Mexico.

This Project Summary was developed by EPA's National Risk Management Research Laboratory, Cincinnati, Ohio, to announce key findings of "Exfiltration in Sewer Systems" that is fully documented in a separate report of the same title (see Project Report ordering information on back).

Introduction

Sanitary sewer systems are designed to collect and transport to wastewater treatment facilities the municipal and industrial wastewaters from residences, commercial buildings, industrial plants, and institutions, together with minor or insignificant quantities of ground water, storm water, and surface waters that inadvertently enter the system. Over the years, many of these systems have experienced major infrastructure deterioration due to inadequate preventive maintenance programs and insufficient planned system rehabilitation and replacement programs. These conditions have resulted in deteriorated pipes, manholes, and pump stations that allow sewage to exit the systems (exfiltration) and contaminate adjacent ground and surface waters, and/or enter storm sewers.

Untreated sewage from exfiltration often contains high levels of suspended solids, pathogenic microorganisms, toxic pollutants, floatables, nutrients, oxygen-demanding organic compounds, oil and grease, and other pollutants. Exfiltration can result in discharges of pathogens into residential areas; cause exceedances of water quality standards (WQS) and/or pose risks to the health of the people living adjacent to the impacted streams, lakes, ground waters, sanitary sewers, and storm sewers; threaten aquatic life and its habitat; and impair the use and enjoyment of the Nation's waterways.

Although it is suspected that significant exfiltration of sewage from wastewater collection systems occurs nationally, there is little published evidence of the problem and no known attempts to quantify or evaluate it on a national basis. Accordingly, the objectives of this study were to quantify through desk-top estimates the magnitude of the exfiltration problem in wastewater-collection systems on a national basis; identify the factors that cause and contribute to the problem; and document the current approaches for correcting the problem, including costs. The resulting information was used to identify information and technology gaps and research priorities.

Procedure

Causative Factors

A search for publications regarding exfiltration sewage from wastewater collection systems did not locate any exfiltration-specific discussion of unique/causative factors because most factors which cause inflow/infiltration are identical to those associated with exfiltration (i.e., they both occur through leaks in pipes, depending on the relative depth of the ground water).

Factors that contribute to exfiltration include:

- size of sewer lines
- age of sewer lines
- materials of construction (sewer pipe, point/fitting material, etc.)
- type and quality of construction (joints, fittings, bedding, backfill)
- depth of flow in the sewer

Geological conditions that contribute to exfiltration include:

- groundwater depth (in relation to sewer line/depth of flow of sewage)
- type of soil
- faults

Climate conditions that influence exfiltration include:

- average frost line in relation to sewer depth
- average rainfall, which helps determine groundwater depth

The level of ground water and the depth of flow in the sewer will influence the extent of exfiltration rates, since the pressure differential between the hydraulic head in the sewer and the groundwater hydraulic head will force water out of the sewer apertures into the surrounding soil material.

Health and Environmental Impacts

Ground Water

Little published data is available on specific incidents of groundwater pollution and associated health/environmental impacts arising from leaking sewers, despite the widespread acknowledgment that these incidents occur. Several studies have indicated widespread pollution of ground water in urban areas arising from the general leakiness of sewers, including bacteria and ammonium reported from Wisconsin and general pollution in the San Joaquin Valley in California.

Transport of the sewage and pollutants leaking into the subsurface/ ground water depends on a variety of factors, including but not limited to the difference in hydraulic head between the sewage surface and the groundwater table level, the substrate physical/chemical/biological characteristics (which determines attenuation potential), and the sewage pollutants and their concentrations. Fecal bacteria contamination is the most serious health risk associated with domestic sewage exfiltration. Contamination by viruses, protozoa, and other microorganisms is also a concern. Increased concentrations of total organic carbon, nitrate, chloride, and sulfate, however, can also make the water unfit for consumption. Phosphate and boron are good indicators of sewage pollution since they are not naturally occurring in ground water.

The solids present in sewage can plug the porous media beneath the pipe and rapidly decrease the exfiltration rate. In an experiment completed to examine this effect, the leakage was reduced to a steady state within an hour.

Water Supply Distribution Systems

Because of minimum separation requirements for potable water supply distribution systems and sanitary sewers and vigilant application of cross-connection control programs, the opportunity for sewer exfiltration to contaminate drinking water supplies is theoretically rather limited. Sewage from exfiltration can enter a distribution system through a broken water main or, under reduced pressure conditions, through a hole which leaks drinking water out under normal positive pressure conditions. Situations which could allow infiltration of the sewage through a lowering of water main pressure primarily involve backflow and surges.

Despite the best efforts of utilities to repair water main breaks using good sanitary procedures, these breaks represent an opportunity for contamination from exfiltration to enter the distribution system. When a main breaks, utilities typically isolate the affected section, superchlorinate, and flush the repaired pipe. Flushing velocities may not always remove all contaminated debris, however, and microbiological testing of the final water quality may not detect contaminating microorganisms. In 1989, Cabool, Missouri experienced a suspected cross-connection between sewage overflow and two major distribution system line breaks (backflow may have occurred during simultaneous repair of numerous water meters) caused by freezing temperatures, resulting in 243 cases of diarrhea, 32 hospitalizations, and four deaths due to *E. coli* O157:H7 strain. This town of 2000 was on an untreated groundwater system and did not superchlorinate during repairs of the water main breaks.

Backflow devices to prevent the entry of contaminated water constitute an important distribution system barrier. Because of cost considerations, backflow-prevention devices are primarily installed on commercial services lines at facilities that use potentially hazardous substances.

Recent research is focusing on transient pressure waves that can result in hydraulic surges in the distribution system. These waves, having both a positive and negative amplitude, can draw transient negative pressures that last for only seconds and may not be observed by conventional pressure monitoring. Because these waves travel through the distribution system, at any point where water is leaking out of the system, the transient negative pressure wave can momentarily draw water and sewage (if present) back into the pipe.

Surface Water

No data or narrative information in the literature demonstrate, or even suggest, that sewer exfiltration has directly contaminated surface waters. Several factors that control the occurrence of sewer exfiltration may explain the absence of a linkage between exfiltration and surface water pollution.

The occurrence of exfiltration is limited to those areas where sewer elevations lie above the groundwater table. Since groundwater elevations near surface water bodies are typically near the ground surface, sewers near surface water bodies generally are below the groundwater table, and infiltration (rather than exfiltration) will dominate the mode of sewer leakage in these areas. In areas of steep topographic conditions, where sewers are located near surface waters and at elevations that lie above the surface water, exfiltration impacts may be possible. However, these situations are assumed to be sufficiently rare that exfiltration impacts on surface waters are not observed.

Exfiltration Magnitude Estimating Methodology

The process of estimating the magnitude of the exfiltration problem on a national scale performed as a series of two independent steps:

- Qualitatively assessing the portion of the nation's sewer systems that are susceptible to exfiltration;
- Applying assumptions about exfiltration rates (percent of base sewer flow) to the exfiltration susceptible sewer systems to provide an assessment of the extent of sewer exfiltration on a national scale.

Identification of Exfiltration Susceptible Sewer Systems

The key factor influencing the occurrence of exfiltration is the direction of the hydraulic gradient between the sewer flow surface and the groundwater table (GWT) external to the sewer. In much of the northeastern, southeastern, and midwestern United States, relatively high groundwater tables typically result in infiltration conditions. Exceptions include shallow sewers and service laterals, and seasonal variation in GWTs that can significantly change the spatial extent of the sewer system that lies above the GWT (i.e., that can be considered to be "exfiltration susceptible").

Given the importance of first screening out those areas that are not "exfiltration susceptible," the initial desktop analysis task was to perform spatial analysis of sewer depth relative to regional GWT elevations. Existing national-scale groundwater information was examined, such as that provided by the U.S. Geological Survey (e.g., USGS Groundwater Regions of the United States). As the various national ground-water data sources were reviewed, however, it was determined that mapping in support of the purposes of this study was not readily available. For this reason, a national depth-to-ground water map was prepared under this project from groundwater level data available in the national databases (U.S. EPA STORET and USGS WATSTORE).

National-scale sewer depth data does not exist, but for purposes of the desktop analysis some assumptions about this parameter can be made. For example, typical service lateral depth can be assumed to be 8 feet for buildings with basements, and 2 to 4 feet for houses built on slabs. Typical sewer main depth can be assumed to be 6 to 10 feet; it may be possible for more detailed assessments to develop a typical depth distribution (i.e., x % 4-10 ft deep, y% 11-15 ft deep, z% > 15 ft deep). Regional differences should be considered; for example, sewer depths typically are shallower in the western United States than in other areas of the country. Sewer system density (miles/acre) can be correlated with readily available national population density data to create a GIS coverage of sewer system density.

GIS processing incorporating the general spatial (mapped) relationships between sewer depth and groundwater elevations allowed the development of a characterization of the "exfiltration susceptibility" of various areas. This was attempted at the national level, but the data required to support this analysis are unavailable; thus, a representative area (Albuquerque, New Mexico) for which a recent exfiltration study had been completed, was selected on which to perform the analysis. National exfiltration rate assessments can be extrapolated from this analysis. However, more detailed identification and inventory of exfiltration susceptible areas is required to support a meaningful quantification of national exfiltration rates.

For purposes of this study, unit rates for exfiltration (gallons/day/ inch/mile) available from the 1989 EPA study were used to generate the assessment of the magnitude of the national exfiltration problem. These unit rates were applied to the "exfiltration susceptible" areas (together with assumptions about the inch-miles of sewers/laterals in those areas) to generate exfiltration rates in the Albuquerque case study. The unit rates based on gallons/day/inch/mile were compared with estimates based on percent of base sewer flow. Comparisons of the two methods proved useful in developing the final estimates.

Corrective Measures

The proper selection of corrective or rehabilitation methods and materials depends on a complete understanding of the problems to be corrected, as well as the potential impacts associated with the selection of each rehabilitation method. Pipe rehabilitation methods to reduce exfiltration (and simultaneously infiltration) fall into one of the two following categories:

- External rehabilitation methods
- Internal rehabilitation methods

Certain conditions of the host pipeline influence the selection of the rehabilitation method. It is therefore necessary to assess these factors to prepare the pipe for rehabilitation. Rehabilitation is proceeded by surface preparation by cleaning the pipe to remove scale, tuberculation, corrosion, and other foreign matters.

External Sewer Rehabilitation Methods

External rehabilitation methods are performed from the aboveground surface by excavating adjacent to the pipe, or the external region of the pipe is treated from inside the pipe through the wall. Some of the methods used include external point repairs, chemical grouting, and cement grouting.

Internal Sewer Rehabilitation Methods

The basic internal sewer rehabilitation methods include chemical grouting (most common method for sealing joints), cured-in-place pipe (insertion of a flexible lining impregnated with a thermosetting resin), sliplining (pipes are inserted into an existing line by pulling or pushing pipes into a sewer), closed-fit pipe (uses temporarily deformed new pipe), fold and form pipe (deformed into a "U" shape before insertion), spiral wound pipe (winds strips of PVC in a helical pattern to form a continuous pipe), pipe bursting (fragments existing pipe and replaces with new pipe in void), and spot (point) repair (used to correct spot problems).

Results and Discussion

The findings of the Albuquerque case study were combined with the national depth-to-groundwater mapping to present a qualitative assessment of the extent to which sewer exfiltration represents a risk to water quality and human health on a national scale.

National Scale Quantification

Although exfiltration is not a widely studied phenomenon, several exfiltration studies and investigations have been completed throughout the world. These include work completed in the United States for the U.S. EPA and several studies in Europe, the majority of which are focused on Germany. Some of the more applicable previous studies are discussed below.

Three basic approaches have been used to quantify sewer exfiltration rates: (1) direct measurement of flow in isolated sewer segments; (2) theoretical estimates using Darcy's Law and related hydraulic theory; and (3) water balance between drinking water produced/ delivered and wastewater collected/ treated. Each of these approaches has been applied to the Albuquerque case study and is described below.

Estimates Based on Direct Measurements (U.S. EPA Study)

An EPA study entitled "Evaluation of Groundwater Impacts of Sewer Exfiltration" was completed in the late 1980's. The work measured exfiltration in two California city sewer systems to develop a correlation between exfiltration and infiltration. The tests were conducted in areas of vitrified clay pipe (VCP) predominance, where older pipe of known or suspected poor condition existed. Only those pipe segments located above groundwater levels were tested. Water consumption was metered for all sewer service connections corresponding with each measured sewer line to determine the actual quantity of wastewater flow entering the system. It was assumed that all internal household water entered the sewer system. Measurements of sewage flow in the sewer lines were made by continuous flow monitoring and by hydrostatic testing. Calculated sewer exfiltration was reported in units of gallons per inch diameter per mile length per day (gpimd).

The study revealed that a large discrepancy exists between the results from the continuous flow monitoring and the hydrostatic testing at one Santa Cruz location. The study concludes that the continuous flow monitoring achieved reliable data and that the hydrostatic test data was influenced by the tidal cycle. A correlation model between exfiltration and infiltration was developed, but not field tested.

A second evaluation was performed using field measurements at another location to verify the correlation model. This evaluation used similar methodologies as the first task. Exfiltration measurements were made in the Washington Suburban Sanitary Commission (WSSC) sewer system near Washington, D.C., and in Lexington Kentucky.

Several problems with the measurement methodologies were noted, and overall the hydrostatic test method was judged to be not successful. It was resolved that the flow monitoring procedure worked well and should be applied to areas with a minimum of 400-500 linear feet of pipe with little or no service connections.

Estimates Based on Darcy's Law and Related Theory (European Studies)

The study of exfiltration has been of great interest in Germany. This country has a very old, deteriorated infrastructure. The cost to complete the necessary repairs to Germany's sewer systems is estimated to be nearly $100 billion (U.S.). Therefore, several exfiltration studies have been conducted to prioritize repair work. These studies have both applied theoretical (Darcy's Law) approaches and direct measurements to estimate sewer exfiltration. Excerpts from some of the studies are summarized below.

- A report from England provided an estimate of 300 x 10^6 m^3/yr (793 x 10^8 gal/yr) or approximately 1 liter / day/m (397 gal/day/mile) for the exfiltration of the 880,000 km (547,000 miles) of sewer lines in Germany, although the basis of the estimate is not clear. This very low sewer leakage rate is actually net exfiltration, which is the difference between exfiltration and infiltration. The study indicates that total exfiltration and infiltration in Germany are nearly equal, but the amounts are not provided.
- To better understand the mechanics of exfiltration, sewage migration from leaking pipes to ground water was correlated in a study using Darcy's Law (see Equation 1). The rate of exfiltration is linearly dependent on the area of the pipe exfiltrating and the pressure head:

(1) $Q = L\,A\,dh$

where Q is the exfiltration rate (ft^3/s) through a pipe leak area A (ft^2) at a pressure head of dh (ft), and L is leakage factor (s^{-1}).

The leakage factor is defined in Equation 2:

(2) $L = K/dl$

where K is the permeability of the surrounding soil (ft/s) and dl is the thickness of the soil layer (ft). This study found that the settle able solids in the wastewater act to reduce the permeability of the bedding material and lower the exfiltration rate rapidly at low flows and velocities. This clogging reduces the rate of exfiltration immediately. In fact, a steady-state rate of exfiltration was reached after one hour, even with large area of joint damage.

- A research project undertaken by the Institute of Environmental Engineering (ISA) at the University of Technology of Aachen, Germany, studied the water pollution hazard of leaking sewers. The ISA developed and used a special exfiltration measuring device at every joint in several sections of sewer pipe on several tests conducted throughout Germany. This study determined that the most significant VCP sewer damages which permit exfiltration are leaking service junctions, leaking sewer joints, pipe cracks, and pipe fractures. At a pressure head below the sewer crest, which is typically the case in gravity flow sewer lines, exfiltration rates were minimal. At a pressure head of one pipe diameter, the exfiltration rate increased dramatically, to more than 26 gph per joint in some segments. This high leakage rate can in part be attributed to the generally poor condition of the old sewer systems.

Estimates Based on Drinking Water- Wastewater Balance

Exfiltration from Albuquerque's sewer system was estimated using a water/sewage balance calculation, backed up by some previous local studies on infiltration. The results are then compared with leakage rates calculated from the other methodologies and unit rates derived from the EPA and European studies presented above.

A direct method for estimating exfiltration is to compare water pumpage and usage with wastewater received at Albuquerque's Southside Water Reclamation Plant (SWRP). To make this comparison, it is necessary to identify the base water demand, which is the indoor component of the total household use. Demands during mid-winter (January and February) are assumed to be near base flow because no or very minimal outdoor water usage occurs. Water and wastewater data obtained from the City for January 1998 revealed the following:

- Average daily influent flow at the SWRP: 51.4 mgd
- Average daily water pumpage into transmission/distribution system: 61.2 mgd (this is then considered to be the daily base flow for that month)

Subtracting wastewater flow from the pumpage rate yields a difference of 9.8 mgd, which is the first approximation of sewage leakage. However, several other factors also impact the water balance in the water and wastewater systems. These are:

- Sewer infiltration
- In-house water consumption
- Water distribution system leakage
- Sewer exfiltration

City of Albuquerque staff, using a range of available information (including meter and billing records, pumpage records, and other data), have estimated losses in the water system at about 11 percent of the total amount pumped. A 1997 study found water system losses ranging from 8 percent in Hong Kong, which is considered to have a relatively "tight" and high-quality system, to the 20-25 percent range in England, which has many very old distribution systems. An 11 percent loss in the system would account for a daily average loss of about 6.73 mgd.

In-house consumption is that portion of the water entering the house that does not leave as sewage, but is consumed in cooking, drinking, watering plants, cleaning, etc. National experience indicates that about 3 percent of water entering the home is consumed on an average day in January 1998. With negligible non-domestic consumption, the remaining amount of water, about 1.4 mgd, represents the net difference between the two other factors in the water balance: sewer infiltration and exfiltration. The net amount is positive, indicating that exfiltration exceeds infiltration by 1.4 mgd, which is plausible given that the great majority of Albuquerque's sewers, and particularly those most susceptible to exfiltration (older VCP), are in exfiltration areas (well above groundwater levels).

In order to estimate the exfiltration volume, previous studies addressing infiltration in the Albuquerque sewer system were reviewed. One of the studies utilized several approaches to gain an approximation of inflow and infiltration in the Albuquerque system, most of which was attributed to infiltration in the valley of the Rio Grande. Some of these methodologies are described below:

- A flow comparison between winter water use and sewage flow. This methodology resulted in an infiltration flow of 3.7 mgd. However, the report stated that "this estimation is probably within ± 50 (percent) of the actual value…"
- Early morning sewage flow versus water use. This methodology resulted in an infiltration flow of nearly zero.
- Sewage flow versus population. Using a 100-gallons-per-capita-per-day wastewater flow and a population of 300,000, infiltration was estimated at 5 mgd. It was also noted that the average sewage flow for Albuquerque at this time was actually 117 gpcd.
- Influent BOD versus domestic wastewater BOD. The expected BOD concentration in the wastewater was calculated based upon a generally accepted BOD loading of 0.17 lb/cap/day. This BOD concentration was compared with the average influent concentration to calculate an infiltration flow of 5.9 mgd. However, this was thought to be a high estimate based upon the relatively small industrial component and the high institutional contribution.

In addition, the study field-verified the areas subject to infiltration. Based upon the above calculations and results of the field tests, infiltration was thought to be somewhat less than 3 mgd, or 9 percent of the wastewater flow in 1975. Nine percent of today's wastewater flow would be in the 5-mgd range.

Another infiltration analysis was completed as part of the Albuquerque ASAM Model Loading and Verification Task. Interceptor manholes which were within 2 feet of ground water were identified. Flow monitoring was completed in a sewer subbasin, and the resulting flows were compared with the predicted flows to determine infiltration. The infiltration rate for Albuquerque was calculated at 0.925 mgd, but, again, the impact of exfiltration was not included. Therefore, the work revealed a net infiltration rate, indicating that actual infiltration is about 1 mgd greater than total exfiltration.

From the foregoing investigations, it is estimated that the total average infiltration rate for the Albuquerque system is in the vicinity of 3.5 mgd. The 9 percent field-verified rate reported in the Molzen-Corbin report is probably high, given the repair and replacement of major interceptors in the valley that have occurred since 1975, as well as the use of better quality materials and construction techniques for new pipelines since then. On the other hand, repairs have generally not been made to the sewers most susceptible to exfiltration (old VCP pipes).

The total exfiltration rate is obtained by adding the 1.4 mgd remaining in the water balance to the infiltration rate, for a total of 4.9 mgd, or approximately 5 mgd.

National Depth to Groundwater Mapping

In order to extrapolate the Albuquerque findings to a national scale, a qualitative assessment of exfiltration susceptibility using depth-to-ground water information was made. Since no such mapping at a national scale suitable for this purpose was readily available, an initial mapping effort was undertaken as part of this study.

The development of a nationwide depth-to-ground water atlas is difficult at best due to the lack of easily obtainable data for most of the country. Data to determine the depth to the shallowest water table may be gathered from local, state, federal, and private sources through well logs, water level measurements, location of wetlands and seeps, characterization of streams and rivers, and locations of lakes and other water bodies. A thorough characterization of the U.S. water table is a long and exacting process.

Within the context of this study, a depth-to-groundwater map was created using readily available data from the EPA STORET and USGS WATSTORE databases of depth-to-groundwater parameters. The data were downloaded from CDROM databases resident at the CDM Hydrodata Center in Denver, Colorado. The data were screened to eliminate missing depth-to-water values, missing latitude and longitude, duplicate data, and easily recognized anomalous data. The resultant set contained approximately 93,000 data points in the coterminous United States, Alaska, and Hawaii (only the coterminous U.S. is shown below). Since the data retrieved from STORET and WATSTORE is dependent upon the data owner for accuracy, there is no comprehensive method of quality control. USGS data are continually reviewed, however, and these data may be deemed reasonably accurate. The STORET and WATSTORE databases, while certainly robust, do not contain all data available; therefore, data gaps exist.

Despite the large dataset applied to build the map, many regions of the United States have relatively limited data; these areas are unshaded on the map. Areas with the greatest concentration of valid data points within the deep ground water range are generally west of the Mississippi River and along the Appalachian Mountains.

Conclusions

Most of the urban areas in the northeastern, southeastern, and coastal areas of the U.S. have relatively shallow groundwater tables (<15 feet). In these areas of the U.S., where a significant portion of the population (and therefore sewer systems) exists, relatively few exfiltration susceptible sewer systems are expected. One caveat is exfiltration from service laterals. Even in these areas of the U.S., many shallow service laterals may exist above groundwater tables. However, the hydraulic head available to drive exfiltration in these service lines is generally very low (typically only one or two inches, and intermittent). Further study in this area may be warranted to assess the extent of service lateral exfiltration.

Based on a review of the depth-to-groundwater map, it is expected that widespread exfiltration is probably limited to a relatively small portion of the total U.S. population, as relatively few large urban areas in the U.S. are located in these deeper groundwater areas. Cities such as Albuquerque, Phoenix, Tucson, and others are among the larger urban areas where significant exfiltration potential exists. Further study of exfiltration conditions in cities such as these, with relatively large areas with sewers above the groundwater table, may be warranted on a case-by-case basis where evidence of exfiltration (e.g., groundwater contamination) has been observed, or is revealed by more detailed evaluations. Areas with extremely deep groundwater tables probably experience relatively less risk associated with exfiltration due to the long subsurface travel times and distances of the exfiltrated sewage from the sewer to the groundwater table. Areas with significant portions of the system above, but in close proximity to, the groundwater table are probably at greatest risk. There is an increased risk in the relatively few areas with significant exfiltration potential when there is, for example, a thin soil and fractured rock hydrogeologic setting which allows pathogens and other contaminants from the sewage to reach the ground water quickly and with minimal attenuation. However, since public water supplies are treated with chlorination, ozonation, or other systems to kill fecal bacterial contamination, an added measure of protection is provided.

A greater potential problem, albeit isolated, may be exfiltration from sewers carrying industrial wastewater. Organic and inorganic constituents of industrial sewage can be overall much more persistent than those of domestic sewage, and therefore much more likely to reach the ground water in areas of significant exfiltration potential. The disposition of industrial sewage contaminants which reach ground water used for drinking water supplies may not be the same as that of fecal bacteria from domestic sewage [i.e., the treatment processes (flocculation, filtration, chlorination, activated carbon filtration, et. al) may not eliminate or reduce these contaminants to render them harmless]. Untreated well water in some rural, small community, commercial, and private-owner drinking water systems does not enjoy this added protection. However, these systems are not typically in close proximity to large municipalities and associated sewer systems/exfiltration potential.

The Albuquerque Case Study concluded that the rate of exfiltration from that sewer system, expressed as a percentage of base flow, is on the order of 10% of average daily base wastewater flow - in absolute terms, roughly 5 mgd. This rate, expressed as an average annual rate, is 1825 Mg/yr. Another relevant conclusion of the Albuquerque study was that there is a greater impact on ground water from septic tank usage than from sewer exfiltration. As the foregoing depth-to-ground water analysis indicates, however, exfiltration is expected to vary significantly on a regional basis. Further study should expand the initial depth-to-ground water analysis performed here and identify more precisely the "exfiltration susceptible" sewer systems throughout the U.S. and the extent to which exfiltration impacts ground water in these systems.

In summary, exfiltration does not appear to be a significant national problem based on an evaluation of 1) available groundwater table data to nationally assess the extent to which sewer systems are susceptible to exfiltration, 2) past studies of measured and estimated exfiltration rates, and 3) protective mechanisms, particularly natural soil/hydrogeological setting attenuation and drinking water treatment plants. Exfiltration may be a regional or more likely local problem where the GWT lies closely under the sewage flow surface and/or where the exfiltrate can reach even deep ground water through a thin soil/fractured rock hydrogeologic setting especially where persistent, potentially toxic contaminants are present, such as those often associated with industrial sewage.

Corrective Measure Costs

Given the relatively high rates of exfiltration that potentially discharge from exfiltration susceptible sewer systems in the U.S., corrective measures may be required to adequately protect the groundwater resources, and in some limited instances surface waters, in these areas. Given the site-specific nature of exfiltration problems, however, a more detailed assessment of the larger urban areas in the exfiltration susceptible western U.S. should be completed before a meaningful estimate of corrective costs can be developed.

Corrective actions to address exfiltration in those situations where local-level evaluation calls for such action will generally be accomplished with similar technologies as those used to address infiltration. Although an estimate of national-scale costs to address exfiltration must follow more detailed evaluation of exfiltration-susceptible sewer systems, corrective action costs on a unit basis [i.e., cost ($) per lineal foot of sewer] were developed for this study and ranged from $60 per lineal foot for an 8-inch-diameter sewer to $590 per lineal foot for a 36-inch-diameter sewer.

Recommendations

This study identified the following data/ technology gaps associated with exfiltration. Recommendations for research and development to fill these gaps were developed for each data/ technology gap identified.

1. Data Gap - comprehensive national depth-to-groundwater maps: Although a large portion of the U.S. has readily available, accurate depth-to-groundwater data, many regions of the United States have relatively limited data.

   Recommendation:

   An effort to refine the initial depth-to-groundwater mapping produced in this study with an expanded and updated database would support a more detailed national estimate of exfiltration and the cost of associated corrective measures.

2. Data Gap - extent of exfiltration in municipalities: There are relatively few large urban areas in the U.S. which have the potential for widespread exfiltration. Western arid U.S. cities such as Albuquerque, Phoenix, and Tucson are among the larger metropolitan areas where significant exfiltration potential exists and little is known about it. Albuquerque's exfiltration has recently been extensively studied.

   Recommendation

   Further study of localized exfiltration conditions in cities with high exfiltration potential may be warranted on a case-by-case basis where evidence of exfiltration has been observed, or is revealed by more detailed groundwater study. This study should be preceded by assessment using the refined depth-to-ground water mapping recommended above to produce a national inventory of exfiltration susceptible areas. This localized study will be of greater value than an attempt to quantify the problem nationally, due to the localized nature of the problem.

3. Data Gap - exfiltration fate and transport: No information is available regarding the biological disposition of sewage exfiltrate. Also, it would be useful to determine if a biological crust forms in the bedding below an exfiltrating sewer that would serve to insulate/protect ground water and/or water supply distribution systems.

   Recommendation:

   Research to fill the exfiltration disposition data gap could involve the use of existing sewage systems known or determined to be leaking in significant amounts (using carefully excavated examination of the bedding beneath and adjacent to the leaking sewer joints) or by construction of an experimental leaking sewer system (artificially introducing sewage into the sewer systems bedding). An analysis of bedding samples from points at increasing depths and horizontal distances from the leak would help to reveal the extent of exfiltrate transport.

4. Combined/Separate Sewer Considerations for Detailed Urban Study Recommendation

   The sewer systems to be considered in future exfiltration assessments should include both combined and separate sewer areas, since combined sewers are often located in highly urbanized areas where imperviousness is high. The result is a decreased rainfall infiltration into the soil and lowering of the GWTs, making these sewers potentially more susceptible to exfiltration. Additionally, combined sewers are often shallower than separate sewers, older than separate sewers, and constructed with less-watertight pipe joints - all factors that can contribute to higher exfiltration rates. Another special case that must be considered in more detailed studies is force mains. Although they are often constructed with tighter pipe joints and more durable pipe material, they nonetheless operate under pressure and may therefore be more exfiltration susceptible.

5. Inclusion of Service Laterals Recommendation

   It will be important to more detailed exfiltration assessments of urban areas to consider service laterals together with public sewers in identifying and evaluating the exfiltration susceptible sewers, as laterals are the shallowest portion of the sewer system (largest hydraulic gradient difference with GWT) and typically of the poorest construction.

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The complete report, entitled “Exfiltration in Sewer Systems” is available at http://www.epa.gov/ORD/NRMRL/Pubs/600R01034/600R01034.pdf.
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