An Investigation of Leaky Sewers as a Source of Fecal Contamination in the Stormwater Drainage System in Singapore

By
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Abstract

A preliminary investigation was conducted into possible pathways for fecal contamination to enter stormwater drains from leaky underground sewer lines in Singapore. The island's drainage channels flow into catchment reservoirs that are used to store water for future supply needs. Singapore's Public Utilities Board wishes to open up the reservoirs for recreational purposes and requires the water quality in the reservoirs to meet certain standards.

Findings were assembled from the literature on sewer-groundwater interaction and Singapore's geology, the history and current state of Singapore's sewer infrastructure, the results of a groundwater model, field observations, and GIS data on the sewer and drainage network layout.
It was found that sewer pipe connections between buildings and the sewer network are particularly susceptible to damage, and that high-flow-rate pathways are likely to exist between a sewer leak near a building and the small drains typically laid along the building periphery. These drains flow into a network of larger drains that eventually flow into a reservoir. Hence, sewer leaks near building connections may be a significant source of fecal contamination in the stormwater system and are worth investigating further.

Thesis Supervisor: Peter Shanahan
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I would like to thank my advisor, Dr. Peter Shanahan, for his meticulous guidance, thoughtfulness, virtually inexhaustible patience, and impeccably timed puns.

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LIS Solutions, I could not have asked for a better team to work and travel with this year. We have come a long way and had a fabulous time along the journey.

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Chapter 1 Introduction

1.1. Objective

Singapore's Public Utilities Board (PUB) is responsible for ensuring an adequate supply of safe water for drinking and domestic purposes. Much of Singapore's drinking water currently comes from treated stormwater that is collected by an extensive network of stormwater drains. The stormwater collected in these drains flows into one of several catchment reservoirs. One of these reservoirs, Kranji, has been the focus of previous studies by Master of Engineering students from the Department of Civil and Environmental Engineering at MIT. In an effort to increase the public's awareness about the island's freshwater resources, PUB wishes to open up the Kranji Reservoir for recreational purposes, but there is a concern about the water quality in the reservoir. Studies conducted the past few years reveal the presence of fecal contamination in the water that exceeds water quality standards (NTU 2008). Fecal contamination was also detected in the stormwater drains feeding the reservoir, suggesting the source of contamination in the reservoir is not simply runoff flowing into the reservoir. Possible surficial sources of the fecal contamination in the drains include direct discharge of sewage and run-off that flows over fecal matter before entering the drain. This study considers instead the possibility of the contamination emerging from the subsurface piped sewerage network that handles virtually all of the island's sewage.

This thesis begins in Chapter 2 with a literature review on sewer-groundwater interactions and in Chapter 3 with an overview of the nature of the geology and soils on the island. The history, current status, and future plans of wastewater conveyance infrastructure are discussed next in Chapter 4. A USGS MODFLOW groundwater model was built for the study to estimate the scale of time it might take for exfiltrated sewage entering the groundwater to flow into a drain and is reported in Chapter 5. Observations from the field and an analysis of Geographical Information System (GIS) data on the sewer and drainage networks are pieced together to form a picture of the most likely pathways of fecal contamination entering a stormwater drain from a leaky sewer in Chapter 6.

1.2. Singapore – An Overview

This section was written in collaboration with Laurie Kellndorfer, Kathyayani Shobhna Kondepudi, and Suejung Shin.

1.2.1. Active, Beautiful, and Clean Waters Program

As indicated above, the Singapore Public Utility Board wishes to expand recreational activities within Singapore's reservoirs. Singapore has limited land area for recreation, and making use of selected waterways and waterbodies is an integral part of PUB's plan to meet public recreational needs. Singapore has been working to enhance the accessibility, usability, and aesthetics of green spaces and parks, especially near waterways and drainage (Soon et al. 2009). The PUB wishes to open more of Singapore's surface waters to recreational activities, under the Active, Beautiful, and Clean Waters Programme (ABC Waters). The goals of the ABC Waters Programme are to bring the people of Singapore closer to their water resources by providing new recreational space and developing a feeling of ownership and value (PUB 2011b). The program aims to develop surface waters into aesthetic parks, estates, and developments. This plan will minimize pollution in the waterways by incorporating aquatic plants, retention ponds, fountains, and recirculation to remove nutrients and improve water quality. One of the greatest areas of concern with this plan is microbial pollution.

Disease-causing pathogens pose the greatest immediate threat to human health in polluted surface waters. Humans can come into contact with waterborne pathogens through drinking water supply and through recreation in contaminated surface waters. Infection in humans can be caused by ingestion of, contact with, or inhalation of contaminated water (Hurst and Crawford 2007). While the exact total number of waterborne pathogens is unknown, it is estimated that over 1,000 viral and bacterial agents in surface waters can make humans sick. Diseases from waterborne pathogens can range from mild to life threatening forms of gastroenteritis, hepatitis, skin and wound infections, conjunctivitis, respiratory infection, and other general infections. In order to open surface waterways and reservoirs for recreation, PUB must minimize pathogenic pollution in surface waters and keep the public safe.

1.2.2. Singapore's Water History

Water use and water resources have been of great concern to Singapore throughout its history. After over a century under British rule, and Japanese occupation during World War II, Singapore and Malaysia became one independent nation in 1963 (Evans and Scrivers 2008). Singapore separated from Malaysia two years later and became its own independent nation in 1965. Although Singapore had gained political independence, Singapore had no adequate source of fresh drinking water for its citizens. Singapore has been dependent on Malaysia for freshwater for its entire history as an independent country.

To date, Singapore and Malaysia have signed four water agreements—in 1927, 1961, 1962, and 1990 (Chew 2009). Two of these agreements have already expired, but the 1962 Johor River Water Agreement and a 1990 agreement between PUB and the Johor State Government allow Singapore to use freshwater from Malaysia until 2061. With price increases from the Malaysian government and fear of future conflicts, the government of Singapore is currently working toward water independence.

1.2.3. Innovative Water Resource Management

With a dense population inhabiting a small island, Singapore is forced to be innovative with its water management practices. The PUB attributes its success in water management to the separation of storm water and wastewater, incorporation of technological developments, and strict regulation and legislation. About 20 percent of Singapore's water supply comes from rainfall, about 40 percent is imported from Malaysia, about 30 percent comes from reclaimed wastewater, and about 10 percent comes from desalination (PUB 2011a).

Singapore keeps its stormwater and wastewater streams completely separate. Stormwater is collected in a network of drains, rivers, canals, ponds, and reservoirs. All collected water, even from urban catchments is collected and treated for drinking water. Singapore aims for sustainable stormwater management practices and has been using Best Management Practices (BMPs) to treat stormwater before it enters rivers and reservoirs. Many BMPs in Singapore include bioretention and vegetated swales, bioretentive basins, rain gardens, sedimentation basins, constructed wetlands, and cleansing biotopes (PUB 2011a).

Singapore also has the largest desalination capacity in Southeast Asia. Currently, Singapore treats 30 million gallons per day (MGD) of sea water for drinking water. By 2060, PUB hopes to expand this capacity to meet 30 percent of Singapore's drinking water supply (PUB 2011a).

All sewage and wastewater is collected and treated. Wastewater is reclaimed after secondary treatment, dual-membrane filtration, and ultraviolet disinfection through the NEWater program. NEWater reclaimed wastewater is of drinking water quality but is mostly used for industrial and commercial water supply. Its purity is higher than most tap water, making it ideal for industries such as semiconductor manufacturing requiring ultrapure water (Tortajada 2006). Currently there are four NEWater plants in Singapore that contribute approximately 30 percent of Singapore's water needs. PUB plans to expand NEWater to 50 percent of Singapore's water needs by 2050 (PUB 2011a).

1.2.4. Population Growth and Water Use in Singapore

Singapore is highly urbanized, with an ever-growing population living on a 700 km^2 island. As of 2010, 100 percent of the population lives in urban areas (Central Intelligence Agency 2011). Despite Singapore's increasing population (Figure 1), per-capita water consumption has decreased due to successful demand management practices (Figure 2). These include a progressive tariff structure, a water conservation tax, and a water-borne fee. The tariff charges 117 cents per m^3 for 1-20 m^3 of water used per month, with progressively higher rates for 20-40 m^3 used and above 40 m^3 used. The water conservation tax charges 30 percent for consumption of 40 m^3 and under, and 45 percent for consumption above 40 m^3. The water-borne fee charges 30 percent for all consumption blocks (Tortajada 2006). These charges and taxes reflect great increases from original tariffs and fees implemented prior to 1997 and are responsible for the decline in per capita water use.

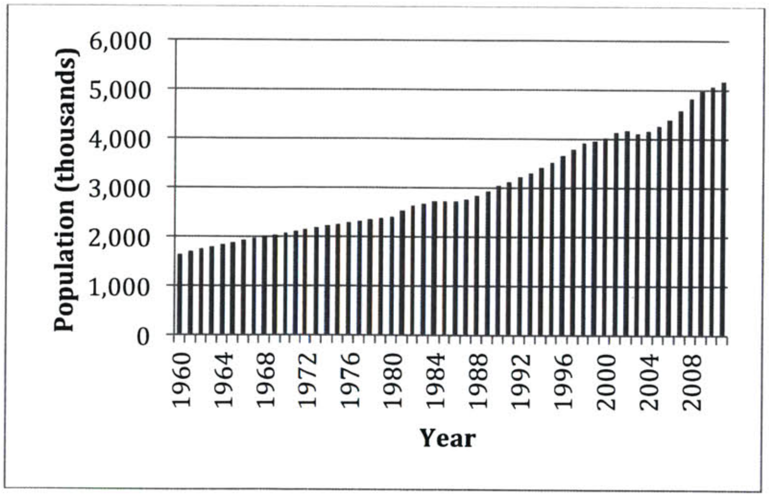


Figure 1 - Singapore population growth over time (Singapore Department of Statistics 2011)

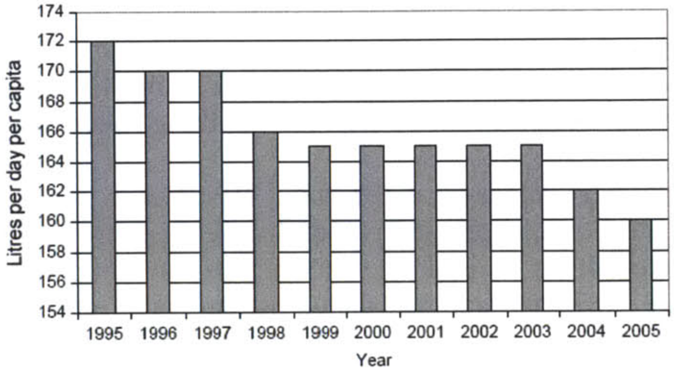


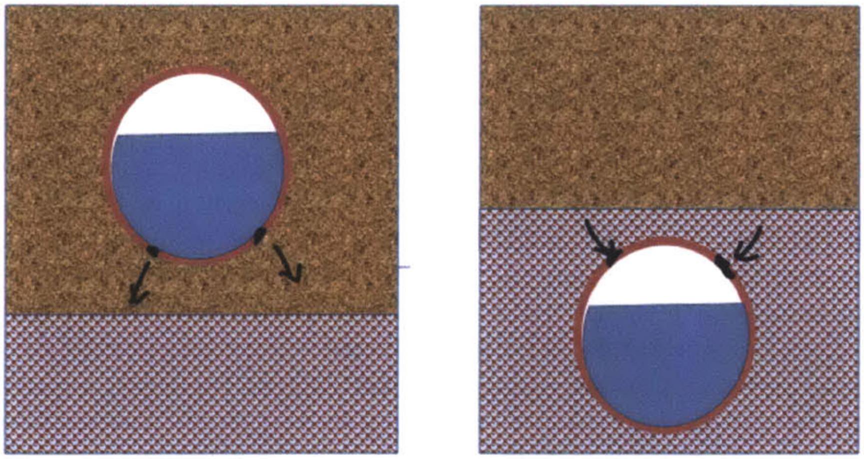
Figure 2 - Per-capita domestic water consumption (Tortajada 2006)

Chapter 2 Overview of Literature on Groundwater-Sewer Interactions

2.1. Infiltration and Exfiltration

Studies on groundwater-sewer interactions generally discuss one of two distinct problems: infiltration of groundwater into sewer lines, or exfiltration from sewer lines into the surrounding soil. Infiltration into sewer lines is a concern primarily because clean groundwater entering the sewer line is sent to a wastewater treatment plant, unnecessarily increasing treatment costs and lowering the local groundwater table (Held et al. 2006). Exfiltration from sewer lines that enters the neighboring soil environment introduces unwanted nutrients and organic, microbial, and other contaminants in the soil. The leaked sewage also increases the biological oxygen demand of soil that it flows through.

Infiltration into sewer lines occurs most readily when the groundwater table lies above the buried sewer i.e. in saturated conditions (Figure 3b). In this situation, the pressure outside the pipe is higher than inside it. Exfiltration can still occur in saturated conditions but our intuition and experimental results both agree it would be at a lower rate than if in unsaturated conditions (Figure 3a) Depending on the nature of the pipe damage, sewage could be continuously leaking out from the pipe, or leaking only occasionally from points higher up in the pipe. Figure 4 shows experimental results that compare modeled exfiltration flux values for different surrounding soil types and pipe water levels for saturated and unsaturated conditions. The graph, albeit displaying modeled rather than experimental results, indicates predictable trends in flux: the flux decreases as the surrounding soil gets finer and as the water level in the pipe is reduced. The modeled exfiltration rates in all scenarios are higher in unsaturated conditions, as expected.



a. Unsaturated conditions **b. Saturated conditions**

Figure 3 – Cross sections of a buried pipe

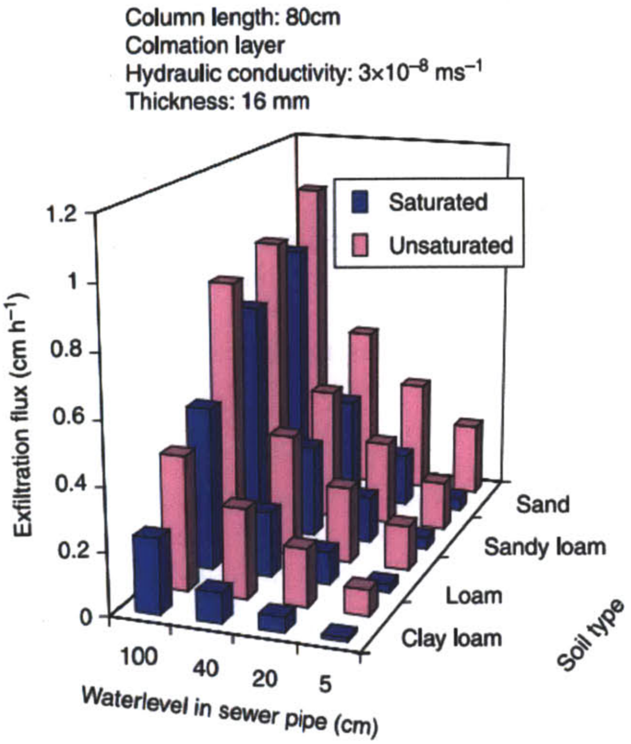


Figure 4 – Scenario analysis of exfiltration under saturated and unsaturated conditions (Karpf et al. 2009)

2.2. Factors Affecting Exfiltration Rate

The rate of exfiltration from sewers is dependent on several factors related to the sewer, the geological environment around it, and local climate conditions. Specific sewer-related parameters include the area and position of leak, and the depth of flow within the sewer (Held et al. 2006). Karpf and Krebs (2011) found that the conductivity of the trench backfill also significantly affects the exfiltration rate and volume. General sewer-related factors include the size, age, material of construction, and type and quality of construction of the sewer (Amick and Burgess 2000). Key geologic factors include groundwater depth relative to the sewer depth, the nature of the soil around the sewer, and the presence of fractures in the bedrock. The hydraulic conductivity and saturation level of the soil around the pipe will greatly affect the rate of adsorption and degradation of the leaked contaminants. The average rainfall, which directly affects the groundwater depth, is the primary climate factor. Typically, the average frost line would also be considered, however it does not apply to Singapore (Amick and Burgess 2000). There are several possible sources of leakage within a wastewater system. Leaks can occur at defective joints and cracks in service laterals, local mains, and trunk or interceptor sewers, and also at manholes if the connection or casing is damaged. A schematic from Amick and Burgess (2000) is shown in Figure 5.

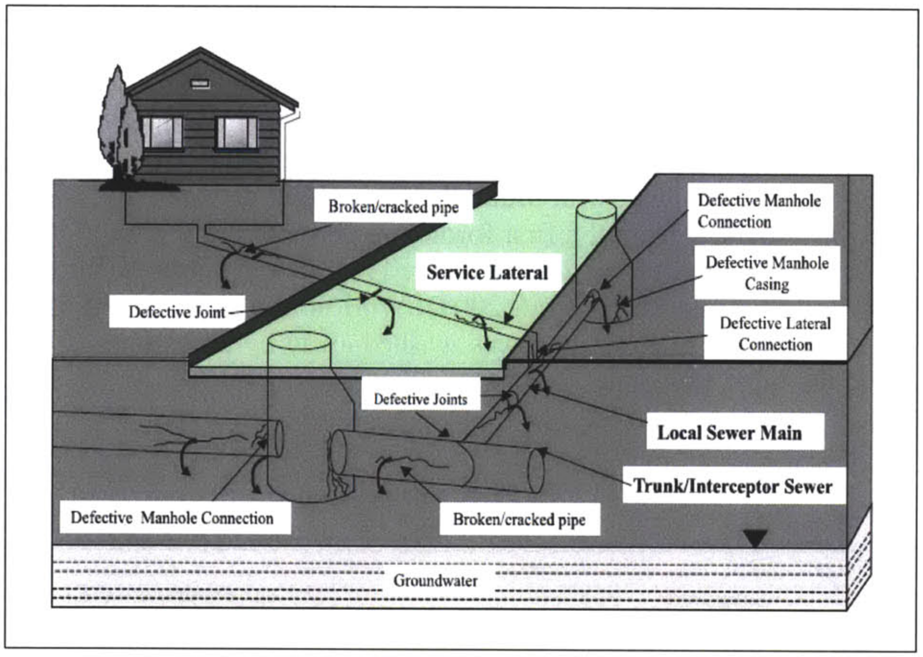


Figure 5 – Sanitary sewer components and exfiltration sources (Amick and Burgess 2000)

2.3. Colmation Layer

Several of the more recent papers on sewer exfiltration have discussed the formation of a clogging layer on the sewer pipe walls and in the area around the leak. This layer is formed in part by suspended solids that clog soil pores and in part by microbiological activity. This nature of blockage is termed colmation, and the layer is referred to as the colmation layer. The presence of this colmation layer is an important parameter affecting the rate and time variability of sewer exfiltration, as is discussed in greater detail in the section below.

In 1994, Rauch and Stegner (1994) published a landmark paper identifying a saturated colmation layer (Figure 6) plugging an opening in a sewer line, and a transition zone in the bedding directly beneath the pipe (Ellis et al. 2009). Since then, several studies have attempted to better understand and, more recently, model this complex, biological, physical, and chemical self-sealing mechanism.

The formation of the colmation layer is a two-phase process. In the first phase, suspended solids in the wastewater clog the pores in the soil, backfill material, and the damaged joint. Experimental results from different studies suggest that the first phase takes about three days during which the rate of exfiltration drops very quickly (Karpf et al. 2009). The role of biological activity is negligible during this rapid formation phase; the process is primarily physio-chemical. After the pores have been clogged by sediments, microbial activity in the form of bacterial and algae growth continues to reduce the rate of exfiltration over a much longer time scale, ranging from weeks to months until an equilibrium exfiltration rate is reached or the layer is destroyed (Ellis et al. 2009, Karpf et al. 2009).

Colmation layer thickness values reported in the literature range from 1 mm up to 20 mm, while values of its hydraulic conductivity, K_C, range from 1.1 x 10^{-6} m/s to 3.5 x 10^{-8} m/s (Karpf et al. 2009). The leakage factor, L, of a colmation layer is defined as the ratio of hydraulic conductivity of the colmation layer, K_C, to the thickness of the layer, Z_C. The leakage factor is conventionally used to characterize the exfiltration through a colmation layer (Vollertsen and Hvitved-Jacobsen 2003). Figure 6 from (Karpf, Traenckner, and Krebs 2009) shows the drop in the leakage factor of a colmation layer with time. The rate of decline slows considerably after the third day, suggesting a transition from the first formation phase to the second. The plot supports findings of many direct field studies that have observed rapidly declining exfiltration rates from open joints and other sewer leaks (Ellis et al. 2009). Wolf et al. (2006) found exfiltration rates multiply by up to 56 after a colmation layer was washed away by an extreme storm event, and near-zero rates while the layer was intact.

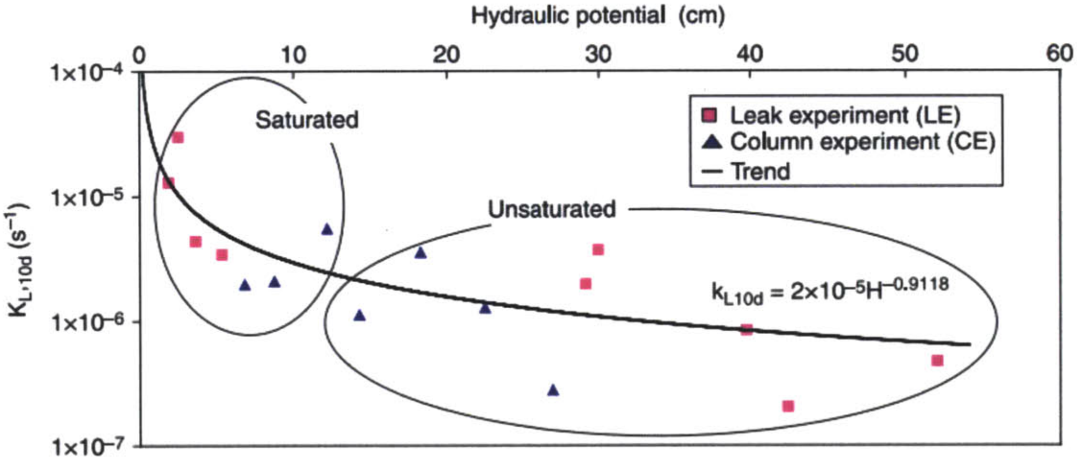


Figure 6 – Leakage factors after 10 days of exfiltration (Karpf et al. 2009)

While it is widely agreed that the colmation layer around a leak greatly reduces the rate of exfiltration coming out of it, there is considerable uncertainty surrounding the properties of the layer and the nature of the actual impact on exfiltration. Studies conducted in the past decade agree on general principles, such as the two-phase formation of the layer and the separate roles of suspended solids and microbial activity. However, the various studies published on this topic in the past decade present varied conclusions about the effectiveness of the colmation layer as a sealant.

Some studies argue that even in sewer systems having frequent joint gaps and cracks, the colmation layer is effective enough to prevent any serious exfiltration after an equilibrium leakage rate is established. Ellis et al. (2009) challenge this view by arguing that it is unlikely that the sealing is permanent because the colmation layer can be ruptured at high flow pressures or by a rising groundwater table, possibly causing a sudden and serious leakage of pooled pollutants. Daily peak flows might not be high enough to rupture the colmation layer, but perhaps the weekly or monthly peaks are. There is no clear consensus on the matter in the literature. The durability of the formation layer is related to too many parameters for there to be generalized solutions to the questions of how long the colmation layer will last, what can destroy it, and what will happen when it is destroyed. Results from direct sewer rig and field studies suggest much higher exfiltration losses than the results of indirect models, further highlighting the complexity of the matter!

The uncertainty and unpredictability of how the colmation layer behaves is highly relevant to this study; it is a possible explanation to the confounding lack of a temporal pattern in the bacterial concentrations in stormwater drains recorded by others (Shin 2012). If sewer leaks are indeed an important source of the contamination, one would expect bacterial concentration values in drainage systems to somewhat mirror peaks in the sewer flow. These peaks would most likely occur in the mornings and evenings. Failure to observe such peaks discounts the hypothesis that sewers are a key source of contamination. However, the current understanding of colmation layers suggests there is a considerable degree of unpredictability and instability in sewer exfiltration rates and incidents, which means the lack of a daily temporal pattern in bacterial concentration does not necessarily preclude sewers as a potential contamination source.

Chapter 3 Overview of the Geology and Soils of Singapore

The geology and soils in which sewer lines are constructed are important factors in the potential for wastewater leakage to migrate to surface drains and water bodies. This chapter reviews the literature on Singapore's geology and soils, focusing particularly on the reported values of soil hydraulic conductivity and the presence of fractures in the bedrock.

3.1. Geologic Formations

The solid rock foundation below Singapore is generally divided into four main series (Sharma, Chu, and Zhao 1999): Bukit Timah granite and Gombak norite (igneous rocks), Jurong Formation (sedimentary rocks), Old Alluvium (Quaternary deposits), and Kallang Formation (recent, alluvium, marine clay). The geological map below includes two other rock types that make up a small part of the island. In many areas of the island we can see that the geology is diverse; the Kranji Reservoir, for example, is on or neighboring all four primary rock types. In equatorial regions, soil formation is a primary result of the gradual weathering of the bedrock (Rahman 1991). Singapore's tropical climate (warm and humid) induces heavy weathering, and thus the categorization of soil types of Singapore is commonly based off its underlying geology.

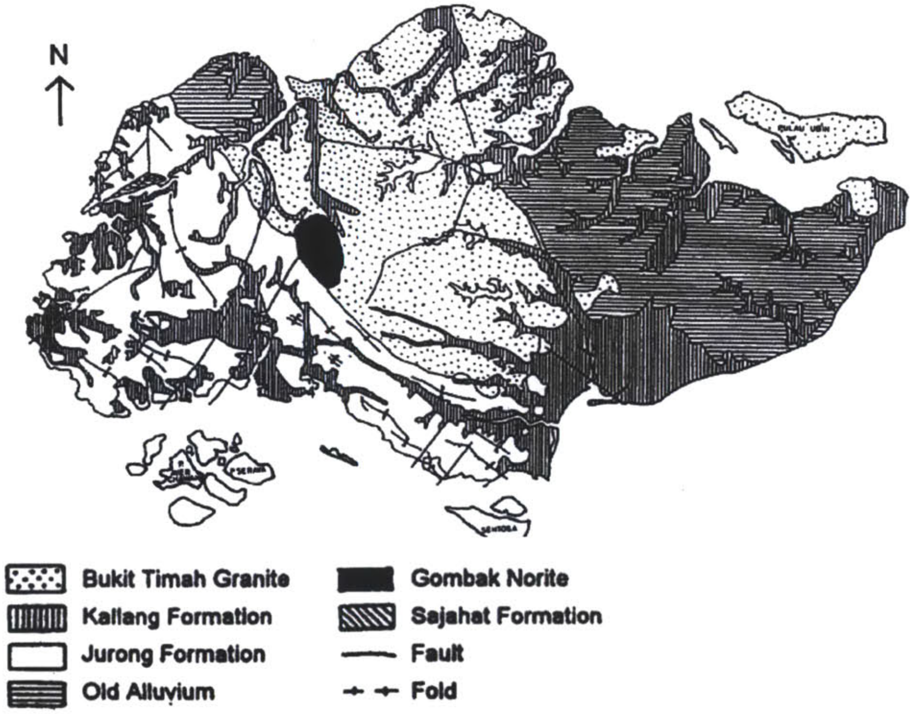


Figure 7 – Geological map of Singapore from Sharma et al. (1999), originally published by Public Works Department, Singapore in 1974

3.2. Bukit Timah Granite

A third of the island of Singapore rests on the Bukit Timah granite foundation made up of igneous rocks. This granite weathers extensively and the regolith (layer of weathered soil covering the solid rock) ranges from a few meters to far above 30 m in many areas (Rahman 1991). The faults in the granite rock are nearly vertical, and Sharma et al. (1999) report that the faults that are water-bearing and water-conducting are in isolated locations. They report granite rock hydraulic conductivity values of 10^{-9} to 10^{-7} m/s (groundwater will flow only in fractured zones), and hydraulic conductivity values of the soil above the rock on the order of 10^{-5} m/s (0.86 m/day). The Bukit Timah soil is sandy silty clay, and its properties vary significantly according to the degree of weathering the soil has undergone. The clay fraction of the soil decreases dramatically with depth, while the silt and sand fractions generally increase with depth.

3.3. Jurong Formation

The Jurong Formation is made up of a number of sedimentary rock types that vary both vertically and laterally, although the gradation of weathering for all of them ranges from fine-grained mudstone to coarse conglomerates. The weathering and soil formation of sedimentary rocks is generally less advanced than that of igneous rocks, in part because igneous rocks are generally older and possibly also because they may have been in different topographical and geological conditions (Rahman 1991). Nevertheless, due to Singapore's climate, the Jurong Formation has undergone heavy weathering. Soil depths range from a few meters to 50 m. The Jurong Formation is folded intensely and the faults are aligned with or perpendicular to its folds which are northwest-southeast (Sharma et al. 1999). Published values of hydraulic conductivity of the soil above the Jurong formation bedrock range from 10^{-9} to 10^{-6} m/s, a thousand-fold range! The soils are mostly composed of interbedded layers of clayey silt and sandy clay. The soil over the Jurong foundation is again, as expected, highly variable in space because of the wide variety of parent rocks, the high frequency of faults, and the thin bedding.

3.4. Old Alluvium

The Old Alluvium bedrock underlies a large part of the island, in particular the eastern section. The deposits are made up of alluvial gravels and sands and thin silts (Thomas 1991). The horizontal hydraulic conductivity of the residual soils is estimated to be between 3.4×10^{-8} to 18.8×10^{-8} m/s depending on the depth (Sharma et al. 1999). Sharma et al. wrote that there was not enough data to determine the vertical conductivity but estimated that it is one-fifth to one-half of the horizontal hydraulic conductivity. Interestingly, the Old Alluvium is economically very significant to Singapore; it is the source of much of the sand used for the island's construction (Sharma et al. 1999).

3.5. Kallang Formation

The Kallang formation is a recent deposit (~120,000 years ago) with marine clay and peaty soils as its most distinctive components. The vertical hydraulic conductivity is estimated to be in the range of 10^{-10} to 10^{-9} m/s, and the horizontal hydraulic conductivity in the range of 10^{-10} to 10^{-8}

m/s. The horizontal and vertical hydraulic conductivity both decrease with depth, primarily due to the drop in the void ratio.

3.6. Soil Hydraulic Conductivity

The space limitations of the island coupled with Singapore's drive for infrastructural development has meant that soil studies rarely impact the decision to develop a plot of land. If the original soil is deemed unsuitable, the project is built all the same on modified, additionally supported, or replaced soil (Rahman 1991). The island's geology makes the extraction of groundwater unfeasible (Rahman 1993), though Pitts (1985) reported that in the low-lying areas of the island the groundwater table is only 1.5 m below the ground surface. Because of the lack of general interest there are only a handful of studies on the soils in Singapore. Most of these studies look at the impact of soils on construction rather than their hydrogeology. However, since the 1980s there have been a couple of studies (Sharma et al. 1999; Rahman 1991; Pitts 1985) aimed at classifying soils around the island and estimating values of hydraulic conductivity. As we would expect (especially given the highly varied geology), these studies report that the soil is extremely heterogeneous and the reported hydraulic conductivity value range is over multiple orders of magnitude (Table 1).

Table 1 – Summary of values of hydraulic conductivity for the major soil types found in Singapore

Underlying geology	Bedrock properties	Residual Soil Hydraulic conductivity (m/s)
Bukit Timah Granite	Igneous rocks (granite)	10^{-5}
Jurong Formation	Sedimentary rock conglomerates	10^{-9} to 10^{-6}
Old Alluvium	Alluvial gravels and sands and thin silts	3.4×10^{-8} to 18.8×10^{-8}
Kallang Formation	Marine clay and peats	10^{-10} to 10^{-8}

The geology and soils in which sewer lines are constructed are important factors in the potential for sewage exfiltration to migrate to surface drains and water bodies. The goal of this section was outline key properties of Singapore's underlying bedrock and residual soils in order to help identify potential regions in which transport of sewage from leaky pipes is plausible due to the presence of certain properties or pathways such as high soil hydraulic conductivity or high frequencies of fractures in the bedrock. From the information gathered from various sources, it appears that extensive subsurface transport is most likely in regions over the Bukit Timah Granite and Jurong Formation bedrock. Both bedrock series have fractures, and the residual soils over these formations have the highest hydraulic conductivity values on the island. The highest reported value of hydraulic conductivity of residual soil is from the Bukit Timah Granite series, at 10^{-5} m/s, or about 0.8 m/day.

Chapter 4 Overview of Singapore's Wastewater Conveyance System

4.1. History

Singapore is small, densely populated, and has a tropical climate that allows diseases to spread easily (Meiyappan 2004). The island has limited land space and, hence, freshwater, making it crucial that drinking water sources are both conserved and protected from bacterial contamination. In the last five decades, Singapore has built and renewed an impressive wastewater conveyance and treatment system to meet demands of rapid housing development growth and to protect waterways from sewage contamination. This section aims to provide a general overview of Singapore's sewerage infrastructure, starting with the history of sewage disposal on the island. With a working understanding of the components of the system and the norms of construction, we can begin to evaluate which sections of the wastewater system are plausible sources of sewage contamination in the stormwater drainage system.

Until the 1910s, sewage, or "night soil," was collected privately from homes in buckets (Figure 8) or discharged directly into open drains built for the monsoons (Meiyappan 2004). The city's first piped wastewater infrastructure project was completed in the 1910s, starting with the construction of four pumping stations at major roads and a water reclamation facility that used a trickling filter treatment system. More parts of the city were sewered until the 1930s, but sewer system development began in earnest in the 1960s and grew rapidly in the 1970s and 1980s.

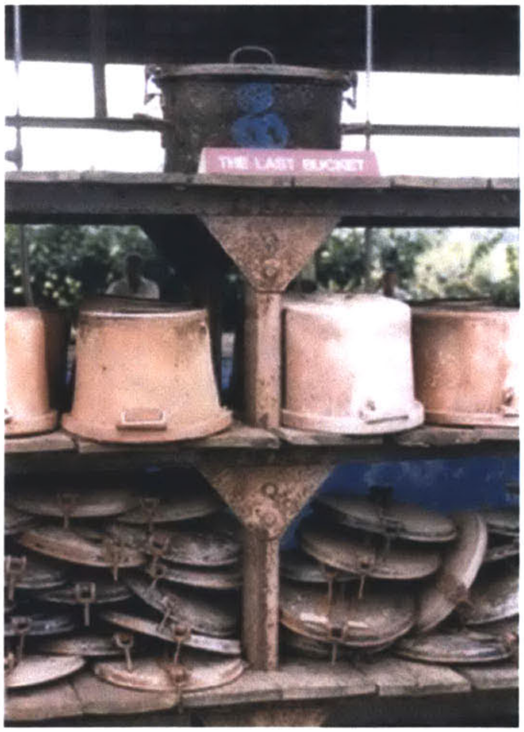


Figure 8 – "Night soil" buckets (PUB 2011c)

4.2. Sewerage Catchments

Singapore, until very recently, was divided into six sewerage catchments based on land use, each with its own water reclamation plant (Figure 9) (Meiyappan 2004). In 2004, Singapore's wastewater conveyance system consisted of 3,100 km of sewer lines, 220 km of pumping mains, 132 pumping stations, and 30 km of effluent pipe (the pipe transporting reclaimed water to the sea), and served close to 4 million residents. Figure 10, from Meiyappan (2004), shows the layout of a typical wastewater catchment scheme in Singapore. Wastewater from households (from toilets, showers, sinks), commercial buildings, and industries travels down pipes that are mostly gravity-fed to a point not far from the water reclamation plant (WRP), where the wastewater is pumped up to the plant to be treated and then discharged into the sea.

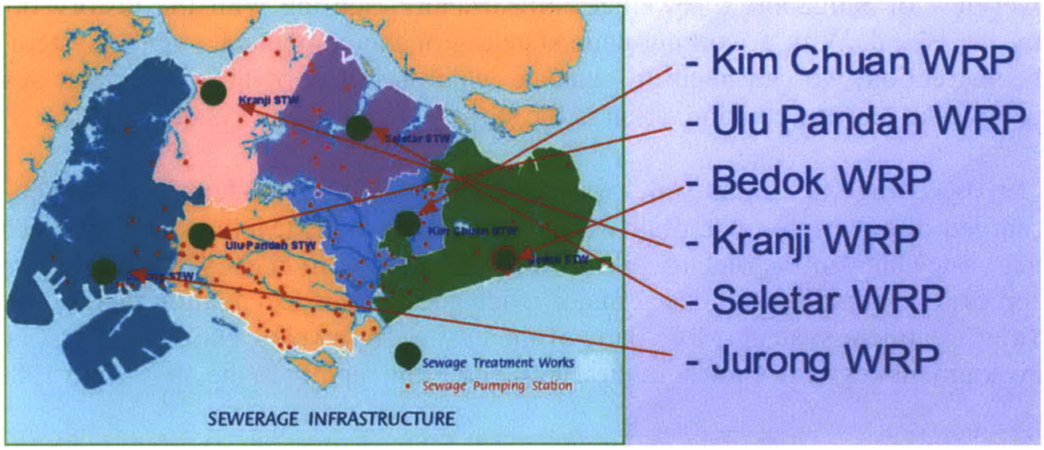


Figure 9 –Water reclamation plants for each sewerage catchment (Meiyappan 2004)

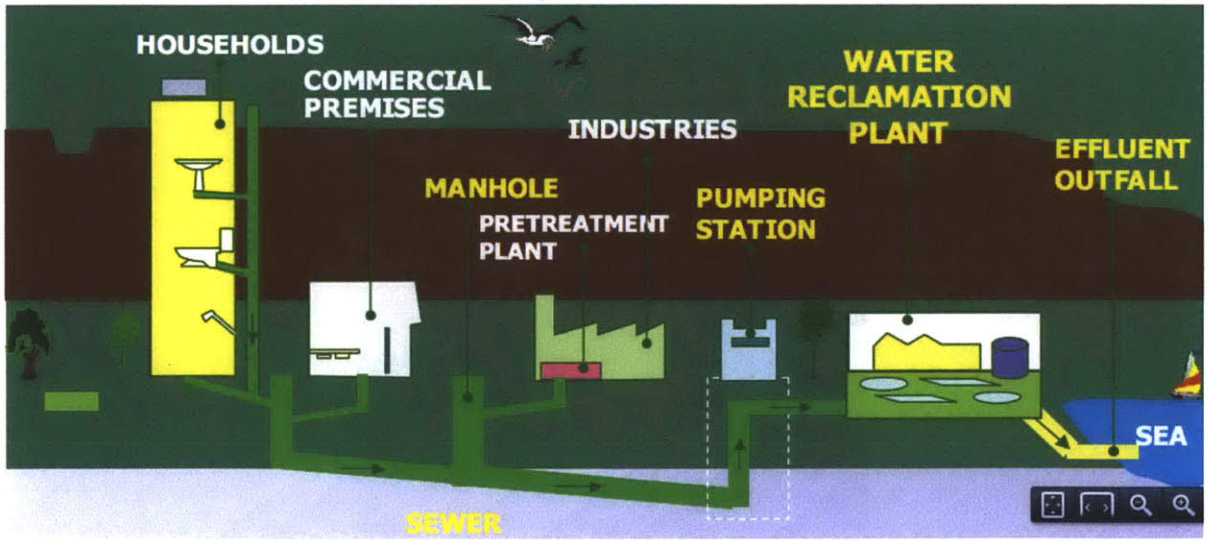


Figure 10 – Sewerage system layout (Meiyappan 2004)

4.3. Deep Tunnel Sewerage System

In the past decade, PUB has embarked on an ambitious and award-winning wastewater infrastructure project called the Deep Tunnel Sewerage System (DTSS) (Loganathan 2008). The DTSS consists of 48 km of 3.3-6 m diameter tunnels buried 18-45 m below ground level. The island's six water reclamation plants and all the pumping stations are going to be phased out eventually, and instead all of Singapore's wastewater will be transported to one of two large water treatment plants located at the eastern and western ends of the island (Figure 12).

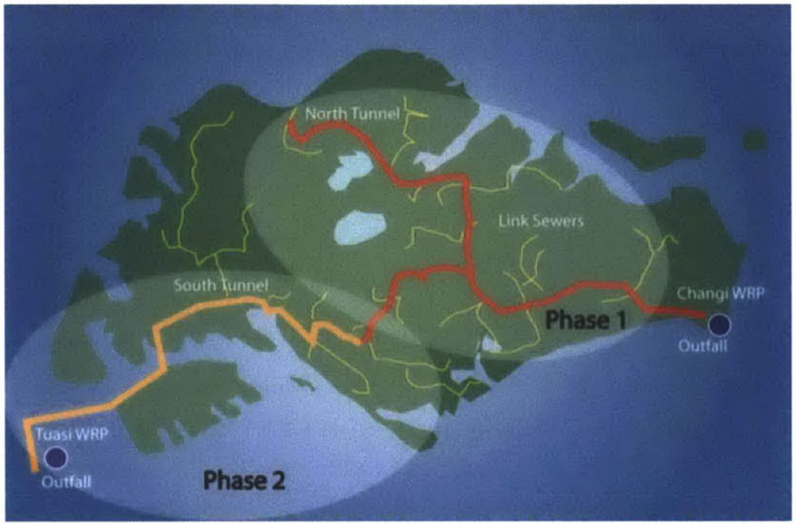


Figure 11 – DTSS pipeline layout (Loganathan 2008)

The DTSS is almost entirely gravity-fed, increasing the system's reliability and eliminating pumping costs from intermediate stations. The phasing out of the six land-intensive water reclamation plants has huge financial benefits. Replacing the six existing WRPs and 130 pumping stations with two large but compact plants will free up almost 800 hectares of highly valued land for development.

In addition to gaining from the financial benefits of the project, PUB hopes the DTSS will reduce the possible pathways for fecal matter to contaminate the island's freshwater resources. The increased capacity and depth of the major sewer lines in the system will mean fewer cases of sewage overflow and a lower risk of freshwater contamination in the event of a leak. However, the smaller diameter pipelines connecting buildings to an intermediary sewer network (called the Link Sewer Network) will remain at the same current depth of roughly 4 m below ground level, so if fecal contamination is currently emerging from these pipes, the construction of the DTSS is unlikely to resolve the problem of fecal contamination in the stormwater drainage system.

This is how a man with an average height of 1.6m compares with the 3.3m height of the link sewer

Constructed at depths ranging from 10 to 30m below ground, this 60-km sewer network connects the existing sewerage system to the deep tunnel.

Used water from existing sewers is fed to this 48-km long tunnel, which is located 20 to 50 m underground, even deeper than the existing MRT tunnels. The deep tunnel uses gravity to direct used water to the Changi Water Reclamation Plant.

Figure 12 – 3D Schematic of DTTS (PUB 2011e)

4.4. Trenchless Technology

Singapore has used trenchless technology to install, repair, and replace a large portion of its sewer pipes since the 1980s, and is widely regarded as a world model in the successful adoption of the technology. Trenchless technology refers to the methods and equipment that facilitate the installation, repair, and replacement of pipes with little or no excavation of the ground above (Piehl 2005). Balasubramanium (2004) writes that Singapore's switch to micro-tunneling, a form of trenchless technology, was largely a result of the serious problems that resulted from open-trench excavations for sewer lines in the 1970s. The loss of groundwater, subsidence, and ground movement, common problems associated with open-trench excavations, caused severe structural damage to the buildings around them. Furthermore, the complex soil conditions in Singapore made open-trench excavations very challenging, and their time-intensive and inherently destructive nature made them a huge public nuisance. The government was under great pressure to find a better way to install and repair pipelines and as a result adopted trenchless technologies long before most developed countries.

There are several benefits of using trenchless methods to handle underground pipes, including the reduction or elimination of traffic disruptions and a much faster speed of installation (Piehl 2005). Trenchless methods also eliminate many of the safety concerns associated with open-trench excavation, such as the depth of deep trenches, the need for work inside trench boxes, and worker exposure to traffic. Furthermore, since less soil is disturbed than if trenches were excavated, there is less of an impact on organisms living in the soil and water bodies in the area (Piehl 2005) .

In Singapore, the installation of most sewer lines using trenchless technology involves two main processes: micro-tunneling and pipe jacking. Micro-tunneling refers to the excavation of a tunnel along a pre-set alignment and gradient while pipe-jacking is the process of inserting pipe material into the excavated tunnel by jacking pipe sections into the excavated tunnel (Balasubramanium, 2004).

Trenchless technology is also being used in Singapore to rehabilitate aged sewer pipelines around the island (Donaldson 2009). The most common method currently being used for this replacement is called cured-in-place pipe (CIPP) lining in which a non-rigid lining tube saturated with a thermo-setting resin is installed into the damaged pipe, often using pressurized water. The lining is then heated, causing it harden into a new pipe within the older pipe.

Trenchless technology is an integral aspect of sewer pipeline installation and rehabilitation in Singapore. An understanding of the trenchless methods used on the island is pertinent to this study because the type and quality of sewer construction is more than likely to have a role in the volume and frequency of sewage exfiltration. Unfortunately, however, there is a dearth of research conducted on the leakage from pipelines inserted or repaired using trenchless technologies which makes it hard to ascertain how Singapore's use of trenchless construction has affected the chances of exfiltration. This is a question that a future geotechnical study could investigate.

4.5. PUB Code of Practices on Sewerage, Sanitary Works, and Surface Water Drainage

PUB began publishing design manuals for sewerage infrastructure, sanitary works, and stormwater drain construction in 1968 (PUB 2004). The Code of Practices on Sewerage and Sanitary Works was last updated in 2004, and the Code on Surface Water Drainage in 2011. Reviewing the code is useful for this study because it can provide insight on which components of the sewerage system are most susceptible to leakage and on possible pathways between the sewer pipes and drains.

The Code on Sewerage Works mandates several measures to keep rainwater out of the sewer lines (PUB 2004), addressing the concern of infiltration into the sewers. Measures against exfiltration are mainly contained in a detailed clause on tests required to measure the water tightness of sewer pipes before they are installed. There is no explicit reference to the stormwater drainage system, except to state that wastewater collected from common corridors, covered areas, and other such parts of a building structure may be connected to the drainage system. There are no references to the sewerage system in the Code of Practices on Surface Water Drainage (PUB 2011).

The Code of Practices on Sewerage Works specifies minimum distances between the edge of building structures and sewer lines (Table 2) and between the edge of buildings and pumping mains (Table 3). It is important to note that these distances are all under 2 m. Chapter 6 describes small drains that smelled of sewage around buildings in a neighborhood in Singapore. These drains were mostly between 1 and 4 m from the edge of the nearest building suggesting that a sewer leak that occurs close to a building could possibly be only a few meters away from a drainage channel.

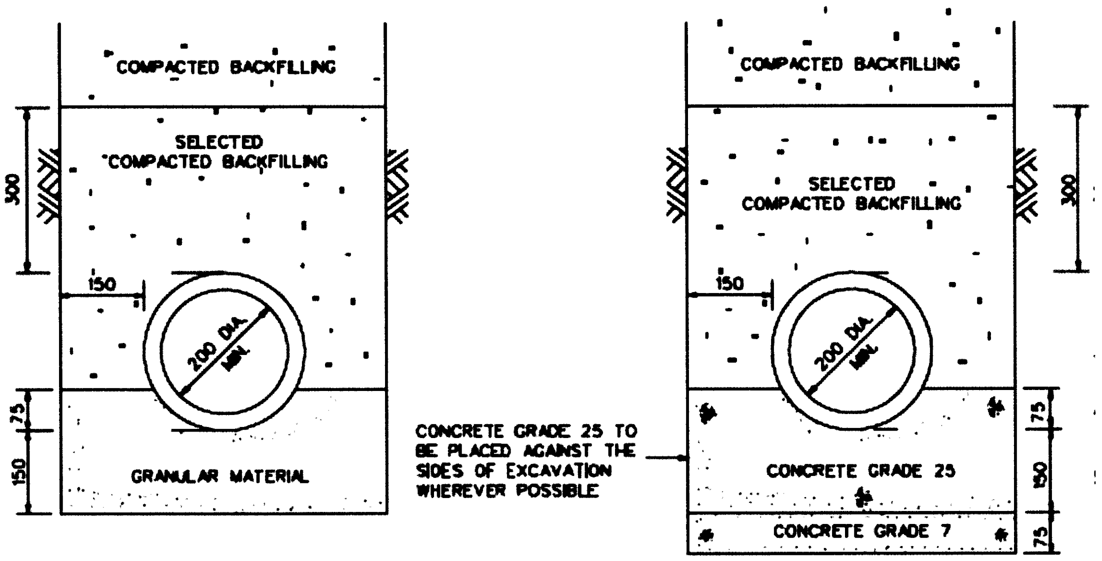
Pipes that are laid by excavating the ground instead of using trenchless methods require the construction of a bed that the pipe will rest on. PUB has published a set of Standard Sewerage Drawings that include specifications with four construction options for the bedding around sewer lines (Figure 13), Type "A" to Type "D" Sections. Type A has granular bedding, whereas Types B, C, and D have concrete bedding. The Code does not specify the nature of the granular material, it only states that the material must be compacted and laid evenly. Which of bedding types A through D is constructed depends on the depth of the trench, the pipe material, and the nature of the soil around the trench. Type A is to be used for flexible pipes (e.g. ductile iron) and rigid pipes (vitrified clay and concrete) in firm ground.

Table 2 - Minimum lateral distances between buildings and sewers (PUB 2004)

Sewer Size (mm diameter)	Sewer Depth (m)	Minimum Distance (m)
150 to 600	≤3	1.0
	> 3 and ≤5	1.5
	> 5	2.0

Table 3 - Minimum lateral distances between buildings and pumping mains (PUB 2004)

Pumping Main Size (mm diameter)	Pumping Main Depth (m)	Minimum Distance (m)
100 to 600	≤3	1.0
	> 3 and ≤5	1.5
	> 5	2.0

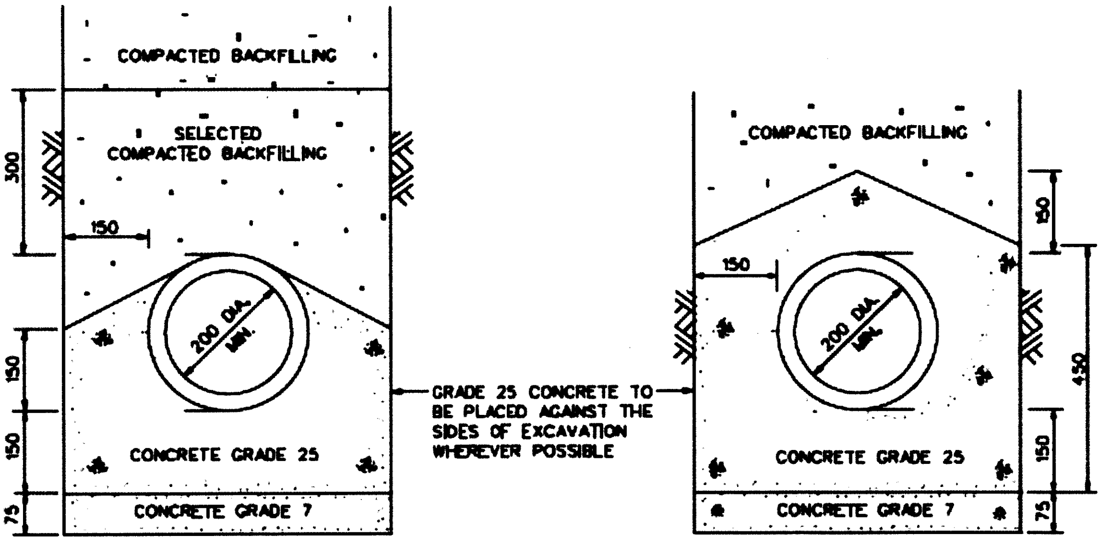


TYPE 'A' SECTION

SCALE 1 : 10

TYPE 'B' SECTION

SCALE 1 : 10



TYPE 'C' SECTION

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TYPE 'D' SECTION

SCALE 1 : 10

Figure 13 - Standard details of minor sewers (PUB 2009)

Chapter 5 Profile Model of sewer exfiltration with MODFLOW

5.1. Overview of the Model

It is important for this study to determine the typical scale of time it might take for exfiltrated sewage to reach a drainage channel in Singapore, in part because of the limited survival time of bacteria in the ground and in part because travel time may explain temporal patterns in bacterial concentrations in the drains. In order to obtain rough estimates of possible travel times, a profile model of subsurface flow was built at the pipe-scale using the U.S. Geological Survey's three-dimensional groundwater modeling program, MODFLOW (Harbaugh et al. 2000). This section presents an overview of how MODFLOW works, how a profile model was built for the study, and the model results.

The model built for the study is a profile model of an unconfined aquifer. A profile model is a two-dimensional model in which the vertical dimension is represented along with one horizontal dimension. In the model developed for this study, either side of the profile is a constant-head boundary. The head at one end is higher than the head at the other, inducing flow between the boundaries, and in between the two boundaries is the leaky sewer. A three-dimensional schematic of the model is illustrated in Figure 14. Because conditions are idealized to be uniform along the length of the pipe, the profile model considers only a two-dimensional profile perpendicular to the pipe axis.

5.2. Pressure Release Nodes

The objective of the model is to emulate the groundwater flow between the sewer and drain, where the lower of the two constant-head boundaries represents the pressure release nodes at the side of a drain. Here, pressure-release nodes refer to the circular holes in the concrete lining on the sides of drains that allow groundwater to seep into the drain (Figure 15). To create these nodes, a hollow PVC pipe is inserted within the formwork for the drain lining before the concrete is poured such that the concrete does not fill the space occupied by the pipe. The purpose of the nodes is to reduce any horizontal hydrostatic pressure from groundwater acting against the near-vertical drain lining so that the lining does not cave in. Figure 16 is a photograph showing traces of orange below the bottom row of pressure-release nodes on the sides of a large drain in Singapore. The orange substance is probably oxidized iron created as iron-rich groundwater leaves the hole, and the stains are thus an indicator of the level of the groundwater table. For the purposes of the model, the nodes represent the elevation at which the groundwater can access the drainage channel since the groundwater that reaches the node just has to trickle down to make it into the drain.

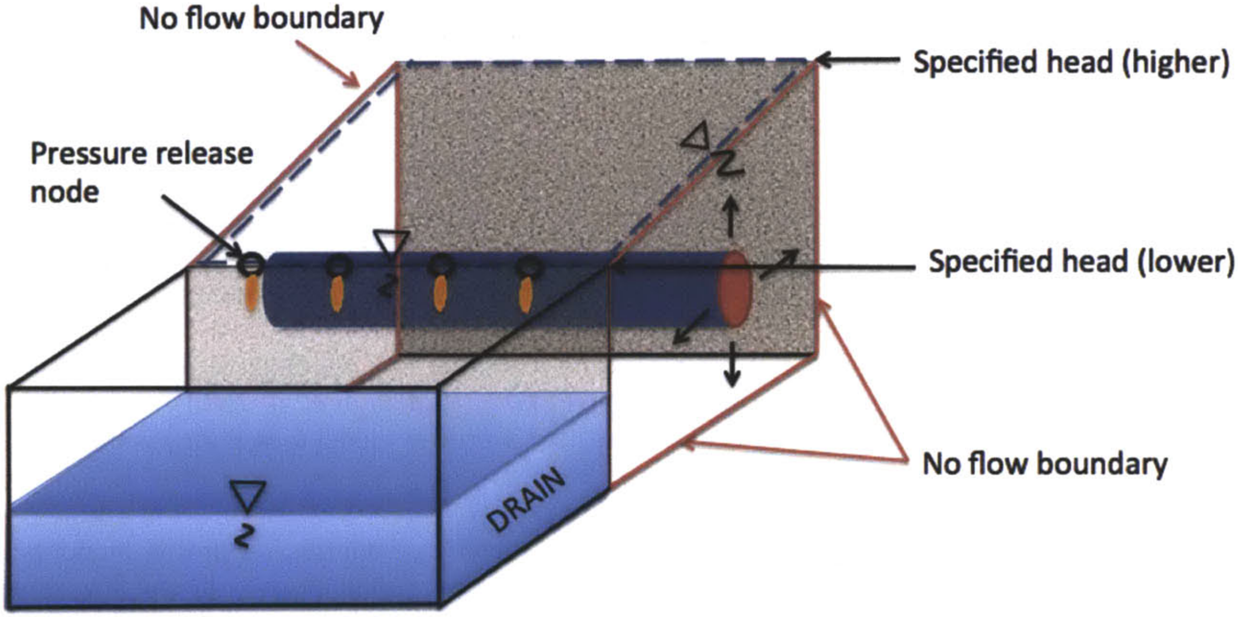

Figure 14 – Conceptual model (adapted from Anderson and Woessner, 1991)

Figure 15 – Close-up of pressure release nodes on the sides of drains (one of several nodes is highlighted by an arrow) (Photo: Laurie Kellndorfer)

Figure 16 – Pressure release nodes in a large drain (Photo: Laurie Kellndorfer)

In the model, the sewer is below the groundwater table. As discussed in Chapter 2, in this scenario infiltration into the pipe is more likely than exfiltration. However, if the flow in the pipe is pressurized enough, exfiltration is still possible. For the case in which the pipe is above the water table, we assume that the exfiltrated wastewater travels down to the water table and flows with groundwater in the aquifer from that point onwards. This assumption does not hold in the case in which the pipe is much higher than the groundwater table, but in the event that sewer depth is close to the groundwater table, the model can still be useful in providing a rough estimate of travel times. A program in the MODFLOW family called MODPATH (Pollock 1994) uses the MODFLOW run results to calculate and display the travel paths and times of "particles" inserted onto the grid. The model for this study was built and run using a graphical user interface called Groundwater Vistas (GV), developed by Environmental Simulations, Inc. of Reinholds, Pennsylvania (http://www.groundwatermodels.com/).

5.3. Building a Profile Model

MODFLOW simulates three-dimensional groundwater flow through a porous medium by solving the groundwater flow equation numerically using a finite-difference method (Harbaugh et al. 2000). It calculates and displays, among other things, the hydraulic-head distribution across a spatial grid using user-specified boundary conditions and hydrogeological parameter values. The program is capable of modeling a wide range of aquifer types and, as a result, the model assembly process is somewhat complex (Anderson and Woessner 1991). MODFLOW looks at a 3D model as a sequence of layers of porous material, where the primary grid of each layer typically lies on the horizontal x-y plane and the layers represent the vertical dimension. There is a limit on the number of layers that can be created and the process for creating and assigning parameter values to each layer is more involved than it is for the primary grid dimensions. As a result, the vertical resolution of the model is generally lower than the lateral resolution.

For this study, the model required is at the pipe-scale and the vertical element of the simulated flow path is pertinent. A high vertical resolution is needed and hence a profile model is created by flipping the orientation of the conventional model. In the profile model, the conventionally lateral 'y' dimension becomes the vertical dimension, and the conventionally vertical 'z' dimension becomes a lateral dimension that extends behind the cross-sectional grid (Figure 17) (Anderson and Woessner 1991). A key step in adjusting the orientation of the model is creating a gradient in the bottom elevation of the rows of the primary layer that reflects the actual elevation of each row in the cross-sectional model. The top elevation for each row is the same across the grid (in the x-direction), but the bottom elevation along each row is specified to reflect the actual height above the bottom row. Recharge in the areal model is applied as a parameter assigned to selected areas of the areal grid. In profile view, recharge values are modeled by inserting wells directly above the approximate water table (Anderson and Woessner 1991).

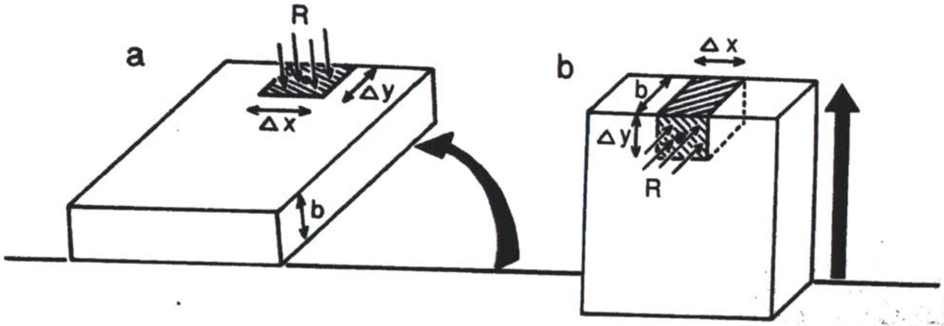

Figure 17 – Conceptualization of a profile model (Anderson and Woessner, 1991)
(a) Standard areal orientation (b) Modified orientation for profile model

The model built for this study has a constant-head boundary on either side of the cross-sectional grid and a no-flow boundary along the bottom. The grid spans 30 meters horizontally and 15 meters vertically, with a uniform grid spacing of 0.5 m. The head on the left side is chosen to be 12 m, and the head on the right chosen to be 10 m. This creates a fairly steep hydraulic gradient but the region we are modeling is where the groundwater table meets a surface water body (the drain), which is typically where the groundwater table is at its steepest gradient. The sewer leak is modeled as an injection well placed in the center of the grid, below the estimated water table.
The distance between the sewer and the drain is modeled as approximately 16 m. This distance is purely hypothetical; the distance between a leakage point and a drain along a pathway would depend on where the leak occurs within the sewerage system and where the sewer pipe is located in relation to the drain. The results of the model can be extrapolated to obtain rough estimates of travel times for distances greater than 16 m. The bottom elevation, one of the model parameters in MODFLOW, is different for each row in order to reflect the actual elevation at each point in the profile model. The bottom row has an elevation 0 m, the next row above has an elevation 0.5 m, and so on. The model setup as described above is shown in Figure 19.

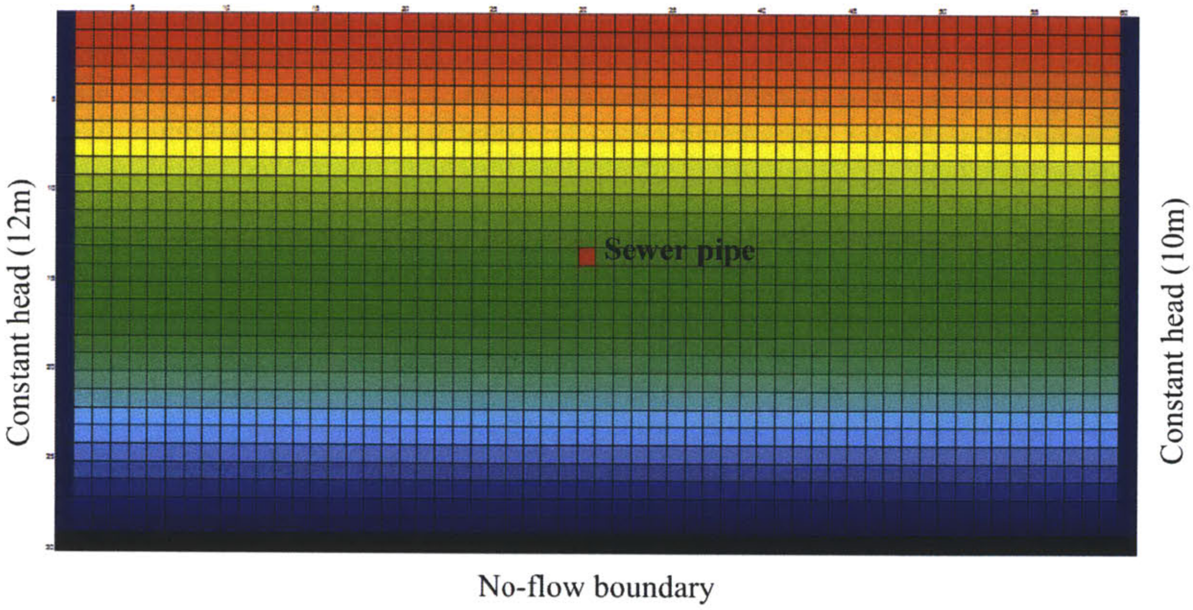

Figure 18 – Model setup

5.4. Model Parameters

Some of the parameters used in the model were selected from values reported in literature on Singapore's hydrogeology and rainfall record. The key parameters for this model are hydraulic conductivity, recharge, porosity, and the rate of exfiltration. For parameters for which no reported Singapore-specific values were found in the literature, the default values in the program were used. The aim of the model is to illustrate the worst-case scenario rather than the most likely scenario, since the most likely scenario precludes sewer lines as a source given the low hydraulic conductivity of soils in Singapore and PUB's extensive sewer rehabilitation campaign. A second model is built with a fracture in the ground being simulated by a region of very low porosity at the same hydraulic conductivity, resulting is very high flow velocities.

The highest value of hydraulic conductivity in the literature on Singapore's geology was of the Bukit Timah Granite residual soil, at a value of 0.866 m/day (Sharma et al. 1999). The Bukit Timah Granite covers a large proportion of the island including much of the area around Kranji Reservoir. A rounded-up base value of 1 m/day for the lateral (x, y) hydraulic conductivity is used for the model. The vertical hydraulic conductivity is taken to be one tenth of this value (0.1 m/day).

The highest average monthly rainfall in Singapore occurs in December and is about 330 mm over 16.5 rain days (NEA 2007). This roughly translates to 20 mm/day of rainfall on a typical December rain day. Generously taking recharge to be 50% of the rainfall, a recharge of 0.01 m/day is used in the model, applied by inserting wells to the grid blocks directly above the estimated water table level. The flow rate in the well at each grid block is entered as 0.005 m^3/day, assuming the modeled width of the profile is 1 m.

The porosity of most of the grid is set as 0.3 except for the region in which a fracture is modeled, where the porosity is reduced to 0.01. The base rate of sewer exfiltration is taken at 1 m^3/day, an estimate derived from the PUB Code of Practices on Sewerage and Sanitary Works. Clause 5.12 of the Code specifies that for pipes being tested for water tightness, the maximum allowable leakage rate is 11 L/hour for every 100 m of pipeline for each 300-mm increment in diameter that is surcharged with 1.5 m of head. A possible leakage rate can be back-calculated from these specifications. If we assume a constant leak from one point in a 100-m stretch of a 300-mm diameter pipe surcharged at 20 m, the leakage rate could be as high as 3.5 m^3/day. The surcharge head of 20 m is not unreasonable given the large number of pumping stations around the island. This exfiltration rate is, however, certainly an over-estimate; it does not account for the formation of the colmation layer discussed in Chapter 2, and assumes the leakage along the 100-m stretch of pipeline is concentrated at one point.

The location of the water table was estimated in a preliminary run of the model, and for the subsequent run, the injection wells that model the recharge were placed in the grid blocks directly above the water table (Figure 21).

5.5. Model Results

The most pertinent model results are shown in Figure 20 and Figure 21: the approximate travel times of flow emerging from the sewer pipe and traveling to the drain, placed approximately 15 m away. Figure 20 shows the travel time, in days, of a particle through soil with a lateral hydraulic conductivity ($K_{(lateral)}$) of 1 m/day and uniform porosity of 0.3. Figure 21 shows the travel time, in hours, of a particle that is released at the same point but that goes through a zone in which the porosity is 0.01 (30 times lower than the porosity everywhere else). This zone represents a rapid flow conduit such as a fracture. The Bukit Timah Granite and Jurong Formation both contain fractures, which, if near a sewer leak, could be transporting exfiltrated sewage over large distances in short periods of time.

MODPATH calculates the travel time and path of flow originating from two locations on the grid. Each arrow along the pathway represents one unit of time; in Figure 20 the unit is days, in Figure 21 it is hours. The pathway through the regular soil takes approximately 45 days to reach the drain, whereas the pathway going through the low porosity zone takes under five hours to the reach the drain. These results serve to illustrate the scale of the time of travel. The model suggests that exfiltrated wastewater travelling through ground without fractures could take several weeks to a few months to reach a nearby drain. If fractures or other such preferential pathways are present, this time could be substantially reduced.

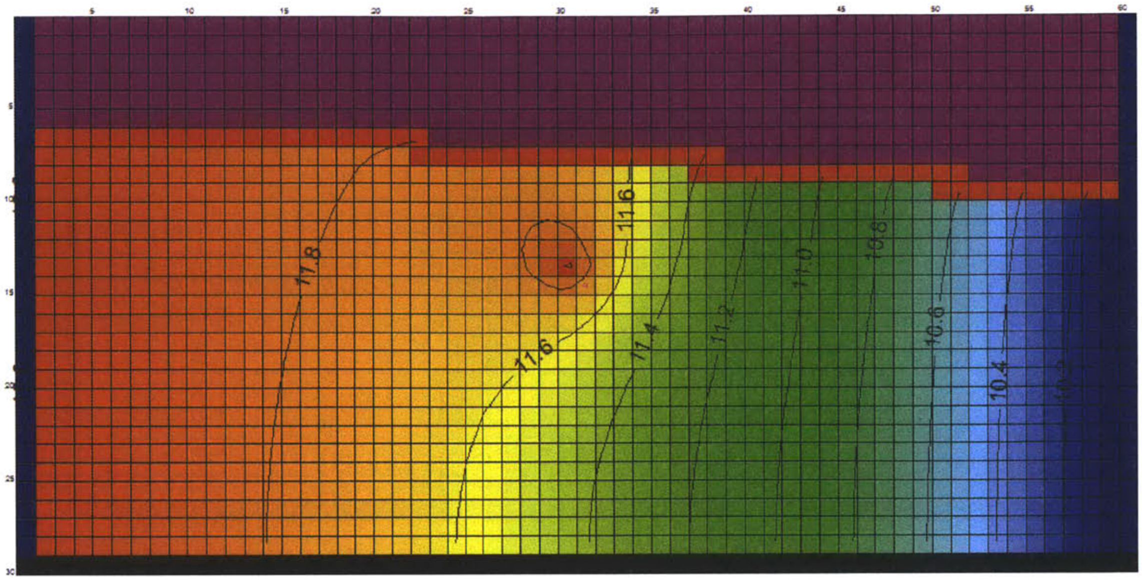

Figure 19 – Recharge wells inserted above water table

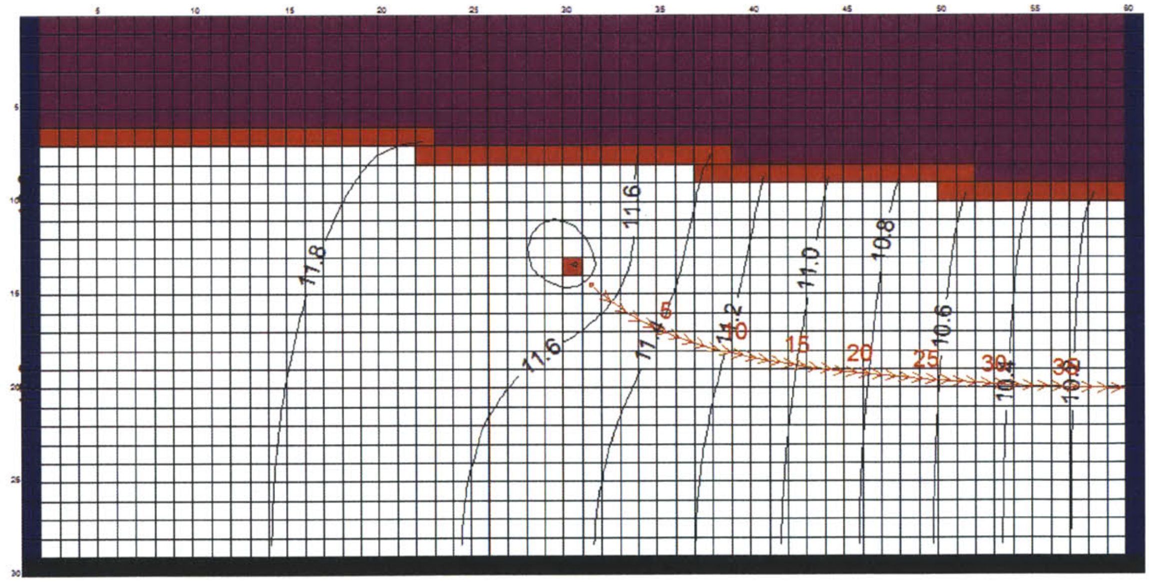

Figure 20 – Travel path and time (in days) using $K_{(lateral)} = 1$ m/day, $K_{(vertical)} = 0.1$ m/day, and uniform porosity of 0.3

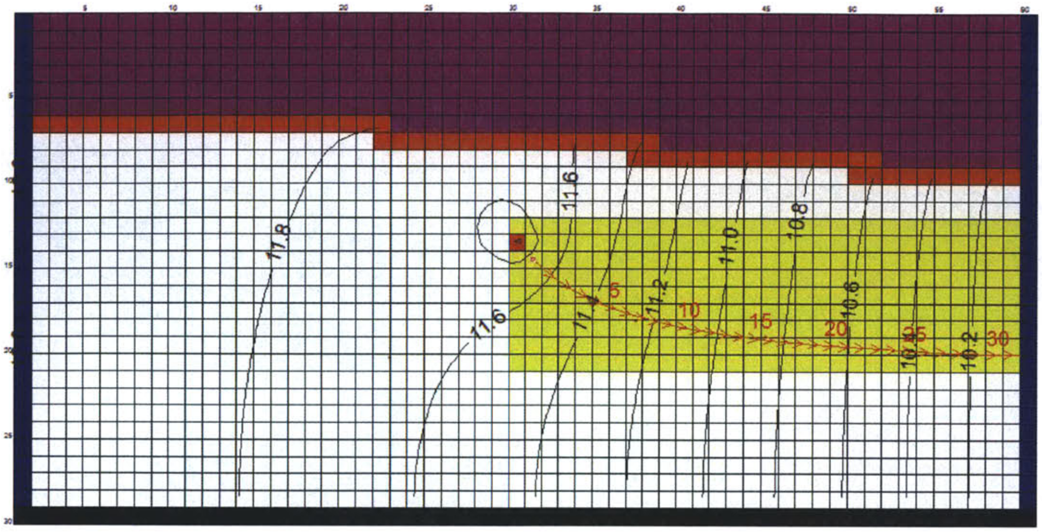

Figure 21 – Travel path and time (in hours) for particle traveling through a low porosity zone (porosity = 0.01)

Chapter 6 Toa Payoh: A Case Study

This chapter contains an analysis of the findings from field observances and sewer line and drainage channel layout maps for an urban neighborhood in central Singapore called Toa Payoh (Figure 24). A possibly significant release point of fecal contamination from sewers emerges from the analysis: damaged sewer-building connections.

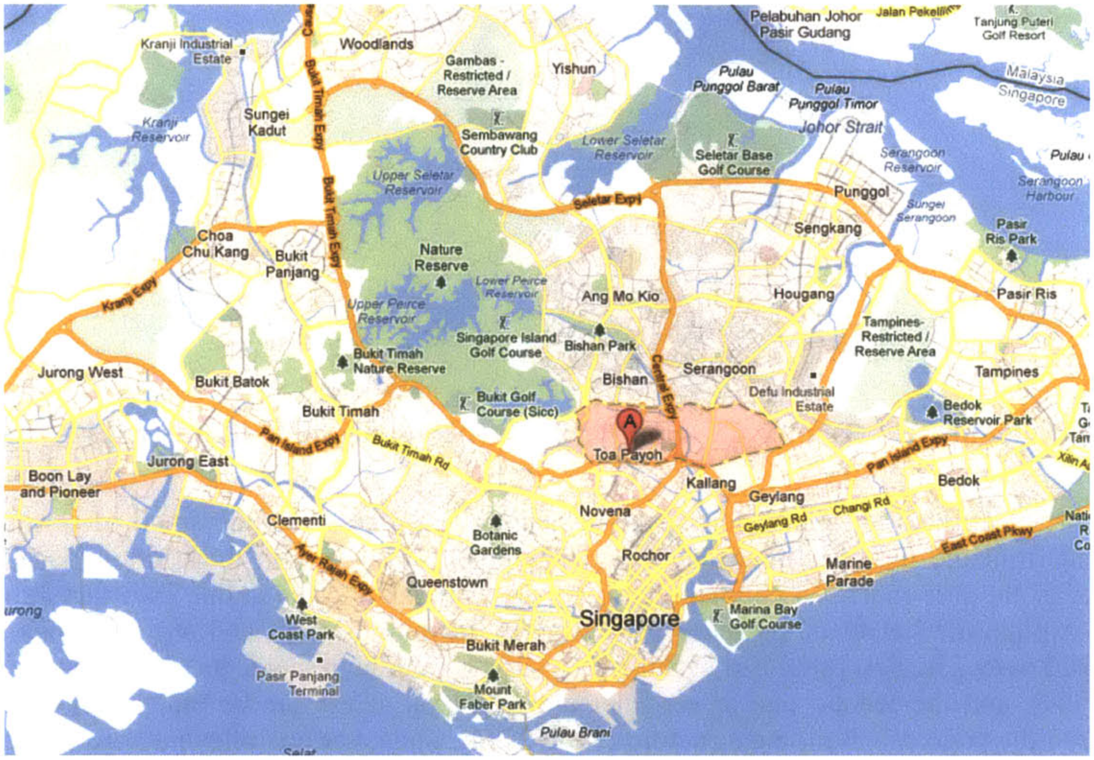

Figure 22 – Location of Toa Payoh

In January 2012, I observed the installation of auto-samplers in a stormwater drain near Lorong 8 Tao Payoh (Figure 23). The surrounding area is mostly residential with several large apartment buildings, a parking lot, and a food court nearby. My research team members and I studied the network of narrow covered drains around the perimeters of the apartment buildings, trying to determine the immediate origin and destination of the flow in them. These drains are placed within a few meters of the edge of buildings and appear to drain just the area immediately around the buildings, i.e. their origin is not far from the buildings themselves. The flow from these smaller drains was traced in the field and found to eventually flow into the larger drain that was being sampled.

Figure 23 – Toa Payoh sampling point (Photo: Shobhna Kondepudi)

An important observation made during this investigative process was the smell of sewage that emanated from the minor drainage network. The smell of sewage in these drains is a strong indicator of the presence of a pathway between a sewer leak and the drain. Two factors can be used to explain the suspected presence of sewage in the minor drains, and why this may not be an isolated case. The first point is that Singapore suffers from high incidents of subsidence (Soon et al. 2009), and the second that sewer lines and pumping mains can be built as close as 1 m (lateral) to the edge of a building structure (PUB 2004). Subsidence is relevant here because the displacement of pipes due to subsidence is generally greater than the more substantially anchored building structures, leading to a greater number of pipe breaks at building connections. Hence, if sewer lines from buildings are connected to sewer lines and pumping mains at a distance of 1 m from the building, it is very possible that there are sewer leaks occurring close to buildings. If there are drains around the perimeter of most buildings, we can begin to see a possible source of fecal contamination that can emerge from any urban part of the island.

A second field observation that is relevant to this study are the orange-colored traces of iron oxide emerging from the pressure release nodes on the side linings of the large drain. These traces indicate that the groundwater table has at some point been at least as high as the elevation of the nodes. Groundwater is often rich in dissolved (reduced) iron; as the water seeps through the pressure release node and comes in contact with the atmosphere, the iron in it oxidizes to form the orange precipitate. This observation is relevant to this study because it means groundwater is flowing into the drain at least occasionally; if a sewer leak is contaminating the groundwater, it is possible that the contaminated groundwater will flow into the drain.

Both of these field observations—sewage odor in building perimeter drains and evidence of groundwater discharge to larger drains—highlight possible pathways for fecal contamination from sewers to enter the stormwater drainage system.

Maps of the sewer layout and drainage channels of the neighborhood also provide some insight. Figure 24 is a map of a section of Toa Payoh containing the layout of the sewer lines, drainage channels, buildings, and the major roads. The map does not show smaller drains, including those at the perimeter of buildings, and pipes connecting sewer stacks from buildings to the main sewer network. The scale at the bottom is in meters. Figure 25 is a close-up of the map around a street called Lorong 8, showing the buildings, sewer pipeline, and major drainage channels near where the auto-samplers were installed. The circles within the sewer pipe layout represent manholes, and the numbers near the manholes are the ground elevation and sewer pipe invert elevation in meters. The numbers that are printed parallel to the sewer lines are the pipe radius (top, in millimeters) and length (bottom, in meters). The key finding from these maps is that most of the sewer network is buried by 4 meters or more. This is fairly deep relative to the stage of the drain that was being sampled, which was less than 2 m deep. The sewers are well below the water table; infiltration of groundwater into the sewers is more likely than exfiltration of sewage from the sewers. The high buried-depth indicates that flow from sewer mains to stormwater drains via groundwater is very unlikely. If the water table is above the sewer line, infiltration of groundwater into the pipes is more probable than exfiltration of sewage into the groundwater. The more likely source seems to be sewage leaking from relatively shallow building connections that is making its way into the smaller drains around the buildings via preferential pathways such as small openings along the cement-soil interfaces.

There are a few locations seen in Figure 24 where the sewer line is laid parallel to a major drainage channel with a lateral distance of around 10 m between them. One of them is shown in Figure 27. On the bottom right of the figure one can see the starting point of a sewer line that is laid very close to a drainage channel. The buried depth at the starting point is just over 2 m. If this pipe is pressurized, it might be possible that exfiltrated sewage from it flows with the groundwater into the drain through the pressure release nodes.

The analysis of the observations from the field and the map of the sewer and drainage networks, along with Singapore's susceptibility to subsidence, suggest that damaged piped connections between the building and the sewer network are the component of the sewerage system most likely to be responsible for any contamination in drains that are coming from sewer lines.

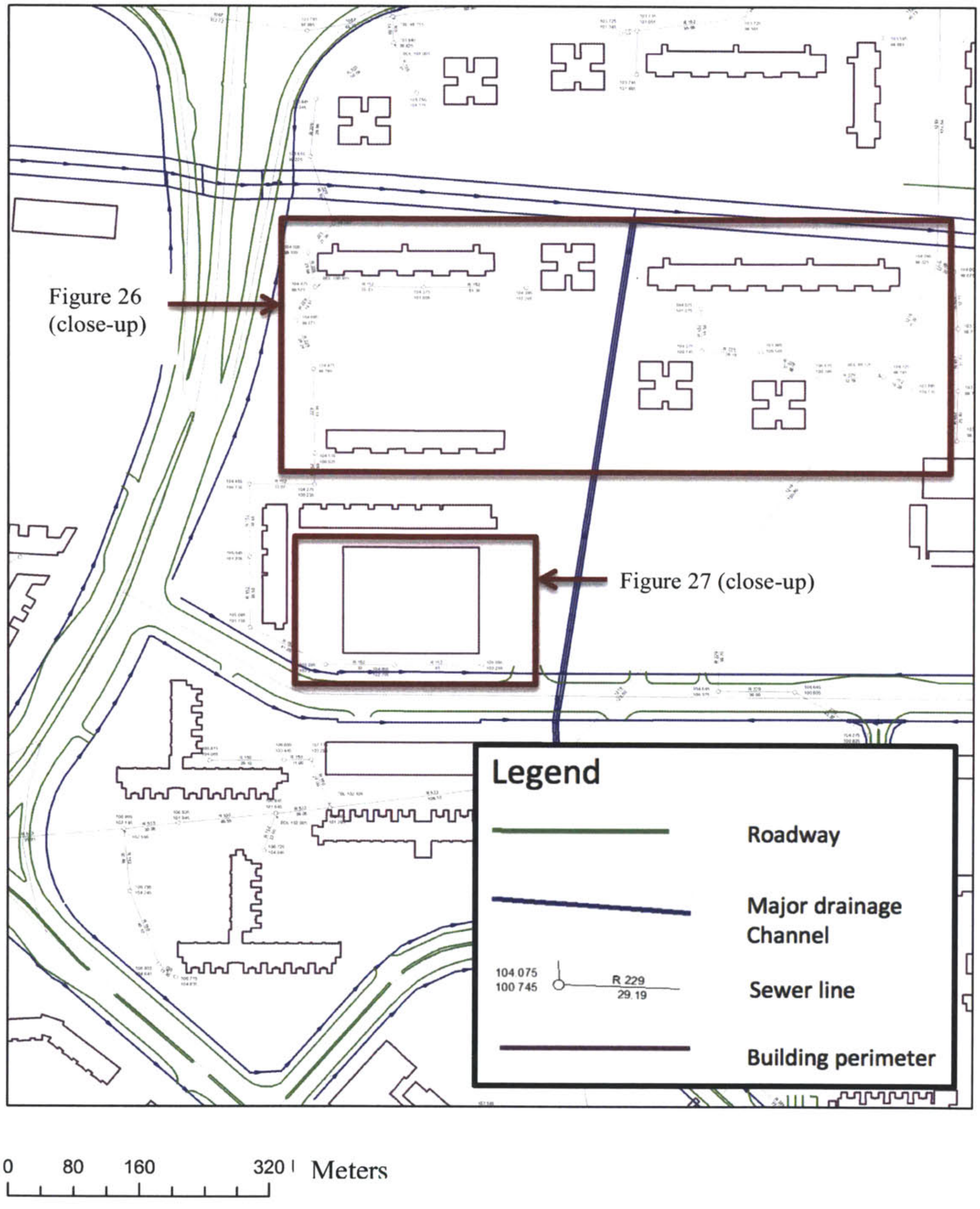

Figure 24 - Sewer pipeline and drainage channel layout in Toa Payoh

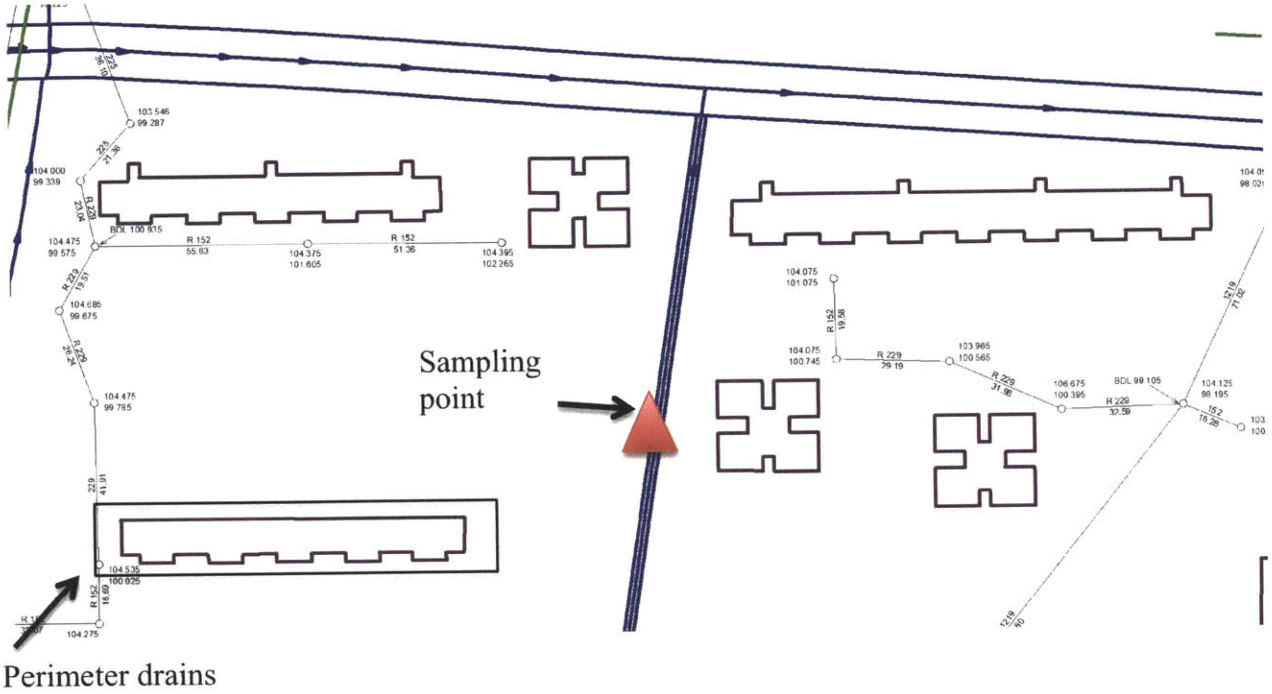

Figure 25 – Close-up of map around the sampling point

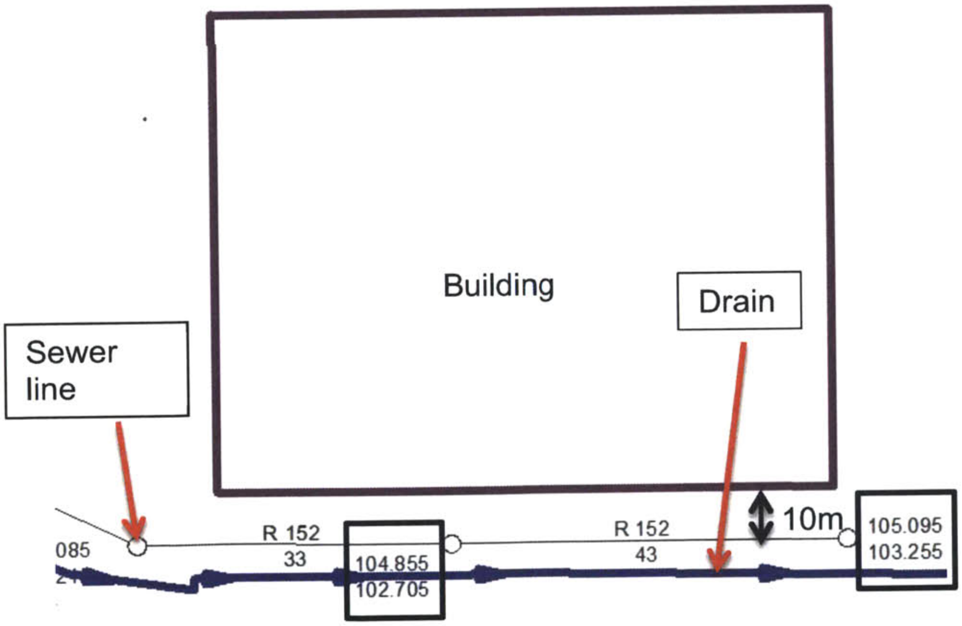

Figure 26 – Close-up showing sewer pipeline laid parallel to a stormwater drain (buried depth of approx. 2 m, horizontal separation of the sewer line and drain approx. 10 m)

Chapter 7 Summary, Conclusions, and Recommendations for Future Work

The purpose of this study was to conduct a preliminary investigation into the possibility that leaky sewers are a source of fecal contamination in the stormwater drainage system in Singapore. The island's drainage channels flow into catchment reservoirs that are used to store water for future supply needs. PUB wants to open up the reservoirs for recreational purposes and thus requires the water quality in the reservoirs to meet certain standards.

The contamination in the drains is most likely coming from multiple sources, including direct discharge of sewage and contaminated run-off entering the drains. Past studies by other MIT students (Dixon et al. 2009, Foley et al. 2010) have considered some of these surface sources. Leaky underground sewer lines are another potential source, however they have not been seriously considered previously largely because the soils in Singapore have low hydraulic conductivity and hence low potential for sewage transport through the ground. However, most of the island's sewage is within the sewer network, and the possible presence of high hydraulic-conductivity conduits between sewer and drains, such as fractures, make sewers a potentially significant source that is worth investigating.

This study was a preliminary investigation into possible pathways for fecal contamination to enter the drains from leaky underground sewer lines. Findings were assembled from literature on sewer-groundwater interactions and Singapore's geology, the history and current state of Singapore's sewer infrastructure, the results of a groundwater model, field observations, and GIS data on the sewer and drainage network layout.

The literature review on sewer-groundwater interactions highlighted three main concepts. The first was that sewer exfiltration is more likely to occur when the groundwater table is below the pipe than above it. Conversely, infiltration is a more likely concern if the groundwater table is above the flow depth in the pipe. The second key concept was that the rate of exfiltration depends on a wide range of factors, the most significant ones being the depth of flow in the pipe and the type of material surrounding the pipe. The third concept was that of the colmation, or clogging, layer. This layer forms naturally around a leakage point in a sewer pipe when suspended solids in the wastewater, along with microbial growth at a later stage, clog the pores in the soil around the leak, temporarily sealing it. The effectiveness of the colmation layer as a sealant is unclear; though the layer can significantly reduce the exfiltration rate, it can be easily destroyed by high-pressure flows. For the purposes of this study, the main insight that emerged from the literature review was that the growth and destruction cycles of colmation layers makes it very hard to predict when exfiltration occurs. The lack of a temporal pattern in the bacterial loadings in drains (Shin 2012) may not then necessarily preclude leaky sewers as a source, since the exfiltration rates need not reflect the daily peaks in sewer flow.

The literature on Singapore's geology and soil revealed a few key findings. The first was that the Jorong and Bukit Timah formations contain fractures in the bedrock. Fractures have the potential to be high-conductivity conduits between sewers and drains; for sewers built on bedrock, this may be a possible (albeit unlikely) pathway for contamination. The other key point from the literature was that the soils in Singapore have low hydraulic conductivity. A MODFLOW model was constructed to simulate the flow of groundwater contaminated by a leaky sewer into a drain using the highest reported value of hydraulic conductivity (0.86 m/day) (Sharma et al, 1999). The model suggested travel times on the order of several weeks for flow through regular soil, but less than a day for flow through a high-flow-rate conduit like a fracture.

Review of Singapore's sewer infrastructure and GIS maps of the sewer network revealed that the buried depth of most of the sewer network is greater than 4 m, which is deeper than the water surface elevation in even the large drains. This suggests that leaks in sewer pipelines that affect the drains are most likely occurring at elevations closer to the ground level, in other words closer to the buildings, rather than from pipes deep within the network. Subsidence is a problem in Singapore, one that often leads to damaged pipes near buildings because of the differential displacement of the pipes relative to the building.

Field observations carried out in January 2012 suggest sewer leaks at building connections may be a significant source of fecal contamination in the drains. Members of the research team found that minor drains around the periphery of an apartment complex in Toa Payoh smelled of sewage. The water in the minor drains flowed into a network of larger drains that would eventually flow into a catchment reservoir.

The findings from literature and field observations together show that pipeline connections between buildings and the sewer network are particularly susceptible to damage, and that high-flow-rate pathways can exist between the leak point and the peripheral drains. Hence, sewer leaks near building connections may be a significant source of fecal contamination in the stormwater system, and are worth investigating further.

Suggestions for future work include conducting a field investigation to collect and analyze water and soil samples from the small drains around one or more buildings in Lorong 8 and the area immediately around them. Researchers could collect soil samples from several locations by digging micro-wells using a hand auger or a PushPoint sampler (such as one from MHE, http://mheproducts.com/downloads.html). If the water table is high enough, groundwater samples collected around drains could reveal more about the potential for contamination entering the drains via groundwater. Another related possibility is to expand on the work done by Dixon et al. (2009) by tracing the contamination up the drainage network up to the small peripheral drains around the buildings.

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