An Investigation of the Potential for Side Sewer Infiltration to Local Freshwater Systems

Thornton Creek, Seattle WA: A Case Study

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A thesis

submitted in partial fulfillment of the

requirements for the degree of

Masters of Urban Planning

University of Washington

2016

Committee:

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Program Authorized to Offer Degree:

Urban Design and Planning

University of Washington

Abstract

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Chair of the Supervisory Committee: Marina Alberti

As the wastewater infrastructure throughout our urbanized land continues to age, pipe failures leading to sanitary backups and contamination of the surrounding areas will become more frequent. Most private side sewers throughout the United States have life expectancies of less than 100 years and are swiftly reaching the end of their design life. It is necessary for municipalities to understand the scope of potential private side sewer failure that may be occurring now or in the near future within their jurisdiction in order to properly plan prevention and mitigation. This research explores Thornton Creek, a stream system located in the northeastern corner of Seattle, Washington that has been impacted by fecal contamination. The City of Seattle has yet to identify the primary source of this pollution, but it is hypothesized that it may be partially caused by failing side sewer systems throughout the watershed. In Seattle side sewers are privately owned, hindering the city's ability to collect adequate information about their conditions.

Because of this lack of direct data on side-sewer condition, I investigated whether other existing data sources could be used to estimate the potential conditions of the side sewers in the City. Using City of Seattle Department of Planning and Development side sewer repair and replacement data, three questions were evaluated: (1) is there evidence of correlation between pipe age and the number of line repair/replacement permit requests? (2) is there evidence of correlation between pipe proximity to a creek and the number of line repair/replacement permit requests? (3) is there evidence of correlation between slope and the number of line repair/replacement permit requests? Results of this study indicate that there may exist a correlation between the pipe age and the number of line repair/replacement permit requests as well as a correlation between distance from steep slopes and the number of line repair/replacement permit requests. Yet, due to the assumptions and a lack of data no definitive conclusions can be made. This study indicates possible ways the City can utilize available data to investigate the hypothesized source of contamination due to side sewer conditions and the additional data on the side sewer system necessary to complete a more rigorous analysis.

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Acknowledgements

I would like to acknowledge the hard work and support shown by my friends and collegues at Seattle Public utilities. I would like to give a special thanks to Jonathan Frodge for motivating and supporting through this process, Holli Brandt for introducing me to the project while I was an intern under her supervision, as well as David Shin and Gary Christiansen for their late night editing sessions.

Dedication

I dedicate this paper to my mom and dad.

List of Terms

CCTV Closed Circuit Television is a TV system that broadcasts private signals from a camera to a monitor. Access to transmissions is limited by design, allowing the information to remain private. The cameras allow for visual imagery in sewer pipes to be analyzed to detect pipe failure (Seattle Public Utilities, 2015).

Combined sewer system A system of conveyance mainlines in which drainage and sanitary sources both lead to treatment prior to discharge.

Culvert A pipe used to enclose a flowing body of water. Within Seattle, culverts are typically used to direct surface water flows under driveways and roads to a mainline or receiving body of water. It is important for the City to not only keep track of where these culverts are located, but also to note the points for “culvert ins,” or where water begins to flow into a culvert, and “culvert outs,” or where water exits the culvert. These structures come in a wide variety of materials, but steel, polyvinyl chloride, and steel are the most common (Reese, 2012).

Detention Ponds Constructed ponds that allow water to sit and be released at a controlled rate. Detention ponds allow water to collect to prevent downstream flooding. While the water sits, pollutants may settle so that cleaner water may be released downstream (Thornton Creek Watershed Characterization Report, 2000).

Ditch A U-shaped channel typically between 30”-70” in width dug in the ground to be used for drainage along a road or piece of land. Ditches are generally grass, but are also seen filled with a variety of vegetation, concrete, and asphalt (Reese, 2012).

Mainline A tunnel used to divert drainage and wastewater to an outfall or treatment location (Reese, 2012).

Outfall The point where a pipe within the drainage system empties into a body of water (Reese, 2012).

Pond Any area where surface water pools. This maybe an area of standing water or a location along a stream where flowing water slows and pools due to a bend, woody debris, a weir, or other change in structure.

Seep A water flow or leak from a pore in the ground surface. While a seep is a natural occurrence and not infrastructure, they are still important features for the city to be aware of and have mapped because, depending on their location, infrastructure may be needed to divert the upwelling of water to a location that will not cause a danger to people or their property (USGS, 2013).

Separated sewer system A system of conveyance mainlines in which drainage leads to the nearest water body and sanitary sources lead to treatment prior to discharge.

Side sewer The portion of sewer line that connects wastewater from a building within a parcel to the mainline (City of Tacoma, 2010).

Sanitary Sewer Overflow any overflow, spill, diversion, or release of wastewater from or caused by the sanitary sewer system or the combined sewer system upstream of a City CSO outfall. This includes discharges to surface waters of the State or United States from the sanitary sewer system, and any release of wastewater from the sanitary sewer system to public or private property that does not reach waters of the United States or the State (U.S. EPA, 1996).

Swale Similar to a ditch, swales are generally sloped channels with flat bottoms. Unlike ditches, swales are always lines with grass of vegetation promoting water infiltration into the top layer of soil rather than just direct the water to the nearest culvert. Additionally, the grass and vegetation increase the removal of many pollutants including fine sediments, oils, and metals (Thornton Creek Watershed Characterization Report, 2000).

I: Introduction

Background

Water is a necessary component to sustained life. It provides habitat, it is at the core of many biological and ecological cycles, is the basis of the hydrologic cycle, and is fundamental to a myriad of vital chemical reactions. Additionally, humans have used Earth's water bodies throughout history for transportation, agriculture, and recreation. It is critical to protect our freshwater systems in order to provide clean water to our future generations, ourselves, and the countless species that share our planet while preserving the ecological functions that allow us to survive and flourish.

The 1977 Clean Water Act set a national goal of keeping our nation's waterways clean by eliminating the discharge of pollutants into our water bodies. We greatly focus our attention on large spills and major point source contributors, but many minor contributors can cause a lot of harm as well. Non-point source pollution contaminates fresh water systems in a variety of forms including microorganisms, temperature, turbidity, heavy metals, and nutrients. It is highly backed by human activities, especially in urbanized environments, stemming from runoff from lawns and impervious surfaces.

Side sewers are a potential contributor to pollution in urban areas. The concrete pipes that compose much of private sanitary systems have a life span of approximately 80 years on the high end (Bhatt, 2016), so many of the World War II era buildings are reaching an age where their original pipes are due or overdue for replacement. Side sewers are the pipes that connect a building's plumbing to the City-maintained sanitary conveyance system. Many property owners do not know if their side sewers are failing unless it is causing a backup into their home or office. The pipes are located under the ground contributing to an "out of sight – out of mind" mentality. If there is no sign of a problem, then why hire a CCTV crew to look for a problem?

This neglect can exacerbate pipe failure, creating a much larger problem than needed to exist. In 2015, a side sewer in a Seattle, seven-unit apartment building failed at the joint (Bhatt, 2016). This failure led to a stream of sanitary waste to run down a public stairway with every toilet flush. Because the break led to pollution that was easily noticed by the neighborhood, the problem was detected and repaired in a timely manner, but we cannot assume this to be the typical scenario. Many pipe failures have the potential to saturate soils and contaminate fresh water resources with raw sewage. Preventative measures should be taken to better plan for these failures in order to protect human health as well as our natural systems.

It is common for side sewers to be privately owned. This means that the infrastructure is out of reach for public municipalities to inspect these pipes, while the failure of this infrastructure can pose a public health risk. With little data available to municipalities about the private sewer system, what steps can be taken to analyze the health risk to the side sewer portion of the sanitary system?

Case Study: Thornton Creek, Seattle WA

Seattle, Washington is located in the northwest corner of the continental United States. The western edge of the city is bordered by the Puget Sound and the eastern border is composed of the shore of Lake Washington which is fed by the Cedar River watershed. The estimated 2015 population was 662,400 (Department of Planning and Development, 2016) and the city has been steadily increasing in population with a 9% increase between 1990 and 2000 and a 8% increase between 2000 and 2010 (U.S. Census Bureau, 1990, 2000, 2010). As of 2014, Seattle took the place of the tenth most populous city in the country with 7,962 people per square mile (Balk, 2016).

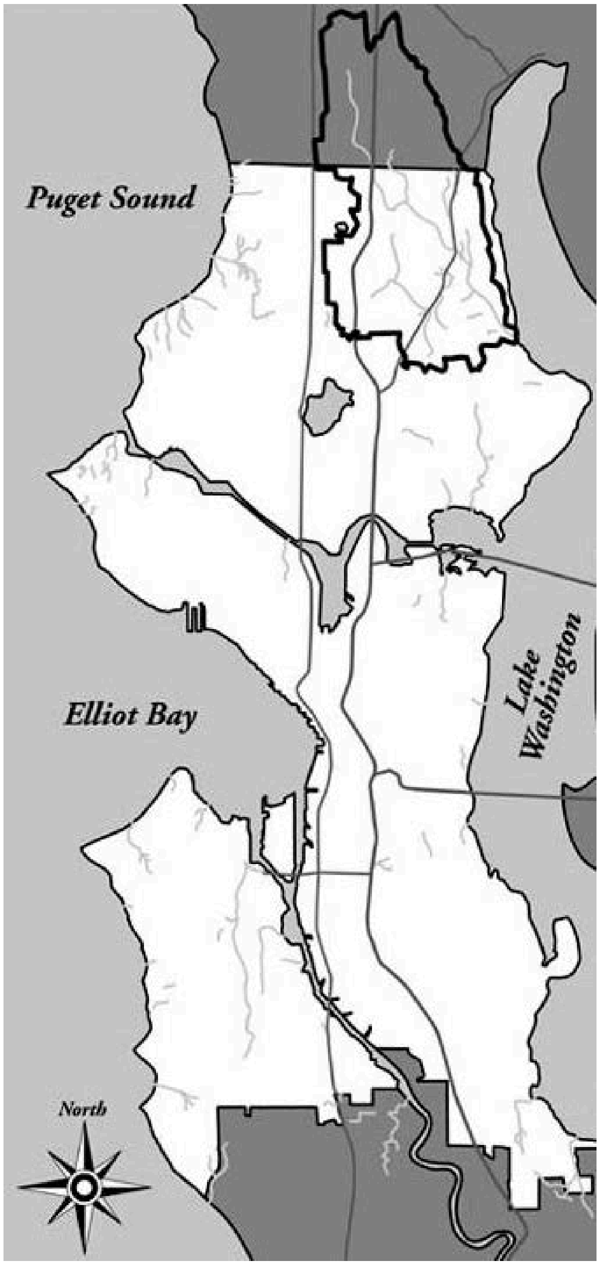

Figure 1: Map of Seattle with outline around Thornton Creek Watershed. Source: http://www.seattle.gov/util/groups/public/@spu/@DrainSew/documents/webcontent/COS_002621.pdf)

Seattle's climate is temperate with mild temperatures and fairly distinct wet and dry seasons running yearly from roughly October through March and April through September, respectively (U.S. Climate Data, 2016). Seattle, like many other cities, is faced with the challenge of controlling/minimizing many cases of heavy contamination of surface water within the urbanized region. Thornton Creek, located in the northeast corner of the city, is the largest watershed in Seattle (Figure 1).

Thornton Creek Watershed takes up approximately 7,263 acres and houses more than 75,400 residents (Thornton Creek Watershed Management Committee, 2001). The creek and its adjacent riparian areas serve as habitat for dozen of species of birds (blue herons, bald eagles), amphibians, mammals (raccoons, river otters, possums, coyotes), insects, and fish (salmonids) as it traverses through a variety of urban settings, including Northgate Mall, Jackson Park Golf Course (Thornton Creek Watershed Characterization Report, 2000).

Thornton Creek experienced land use change where forest cover was converted to primarily single family residences and commercial development starting in the late 1800's (Figure 2). By 1894, most of the area had been logged, but the population was in the hundreds rather than the tens of thousands that it is today. Today, approximately half of the watershed is covered by impervious surface that results in heavy amounts of stormwater runoff that affects public and privately owned property as well as degrades natural habitat. Stormwater runoff has the potential to increase sediment loads through the erosion of stream banks and scouring of streambeds, flush salmon eggs and juveniles out of the stream, and increase the risk of flooding. The City of Seattle has been working to reduce the negative impacts of urbanization (Thornton Creek Watershed Characterization Report, 2000).

Today, more than 90% of the main channel of the creek is open and flowing above ground. Thornton Creek's main channel flows through more than 700 backyards and through 15 parks before discharging into Lake Washington. Unfortunately, fecal bacteria pollution levels are high enough within the creek to pose a potential public health risk along the channel and at Matthews Beach, a popular public swimming beach and the discharge location at the lake (Frodge, 2013). Over 98% of water samples collected exceed State criteria for fecal coliform levels (Thornton Creek Watershed Characterization Report, 2000). The likely sources are non-point pollution, sanitary sewers, the stormwater drainage conveyance system, and perhaps even homeless encampments along the adjacent greenbelt (Frodge. 2013). No obvious point sources have been identified to explain the system-wide high contamination levels.

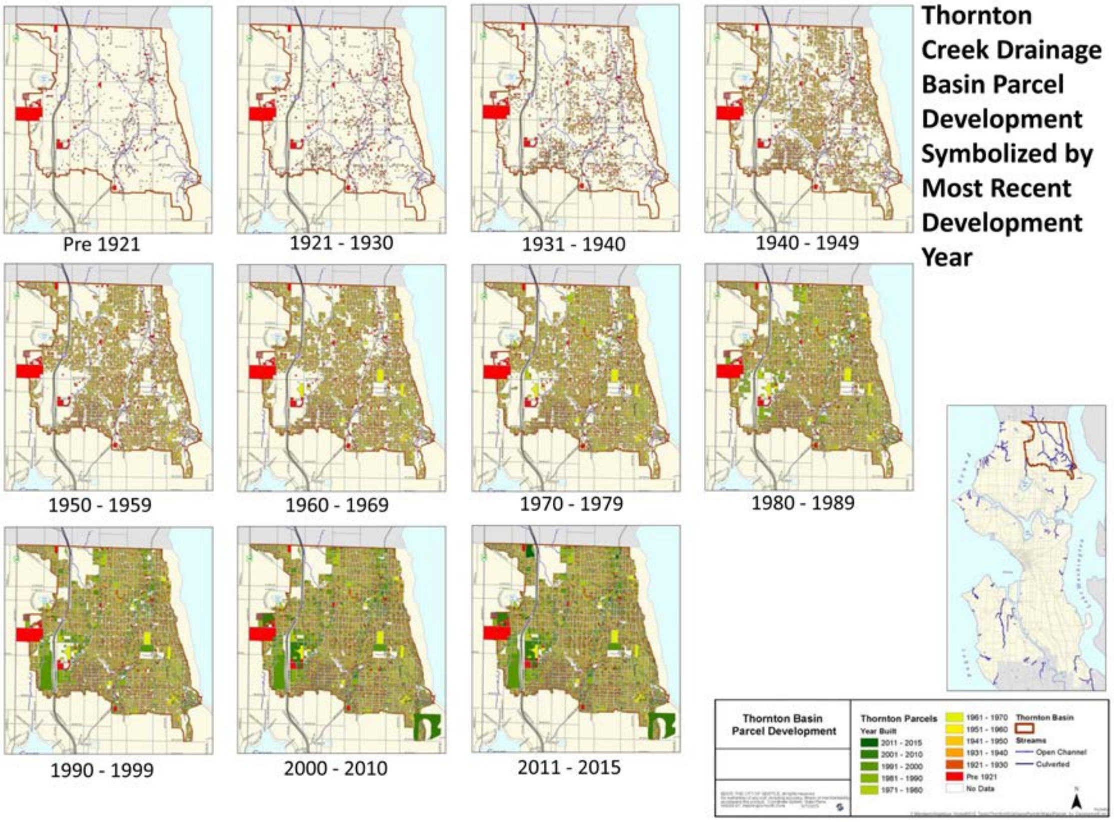

Figure 2: Series of maps of Thornton Creek Watershed depicting development by parcel. Source: DPD Assessor's parcel data.

The Problem: Fecal Coliform Bacteria Contamination

Since the beginning of the Thornton Creek Bacteria Investigation in 2013, the contamination of fecal coliform bacteria within the Thornton Creek system has been a focus for the City of Seattle. During the summer of 2012, a screening was conducted at many of the discharge locations of Seattle's Municipal Separated Storm Sewer System into Thornton Creek. As a result of the study, two illegal residential connections were detected and terminated, however, contamination remains high (Frodge, pers comm, 2015). Water samples continue to be collected by Seattle Public Utilities in an attempt to locate the source of bacteria pollution. A City team is carefully walking the stream mapping all drainage and wastewater infrastructure in and adjacent to the creek while collecting bacteria samples immediately downstream of major outfalls and sewer crossings.

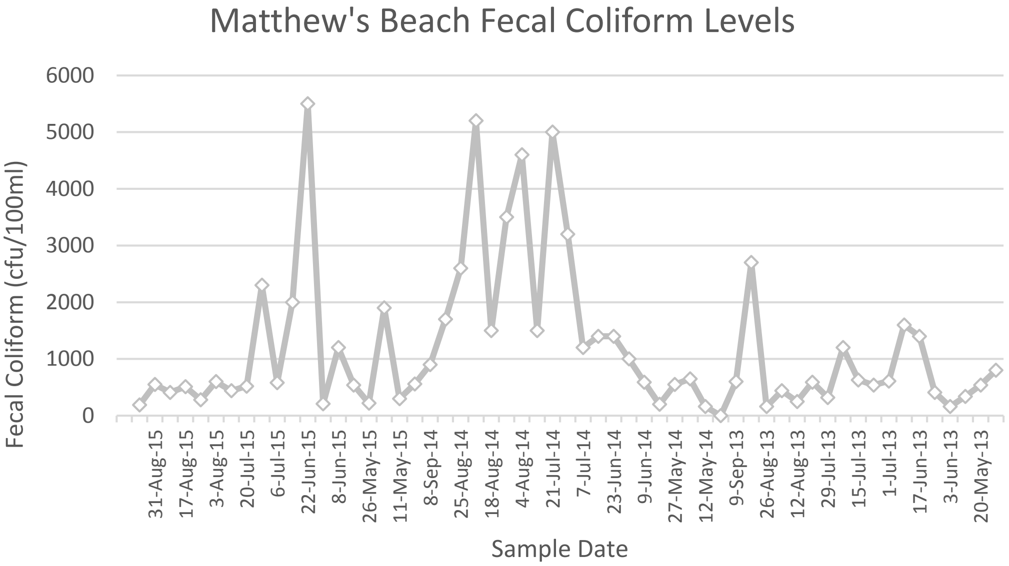

Figure 3: Fecal coliform data collected by King County 2013-2015. Numbers frequently exceeded fecal coliform secondary contact criteria pf >200 cfu/100 ml. Source: King County Water Quality Data

Due to the lack of obvious point sources, Seattle Public Utilities staff hypothesize that one source of the fecal coliform contamination (See Figure 3 for coliform levels) may be due to side sewer failure on private land. Exfiltration from side sewers is point source contamination, but is difficult to identify since breaks and failure is hidden and often unknown. Side sewers are not owned or maintained by the city, rather, ownership and maintenance of these pipes is the responsibility of individual property owners. Side sewer failure can result in a groundwater leak into a side sewer or a sewage leak out of a side sewer, creating a potential public health hazard. In many cases, homeowners are unaware of their responsibility to know the condition of their property's side sewer and maintain/replace their failed side sewers. This lack of accountability, whether intentional or unintentional, could mean that there are known and unknown failing side sewers throughout the sanitary sewer system.

Bacteria samples continue to be taken by Seattle Public Utilities in an attempt to locate the source of pollution. All drainage and wastewater infrastructure in and nearby the creek are being mapped with GPS, and bacteria and water quality samples are periodically collected just downstream of major outfalls and sewer crossings.

Research Question

To test the hypothesis that sewage is leaking from private side sewers through exfiltration and contaminating the stream when direct data on the condition of the pipes is not available, I used existing secondary data collected and maintained by the City of Seattle. This paper explores the potential for patterns in failure rates estimated by construction permits requested for side sewer repair and replacement from the Seattle Department of Planning and Development. I hypothesize that exfiltration is occurring within Thornton Creek basin.

This thesis reviews current literature that explains the issues with surface water contamination and the implications of aging sanitary infrastructure. In addition, three questions are addressed: (1) is there evidence of correlation between pipe age and the number of line repair/replacement permit requests, (2) is there evidence of correlation between proximity of creek and the number of line repair/replacement permit requests, and (3) is there evidence of correlation between bed material slope and the number of line repair/replacement permit requests. This thesis also argues that answers to these questions will help with identifying data gaps and informing the formation of future sampling plans. This information could support the development of a pilot project that may be used to more efficiently test the theory and estimate the extent that side sewer failure contribute to fecal coliform contamination within the Thornton Creek watershed.

This thesis examines side sewer repair and replacement permit data within the Thornton Creek Watershed as well as throughout the entire city of Seattle. This analysis is beneficial for two reasons. First, Thornton Creek is the most contaminated creek within the city (Frodge, 2013). If there are trends detected within the watershed, are the trends similar in the rest of the city? Second, there is limited amount of data available for this study if only data within the watershed is used. Using citywide data also allows for more data points to be analyzed across a study area with similar characteristics.

By answering the questions posed in this thesis, suggestions are made on long term monitoring strategies using CCTV, dye testing, and water quality sampling in order to better obtain information to allow municipalities to address the issue of aging private infrastructure and better prioritize needed interventions.

II: Review of Relevant Literature

Fecal bacteria contamination represents major exfiltration related health risks to the human population (EPA, 2012). The following section will use relevant literature to describe private side sewers, the current threat of failure within the conveyance system, the responsibility and role of planners in maintaining the infrastructure, similar occurrences in other locations, and current practices within the City of Seattle to address this and related problems.

Public Health

Fecal sources pose risks to human health. Many pathogens that threaten human residents are also found in animal fecal matter. These health risks, environmental degradation, as well as general aesthetics are all factors in the laws enforced in many cities across the country requiring pet owners to bag their animal's waste. However, increasing evidence suggests that the growth of fecal indicator bacteria occurs naturally in both aquatic environments, freshwater and estuary sediments, and marine beaches creating doubt that these indicators may actually suggest contamination from sewage or runoff (Litton et al, 2010). Quantifying the risks associated with different sources of these bacteria continues to be a challenge (EPA, 2012). Because of this, as of 2012 the EPA does not take contamination source into consideration when developing recommendations regarding fecal contamination.

Human and animal derived fecal bacteria have a number of adverse health impacts. The National Epidemiological and Environmental Assessment of Recreational Water Study found that fecal contamination is most closely associated with gastrointestinal illnesses, but there are also a number of other afflictions that could be caused by the pathogens within feces. The five listed within the 2012 Recreational Water Quality Criteria produced by the EPA are upper respiratory illness, rash, eye infection or watery eye, earache, and infection around preexisting lesion (EPA, 2012).

Existing Research: Contributing Factors

Non-point source indicates pollution where there is no discrete or discernable conveyance system or source from which pollutants are being introduced into the water (What is Nonpoint Source Pollution 2013). In many urban systems including Thornton Creek, non-point source pollution comes from vehicles, runoff from lawns and gardens, pets, and construction. Pollution is, and has historically been, in the form of fecal coliform bacteria, temperature and dissolved oxygen, pesticides, fertilizers, and sediments that have been found to contain heavy metals, pesticides, PCBs, and hydrocarbons harmful to aquatic life (Thornton Creek Watershed Characterization Report, 2000). There is a tendency to define unidentified point sources, such as leaking side-sewers as non-point source pollution, which decreases the effort to locate and correct these sources of bacteria pollution and this public health risk.

In Seattle and many other municipalities the side sewer system is largely privately owned and maintenance or replacement is the responsibility of the property owner. These pipes are also known as laterals or private sewers. Side sewer failure can result in a groundwater leak into a side sewer or a sewage leak out of a side sewer depending on the level of the water table, and may pose a public health risk. In many cases, homeowners are unaware of their responsibility to know the condition of their property's side sewer and maintain/replace them. This lack of accountability could mean that there are more failing side sewers throughout the system than current estimates.

Construction Feature Contribution

Often, poor workmanship such as not properly removing organic litter and rocks from trenches, supporting pipe sockets on bricks and blocks, and damaging pipes with excavator buckets leads to pipe failure (Davies et al, 2001).

The impact of sewer depth and size on pipe failure rates are subject to disagreement among literature sources. A study completed in 1979 by Lester and Farrar found little association between pipe size and failure, however a study done in 1989 by O'Reiley, Rosbrook, Cox, and McCloskey found that cracks and fractures increased with diameter. Contradictory still, a study done by Balmer and Meers in 1982 found that larger diameter sewers are typically more structurally sound. The 1989 study by O'Reiley et al. also found that pipes buried beneath 5.5 meters had more instances of failure than those buried at more shallow depths, while a 1999 study conducted by Fenner and Sweeting and a 2000 study conducted by Fenner, Sweeting, and Marriott found that pipes within 2 meters of the surface have a greater failure rate.

Factors influencing the structural stability of rigid sewer lines include a variety of variables including load transfer, standard of workmanship, sewer size, sewer depth, sewer bedding, sewer material, sewer joint type and material, sewer pipe section length, sewer connections, surface use, surface loading, surface type, water main bursts and leakage, ground disturbance, groundwater level, ground conditions, soil backfill type, root interference, sewage characteristics, maintenance methods, slope, and age of sewer (Davies et al, 2001). Interactions between these variables occur shaping the rate of deterioration and/or rapid failure. Due to the long service life and the cost of repair and replacement, design assumptions should be made carefully considering all variables.

These side sewer failures and sewage leaks pose environmental and economic costs to the government and also social costs to the community. These social costs include flooding hazards, threats of road collapse, delays in traffic, harm to local aesthetics due to smell and noise, public health risks, and environmental degradation. The Construction Industry Research and Information Association has reported that sewage related pollutants include bacteria (including fecal coliform), inorganic nitrogen species, inorganic ions, phosphate, and boron (Davies et al, 2001).

Side Sewer Failure

Three stages have been documented in the process of sewer failure (Davies et al. 2001). Stage one represents the appearance of the initial defect in the sewer line. At this point the structural stability of the pipe has been compromised, but the pipe may remain intact as long as there is proper stability in the surrounding soil, although further deterioration will likely occur. Stage two is the continued deterioration, often including the loss of surrounding, supporting soil. Stage three is the collapse of the pipe. Collapse is often a random occurrence triggered by an external event rather than simply the result of stages one and two.

While construction error can be a major cause of pipe failure, the likelihood of failure increases with the age of the structure. The City of Seattle experienced dramatic growth between the 1940s and 1960s resulting in an average current pipe age of around 80 years (Martin, 2007). Contradicting the assumption that these systems will continue to serve the purpose for which they were installed, many pipes may have reached the end of their useful lives by 50 years of age (Martin, 2008).

Infiltration and Inflow

Water that flows into sewer pipe mainlines and laterals from stormwater and groundwater is called infiltration and inflow (I&I). Infiltration occurs when groundwater seeps into sewer pipes through holes, cracks, joint failures, and faulty connections. Inflow refers to stormwater that rapidly flows into sewer pipes through holes in maintenance hole covers, roof drain downspouts, foundation drains, and storm drain cross-connections. Most infiltration and inflow is caused by aging, defective infrastructure that needs maintenance or replacement.

Inflow and Infiltration into sewer systems decreases the performance of drainage and wastewater infrastructure because it can overwhelm downstream pipes and treatment plants as well as increase combined sewer overflows.

Exfiltration

Exfiltration is the passage of stormwater or wastewater from the interior of a conveyance system to the environment outside through cracks, holes, and breaks within the pipe material. Exfiltration of sewage is suspected of acting as a source of the high bacteria counts regularly occurring in the City of Seattle. The EPA recognizes the potential for exfiltration from combined and sanitary lines to be occurring in many municipalities across the United States (Amick and Burgess, 2003). A combination of shallow pipe networks and low water tables has led to widespread exfiltration across the country. For this reason, this form of pollution is viewed as a threat particularly during dry weather low flow conditions.

In many areas throughout the country, including much of the northeastern, southeastern, and Midwest states, pipe systems are generally at a greater depth than the shallow groundwater, leaving these areas at a greater risk for infiltration and inflow (Amick and Burgess, 2003). In these areas side sewers located at higher elevations may contribute to pollution. However, these pipes are characterized by low volume and intermittent flows. The same risk occurs with pipe systems at elevations above the water table such as steep slopes and ravines. In these areas, the water table is flowing toward a valley, moving water away from the pipe depth, allowing for a greater risk for exfiltration.

It is important to understand that exfiltration is not the same as sanitary sewer overflows which is also a problem in many municipalities. Sanitary sewer overflows typically occur when excess infiltration and inflow leads to surcharged mainlines, causing sanitary waste to surface. These events generally occur during wet weather conditions when the flow is forced to a maximum capacity. Exfiltration, rather, occurs where sewers systems allow water to leak from pipes to the surrounding soil. Deteriorating systems of pipes, maintenance holes, joints, and pump stations, due to age and construction practices contribute to unintentional wastewater exfiltration into groundwater and surface water systems, as well as contribute to infiltration and inflow. Exfiltration may cause pollution with oil, grease, suspended solids, pathogenic microorganisms, and nutrients. These pollutants may risk the health of the surrounding residents, wildlife and habitat, and threaten the enjoyment of our local waterways. However, studies suggest that the effluent that leaks from the joints and fractures in pipe systems may rapidly plug the exfiltration site, quickly and effectively reducing the pollution into the system until the next pipe cleaning (Amick and Burgess, 2003).

Sewer maintenance and repair oftentimes can be disregarded or forgotten about due to the fact that it can be very expensive and the failure of side sewers are out of view. Construction factors including materials used, type and quality of installation methods, depth of flow, size of lines, and pipe age contribute to exfiltration. Natural factors are also known to contribute to this problem including geologic influences such as soil type, groundwater depth, and fault lines as well as climatic influences including seasonal frost line and average rainfall, both of which influence soil saturation and groundwater depth.

Sewer exfiltration is a well-documented and expected phenomenon that is frequently observed in both field studies throughout the world as well as in experimental lab environments. Leakage rate estimates vary greatly with some of the highest losses coming from lab environments, but it is argued that the average exfiltration rates lie within the region of 0.01-0.2 l/s/km (Ellis, Revitt, Karpf, and Krebs). However, some state that any sealing that occurs at these cracks and holes is likely impermanent and that the onset of elevated hydraulic pressure could result in a rupture (Ellis, Revitt, Karpf, and Krebs). This would again allow exfiltration to begin, leading to contamination of groundwater.

As of 2003, there were no documented cases to demonstrate sewer exfiltration leading to surface water contamination. This is likely because areas adjacent to surface waters generally have high groundwater table levels that remain above pipe elevation leading to water infiltration rather than exfiltration. However, with the quantified rates of infiltration that are available for the conveyance systems across the urban world, it is easy to imagine that in areas with low groundwater levels substantial leakage from combined and sanitary lines occurs polluting our groundwater and surface waters (Ellis et al, 2004). In areas with steep topography where buildings and their associated sewer systems are above the adjacent surface water, exfiltration is possible. These situations are likely rare, but may be more typical in heavily ravined areas such as Seattle.

Other Potential Sources of Contamination

Contamination via cross connections from businesses and residences do occur throughout stream systems. Fecal contamination of the stream system could also be occurring due to the direct discharge of raw sewage from homeless encampments and RV dumping into water bodies and storm drains, wild and domestic animals, and natural growth.

Existing Research: Case Studies

Previous studies examining fecal coliform contamination in urban watersheds suggest that there is not only a link between bacteria contamination and urbanization along the stream channel, but also a link between bacteria prevalence and in stream conditions including morphology, seasonality, and flow conditions. A study conducted by Schnabel et al in 2010 near Anchorage, Alaska compared water quality at 5 sample locations along Chester Creek: one in a densely forested area, one at the mouth of a lake 3 miles within the municipal boundary, one at the lake outlet, one at the University of Anchorage campus (0.8 miles downstream from the lake outlet), and one just upstream from the discharge point (Schnabel et al, 2010).

When comparing the Chester Creek site water quality samples, evidence was found supporting a statistical difference between the fecal coliform concentrations in the forested stream site and the University of Anchorage site as well as the forested site and the discharge site (Schnabel et al, 2010). In both cases it was determined that the fecal coliform levels were greater within the urban region. However, Schnabel found that no statistical difference was indicated between the two urban sites. No seasonal difference was found in the forested site or the discharge site, while there was evidence showing a statistical difference at the University of Anchorage site between the warm and cold seasons with levels higher in the warm season. Between the two lake sites, there was also evidence found supporting a statistical difference between the lake inlet and outlet samples with concentrations higher at the lake inlet. Median fecal coliform concentrations were not strongly linked to seasonal changes, except in the lake region, in which University Lake acts as a settling basin for the fecal coliform.

In a 2006 paper from the Journal of Hydrology, Jon Schoonover and Graeme Lockaby report that stream quality investigations in the southeastern region of the United States support the claim that urbanization poses a threat to water quality (Schoonover and Lockaby, 2006). However, studies near Atlanta, Georgia monitoring for sediment, nutrients, and fecal coliform have shown significant increase in each category linked to land use change from urbanization.

In streams throughout West Georgia, the concentration of fecal coliform was highest during storm events and dry weather conditions within the urbanized region with levels exceeding US EPA review criterion (Schoonover and Lockaby, 2006). Fecal coliform concentrations increased proportionately to increases in impervious surface. In urbanized streams throughout West Georgia, fecal coliform concentrations increased during storm events. The authors hypothesized that these increases may be attributed to faulty sewer lines, but also pointed out that combined sewer overflows, septic drains, and pet waste may also be contributing factors.

Schoonover and Lockaby (2006) state that Columbus, Georgia has aging infrastructure in questionable condition. Limited carrying capacity in drainage and combined mainlines may impact stream water quality. They also found that fecal coliform concentrations varied with seasonal ambient air temperature. During the cooler months from October – March counts were low while during the summer months levels were elevated.

Literatures of Practice

Other municipalities are struggling with leaky conveyance systems and water pollution across the United States. Through a literature review, it was gleaned that side sewer exfiltration is not the only explanation or focus. Seattle's neighbor to the north, Shoreline, WA, is currently exploring options to control their side sewer system due to increased costs associated with treating infiltrating flows. Dyes Inlet, also in the Puget Sound region, has identified commercial sources of fecal coliform that is washing into their urban surface water and a study in Indiana explored reproduction of *E. coli* within soil sediment.

Shoreline, WA

The City of Shoreline has a collection system that was largely installed in the 1950s and 1960s (Pottinger et al. 2009). This system is serviced by the Ronald Wastewater District. Much like Seattle, Shoreline's conveyance system transfers water from the city to the King County Wastewater Treatment Division and the City of Edmonds Treatment Plant. Ronald Wastewater has historically acknowledged side sewers as being overlooked or considered too difficult to address. As of recent years, however, Ronald Wastewater District has begun to explore the benefits of replacing and repairing side sewers as a method of reducing infiltration and inflow. Two options were explored. The first was to require all property owners to replace their side sewers as their property was sold. This option was not deemed favorable because it would require a transfer in ownership before the issue of faulty private side sewers was addressed. Additionally, this method would involve the real estate industry as a stakeholder that may not agree with the idea. The second option was to collaborate with the Washington Association of Sewer and Water Districts to explore legislative options, but members were not able to reach an agreement on timing or approach.

Ronald Wastewater District next sought the opinion of State Attorney General Rob McKenna about taking on the cost with City funding. Ronald Wastewater District asked the question, "May a municipal sewer district repair or replace a private side sewers as part of a district-wide infiltration and inflow reduction program where (1) aging and inadequate side sewers are the most significant contributor to the [infiltration and inflow] in the district's entire system; (2) the purpose of the program is to benefit the district and public through lower long-term capital and maintenance costs, not private property owners; (3) repair and replacement would be subject to a right of entry from the private property owners; and (4) the program costs will be paid back through the district's bi-monthly sewer rates?" (Pottinger et al. 2009). The attorney general responded with AGO 2009 No. 5, which states that municipal sewer districts in Washington do have the authority to use public funds in order to repair or replace private side sewers if that repair or replacement will lead to an increase in capacity by reducing infiltration and inflow. The act of using public funds for a cause that would directly provide a benefit to private property does not pose as an unconstitutional gift if the result poses a significant benefit in the public interest.

Dyes Inlet, Puget Sound

Dyes Inlet in west Puget Sound also has a history of bacterial pollution (Fohn, 2009). The marine embayment has a mixed land use surrounding it with upland areas that are semi-rural and forested, and lower areas consisting of urban residential and commercial land.

Clear Creek serves as the major contributor of fresh water into the northern portion of Dyes Inlet. The sampling station at the mouth of the stream channel from October 2004 until September 2005 had a fecal coliform geometric mean of 143 MPN/100ml. In the dry season of 2005, a public health hazard warning was posted at the creek as the fecal coliform geometric mean rose to 896 MPN/100ml. Routine monitoring found no evidence of cross connections. Fohn states that poor water quality begins at the major commercial corridor with adequate water quality upstream from the commercial area. There was no agriculture within the study area and the majority of sanitary and drainage infrastructure was installed since the 1970s. Water quality may have been compromised by upstream commercial drainage.

Studies tested two hypotheses: (1) fecal bacteria binds to fine particulates within the stormwater system and these are then transported to the receiving waterbodies and/or (2) moist fine materials within the stormwater system and slow moving streams provides good conditions for fecal coliform bacteria regrowth with perpetual fecal coliform sources from rodents and other animals attracted to the commercial zone (Fohn, 2009). To test these theories, commercial businesses were inspected for a variety of issues including proper food waste disposal discrepancies, rodent problems, and stormwater conveyance. Inspections took place between February 2006 and March 2007. Inconsistencies with local codes were noted and enforcement was conducted. Fohn reported that 21% of facilities had the potential to provide food for urban wildlife or discharge food waste into the stormwater conveyance system (Fohn, 2009).

Fohn provided results that claim fecal coliform concentrations were statistically reduced at three of the stream sampling stations during the dry season.

Dunes Creek, Indiana

Richard Whitman et al. described a study that included water quality within Dunes Creek, which feeds the southern shore of Lake Michigan from the state of Indiana (Whitman et al, 2006). Sampling within the Dunes Creek watershed showed that established sources of *E. coli* in soil may provide a continuous source of non-point contamination for many months to nearby surface water features. *E. coli* may be stored and breed within sediments, soils, seeps, and stream pools, influencing nearby streams during high winds or precipitation events. Whitman et al pointed out that *E. coli* counts can change within moments of water sample collection due to the internal processes of inactivation, exportation, and deposition of both point and non-point sources.

III: Case Study: Thornton Creek, Seattle WA

Seattle's Drainage and Wastewater Infrastructure History

Seattle's current drainage and wastewater infrastructure has been developed to convey stormwater runoff and sewage with the intent of protecting residents and their property. The city's first centralized combined sewage system was introduced in 1891 (2013 NPDES Phase 1 Municipal Stormwater Permit Stormwater Management Program: Attachment A, 2013). Prior to that time the conveyance system was composed of an assortment of subpar sewer lines and cesspools draining to nearby water bodies that left neighboring citizens susceptible to recurring threats of waterborne illnesses such as typhoid and cholera. The new system diverted much of the city's wastewater to Elliot Bay and Puget Sound while diverting drainage to Lake Washington. By 1910 the city began removing solids from the wastewater and eventually began separating stormwater from sewage by using separated systems rather than combined. Today, Seattle continues to manage the network of combined and separated sewers systems within the city limits although Metropolitan King County took over the City's wastewater treatment responsibilities in the 1960s.

While the infrastructure was around long before, Seattle's Drainage and Wastewater Utility (DWW) was organized in 1987 (Thornton Creek Characterization Report, 2000). DWW is currently responsible for the management of the existing conveyance system, the mitigation of water pollution, mitigation of flooding, and the regulation of stormwater. By 1997, the City's Engineering Department, the Solid Waste and Drainage and Wastewater Utilities, and parts of City Light combined to become Seattle Public Utilities (Thornton

Creek Characterization Report, 2000). That same year the City developed a comprehensive Stormwater Management Program that outlined Seattle's water needs, programs, and quality and quantity problems. Within two years the Seattle City Council enacted a new drainage policy focused on the improvement of basic services, public and private responsibilities, and environmental protection.

Seattle today has a combination of drainage, sewage, and combined drainage and sewage mainlines (Figure 4). These sewer lines typically run under the street being fed drainage and wastewater through a system of side sewers from residential, commercial, and other inhabited buildings as well as from the formal drainage system. Side sewers are usually buried beneath several feet of soil, though at shallower depths than the sanitary and combined mainlines that they feed. In Seattle, the side sewer is privately owned and therefore maintenance and replacement is the responsibility of the property owner (see Figure 5). It is also known as a lateral or private sewer. The EPA has recommended service laterals to be considered with public sewers when identifying and evaluating exfiltration susceptible lines because they are generally the shallowest and the lines with the poorest construction in the sewer system (Amick and Burgess, 2013).

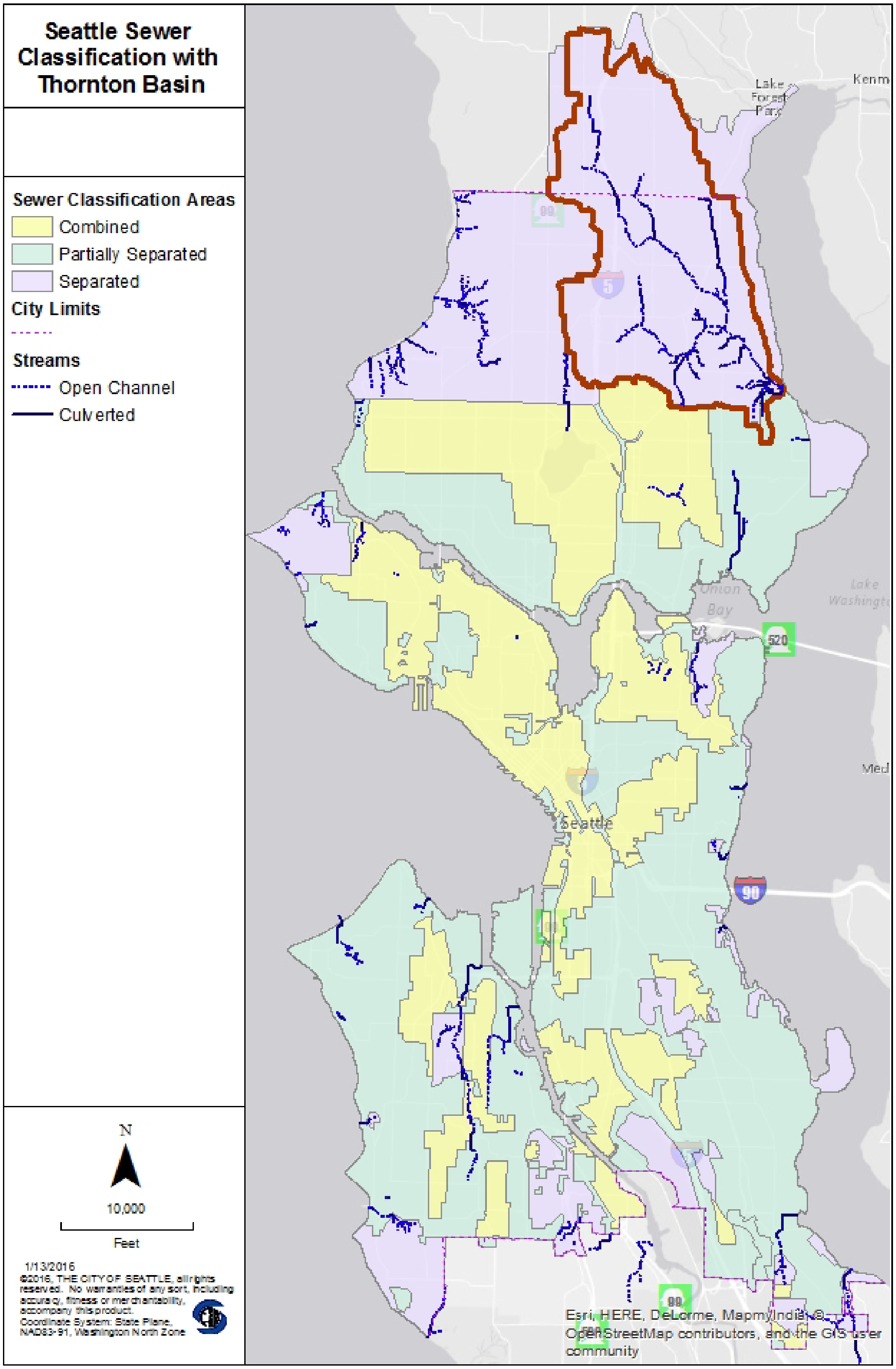

Figure 4: Seattle Sewer Classification map depicting areas of separated, combined, and partially separated conveyance systems with Thornton Creek watershed outlines in the northeast quadrant of the city.

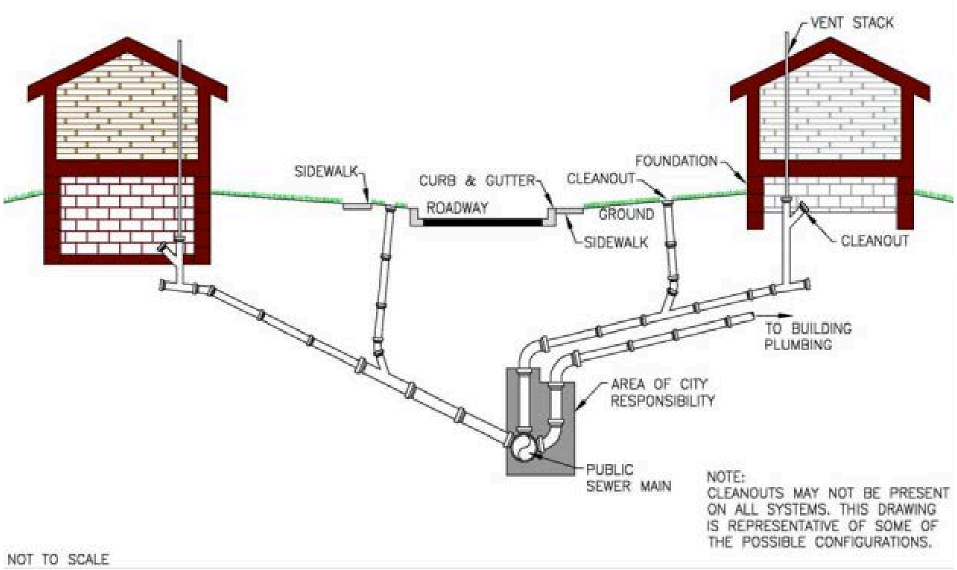

Figure 5: Diagram depicting side sewer and private ownership provided by the City of Tacoma. Source: http://www.govme.com/Common/Doc/DisplayDoc.aspx?category=TipSheet&id=E-201

The Thornton Creek Watershed holds nearly 32% of all of Seattle's length of sanitary mainlines, 1.2% of the city's combined mainline length, 9.7% of the sanitary side sewers, and 4% of the combined side sewers (Table 1). It can be seen in Figure 4 that the majority of the Thornton Creek basin is located in a separated system, explaining why there is a high percentage of the city's sanitary mainlines and a low percentage of combined side sewers. According to city side sewer cards and City of Seattle GIS data, side sewers are generally either drainage or sanitary leading to their associated mainline. Combined side sewers are incredibly rare. All components of the system require inspection and maintenance from time to time by property owners, contractors, or the Public Health Seattle & King County (Thornton Creek Characterization Report, 2000).

Table 1: Seattle wastewater infrastructure data including mainlines and side sewers. Source: Seattle Public Utilities Corporate GIS data.

Probable Flow	**City of Seattle**		**Thornton Creek**	
	Segment Count	**Length (feet)**	**Segment Count**	**Length (feet)**
Sanitary Mainlines	16421	3020175	4582	965920
Combined Mainlines	29002	5865438	336	72987
Sanitary Side Sewers	1382832	22551105	108147	2178927
Combined Side Sewers	134	2703	6	106

Seattle Public Utilities Investigations

Seattle Public Utility works to prioritize sub-basins within the watershed based on water quality sampling and determines stream segments with the largest difference between upstream and downstream bacteria counts (Frodge, 2013). Sanitary mainlines within the priority sub-basins have been inspected by SPU using CCTV. In addition, the SPU stormwater conveyance system has been inspected. Using these inspection processes, a number of cross connections have been identified and corrected, which was credited with localized reductions in in-stream bacteria counts. However, the separated drainage system is not being considered a significant contributor to the bacteria counts within Thornton Creek (Frodge, pers comm, 2015). Though exfiltration from side sewers may be a source of the high bacteria counts within Thornton Creek, there are currently no plans to inspect the private side sewers.

Between 2005 and 2015, the Department of Planning and Development issued 20,522 permits to replace or repair sanitary side sewers (Figure 6). These repairs and replacements are presumably due to failure along the line. Pipe failures may allow untreated waste to be discharged from the side sewer system through exfiltration (Frodge,

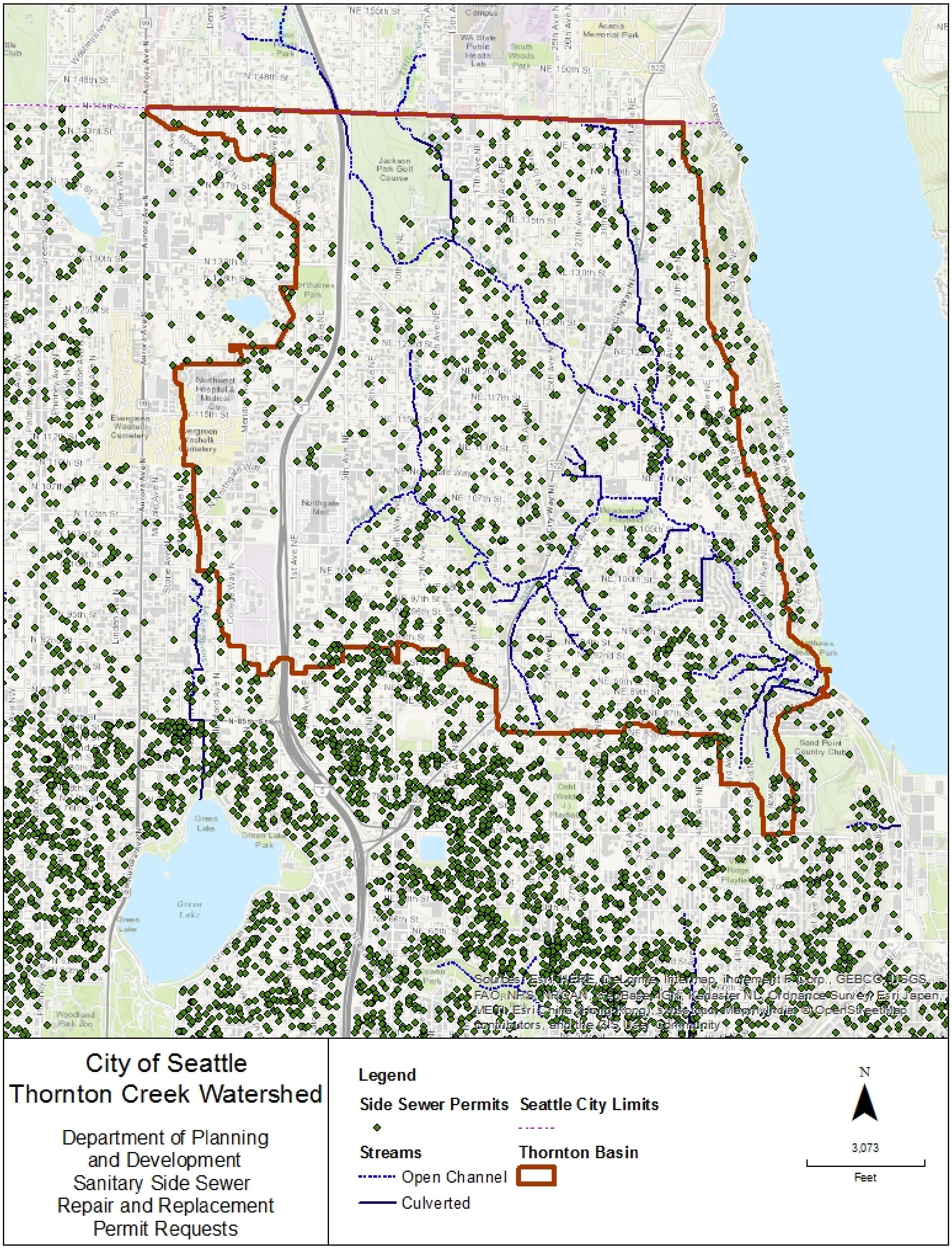

Figure 6: Map of sanitary side sewer repair and replacement permit locations within northeast Seattle. Source: Seattle Department of Planning and Development

pers comm, 2015), however, Seattle Public Utilities does not currently have the data to answer whether or not this is correct. Side sewer failure may result in a waste backup in the home, a pool at the ground surface, infiltration into ground water, or possibly flow along the Vashon Till or soil trench until being discharged into the creek. Because of the private ownership of the system, side sewer failures go unreported. Side sewer repair and replacement ranges between $5,000 and $15,000, making it an expensive surprise for homeowners that may not be able to afford a proper fix. Ronald Wastewater had a difficult time convincing private property owners to allow them access to their property in order to replace side sewers even when stating benefits to the properties including reducing future maintenance and replacement costs, little disruption to the owners property, and increased value to the property (Pottinger et al, 2009).

The suspected failure of side sewer pipes is primarily based on age and material (Frodge, pers comm, 2015). Currently, Seattle Public Utilities uses a Weibull-based failure (Figure 7) distribution to analyze the risk of failure per year in their publicly owned mainline systems.

The stormwater and drainage system within the City of Seattle is regularly inspected by the SPU Source Control and Pollution Prevention team. A number of cross connections have been identified and corrected throughout the city. These corrections do lead to localized reductions in in-stream bacteria counts (Frodge, 2013).

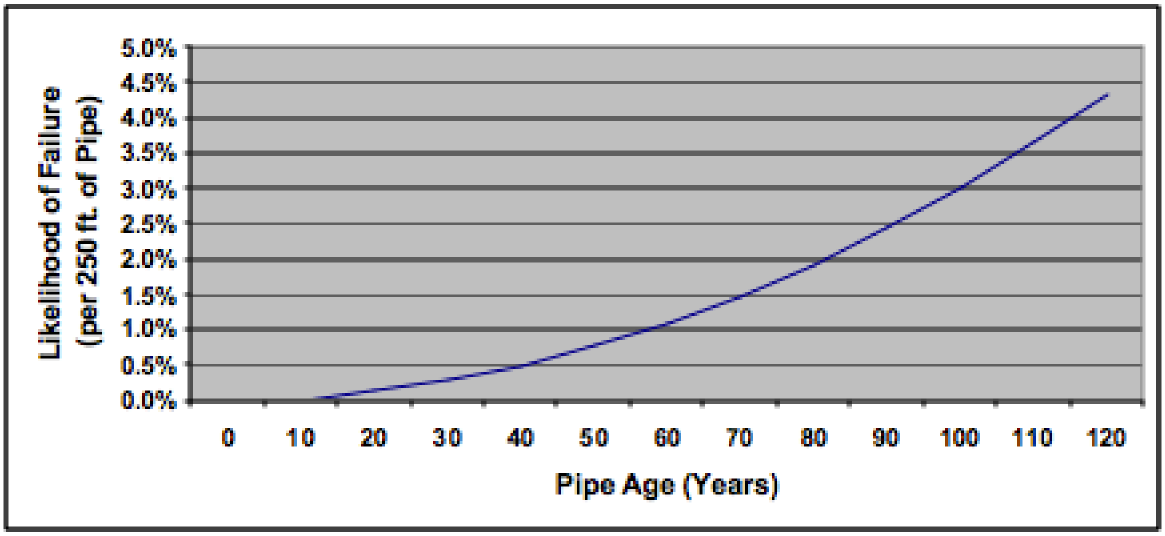

Figure 7: Diagram depicting a graphical example of this Weibull-based failure distribution currently used by Seattle Public Utilities for vitrified clay pipe. Source: *T. Martin, "Using Historical Repair Data to Create Customized Predictive Failure Curves for Sewer Pipe Risk Modeling," for the 2nd Leading Edge Conference on Strategic Asset Management, (2007).*

The City of Seattle has developed and implemented an Illicit Discharge Detection and Elimination (IDDE) program to help protect the municipal separate storm sewer system (MS4). This program in intended to detect, locate, and eliminate all non-permitted discharges into the separated sewer system through business inspections, water quality complaint response, spill response, and source tracing. Illicit discharges include the discharge of sewage as well as wash water, spills, industrial wastewater, hyperchlorinated tap water, and the improper disposal of materials (Seattle Public Utilities, 2014). Illicit connections are verified through dye tests, smoke tests, and CCTV. The goal of this program is to protect aquatic ecosystems, wildlife, domestic animals, and humans from the adverse impacts of these discharges.

As climate change continues, we risk a greater annual frequency of exfiltration during longer, dryer summers, resulting in degraded water quality within the urban environment. In the case of the City of Seattle and its watersheds, such as the Thornton Creek Basin, this may very well be occurring within the system already, resulting in high concentrations of fecal coliform throughout the stream system.

While the City has provided resources to help determine and correct contamination sources, this thesis explains what can be determined using current data, and what else may be needed to properly plan for existing and future private side sewer failures that are contributing to the freshwater pollution of Thornton Creek Watershed.

Mitigation Practices within Seattle

Regardless of the fact that replacing side sewers may be the most direct way to mitigate further declines in water quality within Thornton Creek, as of 2015 the possibility of replacing failed side sewer lines is uncertain. It seems that as long as these lines are individually owned they will typically be inspected for failure at the point of property sale, or when a backup has already occurred.

Rather than mitigating inflow and infiltration by improving the private pipe network, Seattle generally focuses on improving the surface water retention systems as part of a Capital Improvement Program (CIP). Every year, Seattle approves a CIP that allots resources to finance projects designed to improve specific infrastructure. The funds set aside for these projects may be used for the design, engineering, and construction inspection of current ventures and those that are planned to begin within the next six years. CIP projects related to stormwater are designed to improve water quality, control flooding and erosion, enhance habitat, and increase public safety (Thornton Creek Characterization Report, 2000). While these goals generally do not focus on exfiltration as an issue of concern, they all tend to work towards the creation of drainage structures that increase system capacity in order to reduce the likelihood of CSOs while providing an environment of natural settling and filtration.

Several capital improvement projects were completed before 2000 to promote water quality within the Thornton Creek system including:

Jackson Park Golf Course Detention Pond

Detention pond constructed within Jackson Park Gold Course. Approximately four acre-feet in size. Created to reduce flooding, but also serves as a water feature to golfers.

Lake City Detention Pond

One acre-foot detention pond constructed along Littlebrook Creek at NE 125th and 33rd Ave NE.

Meadowbrook Detention Pond

Detention pond constructed at the location that formerly served as the Lake City Sewage Treatment Plant. Approximately 16 acre-feet of water storage with an average depth of three to four feet, but with the capacity to hold a depth of eight feet during severe storms with bypass pipes located within the pond that flows directly into Lake Washington. Area also features a walking trail, artwork, and “natural” habitat areas.

North Seattle Community College Wetland

A constructed wetland at the north end of North Seattle Community College campus. Wetland was constructed to help reduce erosion and peak flows. The project also aimed to provide a source of food for downstream fish and included pollutant removal structures upstream of the wetland.

Thornton Creek Protection BMP

SPU and WSDOT worked together to install a treatment device within the existing stormwater infrastructure to improve water quality in runoff from a section of I-5 before it enters the South Branch of Thornton Creek. It is located beneath the entrance of the Northgate Park-and-Ride. The structure is meant to remove oils, greases, and particulate matter.

A more recent endeavor is the Thornton Creek Water Quality Channel in Northgate. Completed in 2009, this SPU project replaced an abandoned parking lot with 2.7 acres of open space and a daylighted stretch of Thornton Creek that treats urban stormwater from 680 acres of land. The water channel is equipped with terraces, channels, and pools to mimic natural stream features.

The City of Seattle has also completed pilot projects implementing the use of localized Green Stormwater Infrastructure as a way of reducing peak flows and allowing infiltration as a way of preventing an overload in the traditional conveyance system. SEA Streets is a natural drainage system prototype project completed by Seattle Public Utilities completed in 2001 on 2nd Avenue NW between NW 117th Street and NW 120th Street. This project introduced swales on either side of the right-of-way and reduced impervious surface area to 89 percent less than what is found in a traditional street setting. The first three years of monitoring found that the project has eliminated 98 percent of wet season and 100 percent of dry season runoff.

IV: Methods

The research questions posed in this thesis are answered through a combination of geospatial and statistical analysis. All geospatial analysis was completed used ESRI ArcMap and statistical analysis was completed in Microsoft Excel.

Question 1: Is there evidence of correlation between pipe age and the number of line repair/replacement permit requests?
To answer this question, parcel data information was joined with spatial data representing side sewer permit requests within the Thornton Creek watershed as well as citywide. The spatial data was then used to statistically determine whether replacement and repair permits are requested for pipes equally among age groups.

Question 2: Is there evidence of correlation between proximity of creek and the number of line repair/replacement permit requests?
To answer this question GIS was used to create 100, 200, and 400-foot buffers around the Seattle stream system. The buffers were used to identify side sewer permits that were requested within these distances from the stream. The spatial data was used to determine if permits are requested equally within the buffer distances.

Question 3: Is there evidence of correlation between slope and the number of line repair/replacement permit requests?
To answer this question GIS was used to create 100, 200, and 400-foot buffers around areas with a slope greater than 40 percent. The buffers were used to identify side sewer

permits that were requested within these the specified distances from the sloped areas. The spatial data was used to determine if permits are requested equally within the buffer distances.

Data Sources

This thesis is working to address a current lack of data on privately owned side sewers, but also provide an example of what analysis can be completed with data that is available. All data used was preexisting spatial data publicly available from the City of Seattle. These sources include:

Assessor's Data – this data has been acquired from the GIS IT corporate data set. This feature class allows us to know each parcel's land use designation as well as the year of development.

Permit Data – this data was provided by Jennifer Ng of the Department of Planning and Development. The data was sent in two pieces, (1) a point file with permit information for each parcel that submitted an application and (2) a line file with side sewer information. This permit data will be used to determine pipe failure under the assumption that permits are being requested to repair or replace segment(s) of pipe due to a failure somewhere along the line.

Slope Data – this data has been acquired from the GIS IT corporate data set.

This data will be used to help us understand if there is a line repair/replacement permit request rate associated with slopes greater than 40% grade.

Stream Data - this data has been acquired from the GIS IT corporate data set. This feature class allows us to understand spatially where the recognized streams systems are located within the City of Seattle.

Seattle Public Utilities Mainline Data – this data has been acquired from the GIS IT corporate data set. This data is used to represent built area during permit density analysis.

System Variables

To define the system, we shall start by defining the system variables. System variables can be broken into four main categories: water input, water output, human activities, and water policy framework. Water input is defined as water entering the system, and variables include rainfall, runoff from impervious surfaces and permeable surfaces such as lawns, snowmelt, and water outfalling from drainage pipes into the creek. It is important to note that the water input variable includes both the source of the water and the amount of water entering the system from the source. Water output is defined as water leaving the system before reaching the outlet of the creek into Lake Washington and includes diversions and evaporation. Human activity variables (e.g., human activities that could impact the hydrologic health within Thornton Creek) include urbanization leading to increased impervious surface, shoreline alteration, dumping, illicit sewer connections, and homeless encampments. Our last variable is water policy framework which includes conservation, water rights, and the creation, maintenance, and destruction of riparian buffers.

Research Variables

Research variables can be broken into three main categories: pipe construction features, pipe environment, and pipe activity.

Pipe Construction Features

Pipe construction features consist of age, size, and material. Age is measured in years. During statistical analysis, age should be broken down into ten-year increments. For example, does it appear that pipes that are between 40-49 years old more likely to fail than pipes that are between 30 and 39 years old? Size should be measured as pipe diameter in inches. Is there a link between pipe age and a line repair/replacement permit request and an increase/decrease in pipe size? Unfortunately, this information is not widely available so it will not be taken into account. Material should also be associated with what the pipe segment is constructed from, but like diameter, this information is not widely available and will not be taken into account.

Pipe Environment

Pipe environment consists of soil type and climate. Due to the fact that all of the pipes examined will be within a single watershed in northeast Seattle, climate should remain consistent. Similarly, soil type should remain fairly consistent.

Pipe Activity

Pipe activity consists of whether or not the pipe is actively in use or not. This study should focus only on pipes that are actively being used to convey water from building sinks, toilets, bathtubs and other building drains. Abandoned side sewer pipes and side sewer pipes coming from vacant buildings will not be considered in this study.

System Boundaries

Next, we defined the internal and external boundaries of the system. We determined that the internal boundaries of the system are defined by the physical structure of the watershed. Thornton Creek is spatially constrained by ridgelines that designate the flow direction of water, allowing it to enter the Thornton Creek watershed rather than an adjacent one. Refer to Figure 1 for a map of the Thornton Creek watershed. The external boundaries are more complex and include cultural norms, population growth within the boundaries of the watershed, local and national political climate, scientific knowledge, the local economy, urbanization, climate change, and natural habitat modification.

GIS Process

Age of development has been determined using the attribute data for year built (year of most recent development). Parcel infrastructure age is being determined using the assumption that all infrastructure was installed at the most recent development date from the assessor's data.

Spatial permit records for side sewer repair work were obtained from Seattle Department of Planning and Development. All permit data must be vetted before use to remove any data points that only refer to drainage permits or side sewers being installed where nothing had previously existed. These data points will not be needed for this analysis because we are only concerned with work performed due to pipe damage and failure. When sorting through permits, I deleted those that were downspout connections, catch basin repair, or other drainage related assignments as well as permits that were additions or alterations rather than repairs. I included expired permits or those listed as "closed as incomplete" because I am holding the assumption that the permit was requested because there was indeed an issue and follow through was either undocumented or forgotten.

A spatial join was used to combine data from the DPD Assessor's data polygon feature and the DPD provided side sewer permits so that each parcel had information regarding whether or not a side sewer permit had been requested between 2005 and 2015 (Figure 8). Next, a field was added to calculate the age of the pipes using the calculation "2015-[YRBUILT]." This new feature class was named "SSPermit_Property_Info."

To analyze permits within close proximity to the streams, the City's stream layer was imported into the ArcMap project. Using the buffer geoprocessing tool, a 100-foot buffer was created around the streams. The polygon output that resulted from this process was named "Seattle_Streams_100ft." The newly created buffer was then used to select features by attribute. Point features from the "SSPermit_Property_Info" feature class were selected if they intersect the 100-foot buffer polygon. Next, the selected features were exported into the geodatabase and named "SSPermit_100ft." This resulting feature class allows us to identify all permits that were requested within 100 feet of a stream. This same process was used to create a 200 and 400-foot buffer polygon around the streams to select points and create the feature classes “SSPermit_200ft” and “SSPermit_400ft” respectively.

Next, we were interested in examining side sewer permits specifically within close proximity to Thornton Creek. Select by Attribute was used to select features that were Thornton Creek or one of its attributes with names including Thornton – S Branch, Thornton – N Branch, Thornton – Mainstem, Evergreen, Beckler, Kramer, Littlebrook, Littles, Maple, Matthews, Meadowbrook, Mock, Victory, and Willow. These selected features were then exported as a feature class within the create geodatabase and named “Thornton_Creek.” Using the buffer geoprocessing tool, just like with all of the Seattle Streams, a 100-foot buffer was created around the Thornton streams. The polygon output that resulted from this process was named “Thornton_Creek_100ft.” The newly created buffer was then used to select features by attribute. Point features from the “SSPermit_Property_Info” feature class were selected if they intersect the 100-foot buffer polygon. Next, the selected features were exported into the geodatabase and named “Thornton_Creek_SSPermit_100ft.” This resulting feature class allows us to identify all permits that were requested within 100 feet of a stream. This same process was used to create 200 and 400-foot buffer polygons around the streams to select points and create the feature classes “Thornton_Creek_SSPermit_200ft” and “Thornton_Creek_SSPermit_400ft” respectively.

To analyze permits within close proximity to steep slopes, the City’s critical areas layer was added to the ArcMap project. As with the streams layer procedures, using the buffer geoprocessing tool a 100-foot buffer was created around the critical areas. The polygon output that resulted from this process was named “Steep_Slope_100ft.” The newly created buffer was then used to select features by location. Point features from the “SSPermit_Property_Info” feature class were selected if they intersected the 100-foot buffer polygon. Next, the selected features were exported into the geodatabase and named “Steep_Slope_SSPermit_100ft.” This resulting feature class allows us to identify all permits that were requested within 100 feet of a steep slope. This same process was used to create 200 and 400-foot buffer polygons around the steep slopes to select points and create the feature classes “Steep_Slope_SSPermit_200ft” and “Steep_Slope_SSPermit_400ft” respectively.

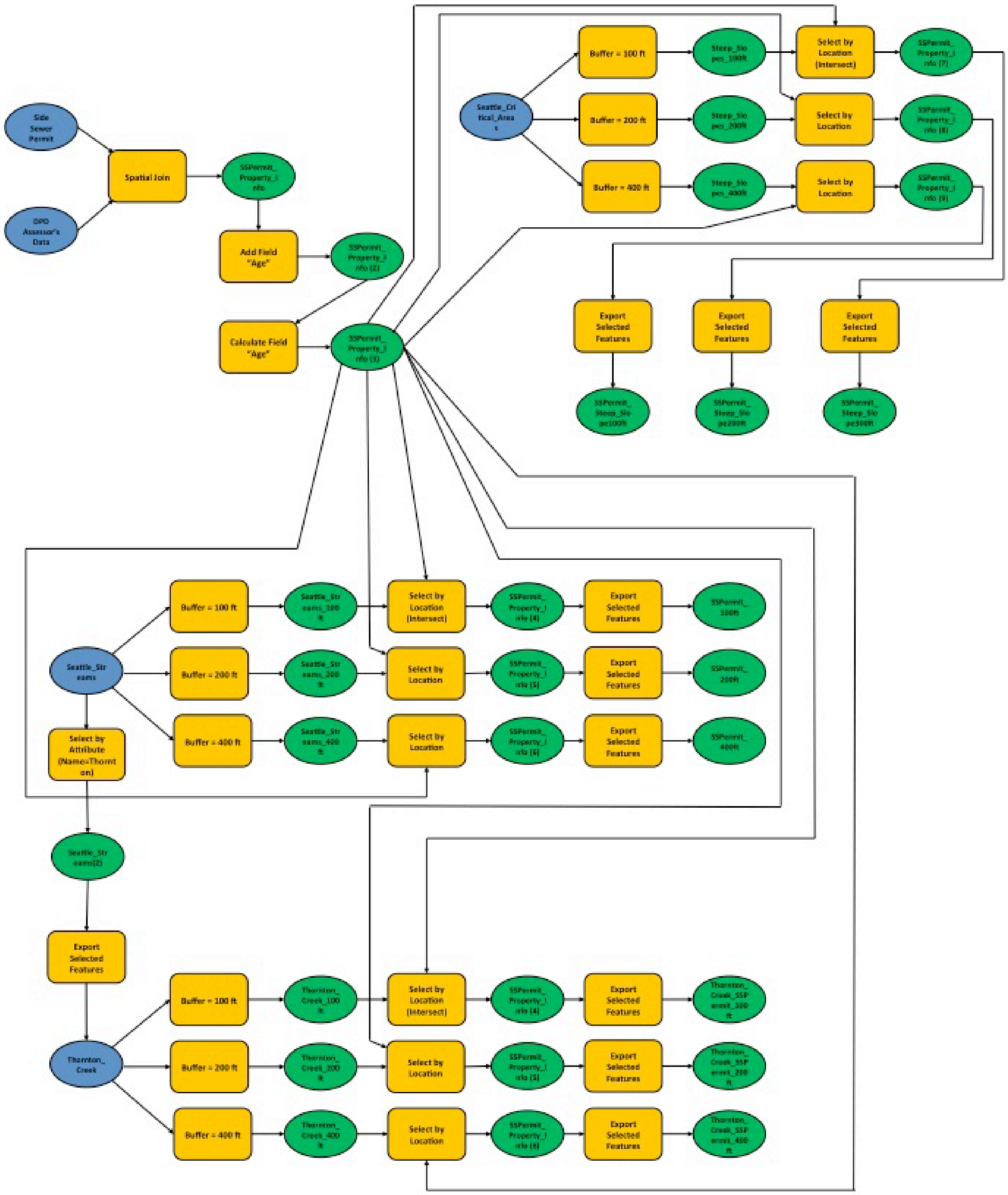

Figure 8: Model of GIS data process to acquire permit information for this study. Source: Author

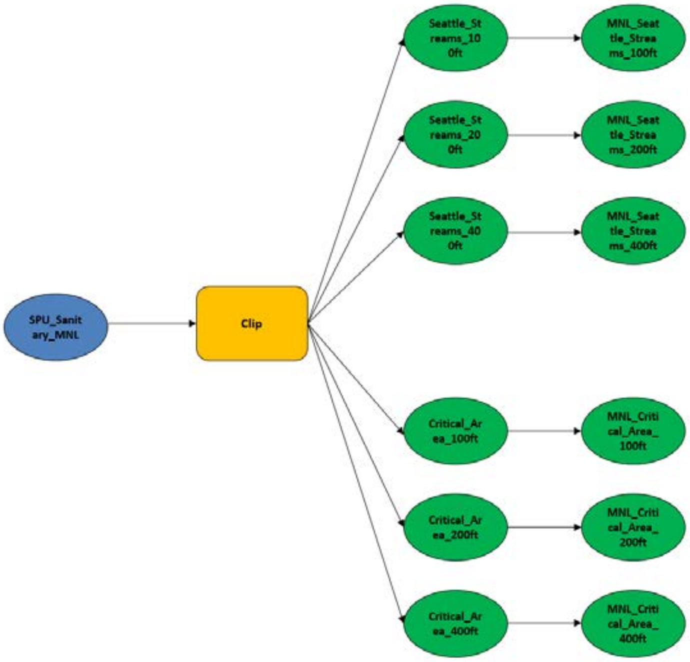

Figure 9: Model of GIS data process to acquire SPU owned mainline information for this study. Source: Author

Seattle Public Utilities mainline data was clipped to each buffer area in order to obtain mainline length within buffers in order to represent built area during analysis (Figure 9).

Data Analysis

Once all GIS processes were complete, data was exported from GIS to Microsoft Excel. The table from SSPermit_Property_Info (3) was used to determine the age of pipes at the time of the permit request. First, all permits were exported and copied to the Excel file, then only permits selected in the Thornton Creek basin were exported. All permits requested from the Thornton Creek data were removed from the citywide data. Ages were grouped into 12 categories: "null" or no data available, 0-9 years, 10-19 years, 20-29 years, 30-39 years, 40-49 years, 50-59 years, 60-69 years, 70-79 years, 80-89 years, 90-99 years, and 100 years or older.

Next, data from the stream buffers was exported. Permits selected within the 100, 200, and 400-foot buffers in both the Thornton Creek watershed as well as citywide were exported and counted. Area in square feet for buffer size within Thornton Creek and citywide was calculated as well as linear feet of city mainline. Using this data, the number of permits per foot of City mainline as well as the number of permits per square foot of buffer was calculated for each buffer in each area.

Lastly, data from the critical areas buffers was exported. Permits selected within the 100, 200, and 400-foot buffers in both the Thornton Creek watershed as well as citywide were exported and counted. Area in square feet for buffer size within Thornton Creek and citywide was calculated as well as linear feet of city mainline. Using this data, the number of permits per foot of City mainline as well as the number of permits per square foot of buffer was calculated for each buffer in each area.

V: Results

Analysis by Age

Table 2: Thornton Creek and City of Seattle repair and replacement data by age. Since the repair and replacement are representing failure for this study, it could also be seen as side sewer failure by age. Source: Author.

Age	City Wide	Thornton Creek (Predicted)	Thornton Creek (Actual)
0-9	817	72	29
10-19	730	64	37
20-29	860	76	40
30-39	1161	102	63
40-49	584	52	60
50-59	1027	91	259
60-69	3101	274	373
70-79	2683	237	148
80-89	3090	273	81
90-99	3192	282	21
100+	3140	277	11

When looking at permit requests with respect to assumed age of pipe, we can see a general trend in the citywide data. Table 2, displays there is an apparent correlation between age of pipes and number of permits requested. This same trend, however, is not apparent when looking at the permits requested in Thornton Creek.

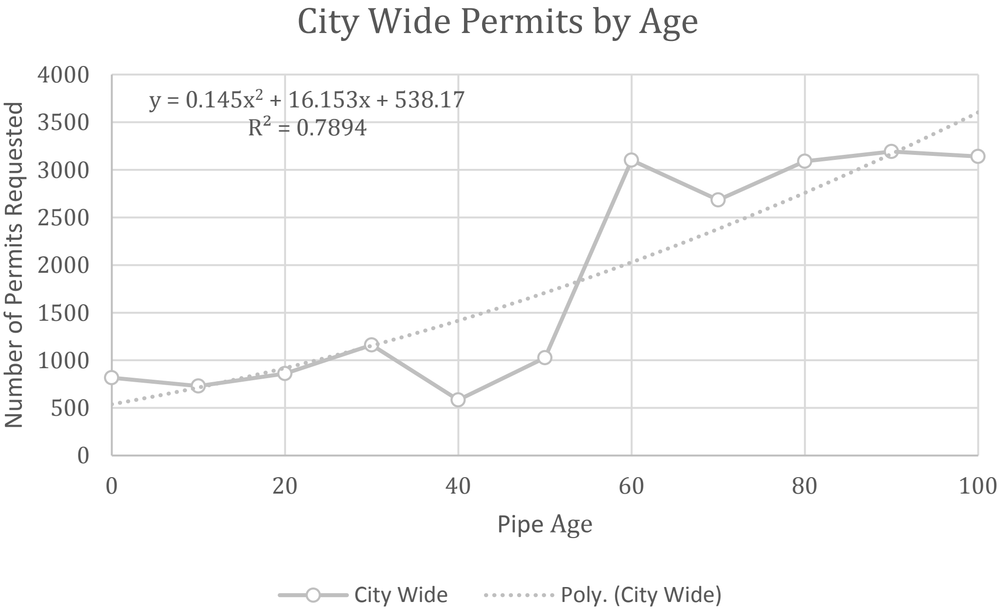

Figure 10: City wide repair and replacement permits by age. Source: Author.

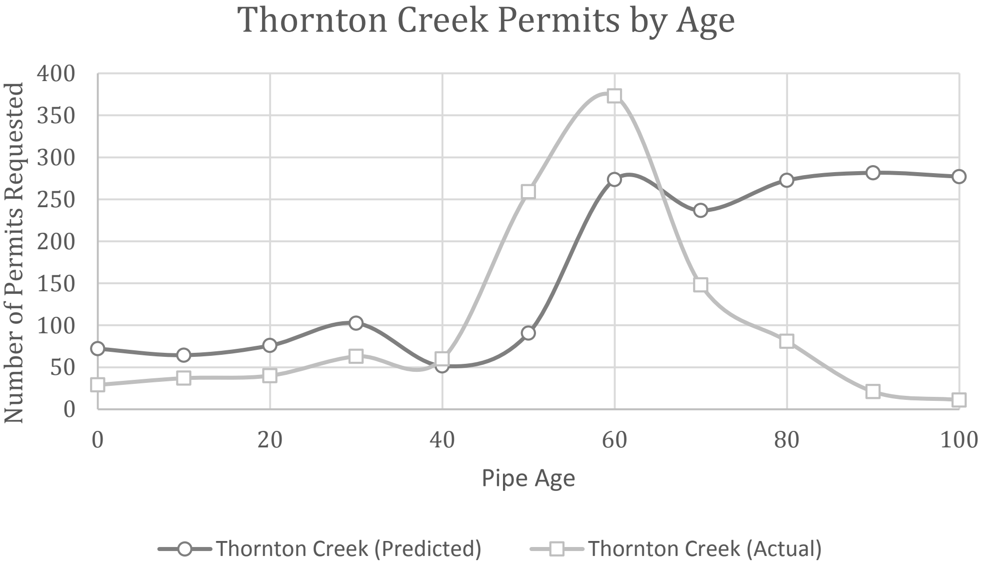

Figure 11: Thornton Creek Basin repair and replacement permits by age. Source: Author.

When citywide age and permit request data is plotted against each other, a polynomial regression line with the equation of $y=0.145x^2+16.153x+538.17$ with an R^2 value of 0.78942 (Figure 10) results.

When values were predicted for Thornton Creek watershed using this same distribution of permits with respect to age, we end up with numbers that look much different from the observed values obtained from the data (Table 2 and Figure 11). The polynomial equation seen in citywide data does not fit the observed data within the watershed. Instead, we see a pattern that more closely resembles a bell-shaped curve with less replacement and repair permits occurring in pipes under the age of 50 years of age and older than 80 years of age and the majority of permits being requested for pipes between 50 – 79 years old.

Analysis by Land Area

Data collected showed that there were 59, 91, and 155 side sewer permits requested from DPD by private residents between 2005 - 2015 within the 0-100, 100-200, and 200-400 foot buffers around creeks within the Thornton Creek watershed, respectively. Citywide there were 326, 248, and 613 side sewer permits requested during the same time periods within buffers applied to all stream systems within the city limits. These numbers do not provide much information by themselves; therefore the number of permits was divided by the total land area within the buffer zones in order to obtain permits per square foot.

Table 3: Thornton Creek and City of Seattle repair and replacement numbers within 100, 200, and 400 foot stream buffers. Permit density was calculated by land area. Source: Author.

Buffer Feet	Thornton Creek Stream Buffer			City Wide Stream Buffer		
	# Permits	Buffer Area (sqft)	Permits/sqft	# Permits	Buffer Area (sqft)	Permits/sqft
0-100	59	21392297.8	2.76E-06	326	93602494.0	3.48E-06
100-200	91	22476226.7	4.05E-06	248	166550384.1	1.49E-06
200-400	155	49362697.6	3.14E-06	613	549932676.5	1.11E-06

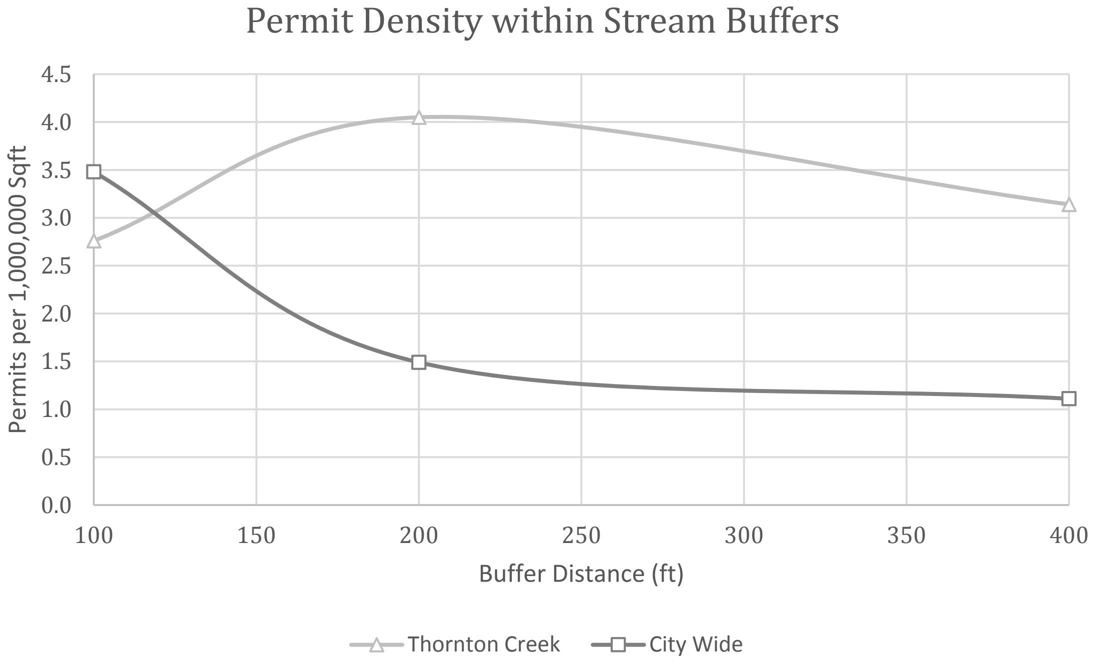

Figure 12: Thornton Creek and City of Seattle repair and replacement numbers within 100, 200, and 400 foot stream buffers. Permits found within buffers were counted and divided by total land area within buffers to determine density. Source: Author.)

Within the 100-foot buffers, Thornton Creek watershed requested 2.76 permits per 1,000,000 square feet while there were 3.48 per 1,000,000 square feet citywide. In the buffer representing the area between one hundred to two hundred feet out from the stream, there were 4.05 and 1.49 permits per million square feet in Thornton and citywide, respectively, and within the 200 to 400-foot buffers there were 3.14 and 1.11. When these numbers are plotted as shown in Figure 12, it is difficult to identify a dependable trend.

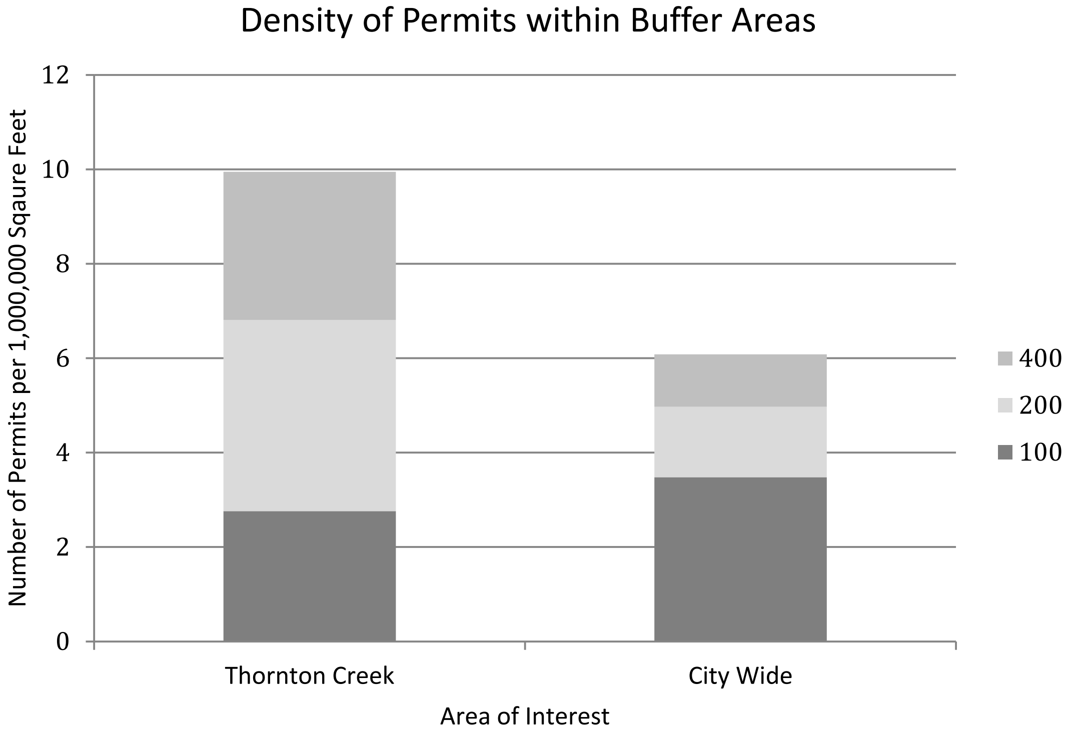

Figure 13: Bar graph representation of Thornton Creek and City of Seattle repair and replacement numbers per 1,000,000 square feet of land within 100, 200, and 400 foot stream buffers. Source: Author.)

Figure 13 uses a bar graph to show the distribution of permits per million square feet within the Thornton Creek and citywide stream buffers. It can be seen that within the citywide data, the majority of permits were requested within the 100 foot buffer zone. However, within Thornton Creek watershed, the 100 foot buffer zone had the fewest number of permit requests.

Table 4: Thornton Creek and City of Seattle repair and replacement numbers within 100, 200, and 400 foot critical area buffers. Source: Author.

Buffer Feet	Thornton Creek Critical Areas			City Wide Critical Areas		
	# Permits	Buffer Area	Permits/sqft	# Permits	Buffer Area	Permits/sqft
0-100	198	42544424.7	4.65E-06	4862	617808224.3	7.87E-06
100-200	144	30308158.8	4.75E-06	3149	352188201.3	8.94E-06
200-400	265	49772688.9	5.32E-06	4723	529918438.7	8.91E-06

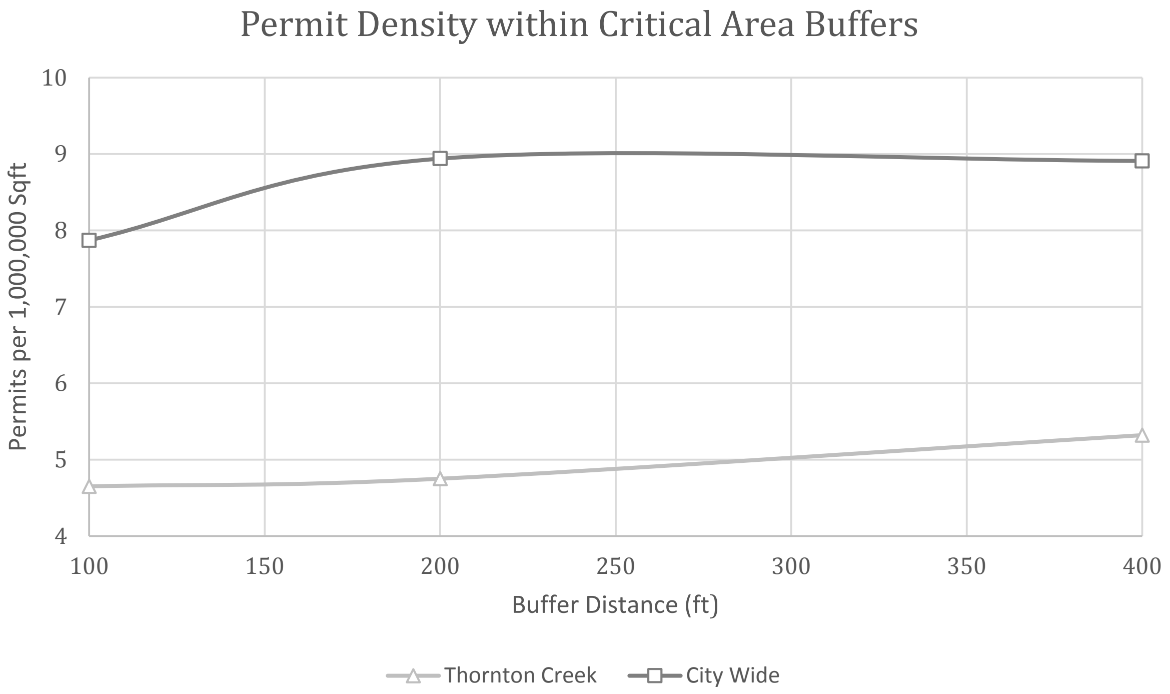

Figure 14: Thornton Creek and City of Seattle repair and replacement numbers within 100, 200, and 400 foot critical area buffers. Source: Author.

The data for permits around critical areas with a steep slope of 40% or greater showed that there were 198, 144, and 265 side sewer permits requested from DPD by private residents from 2005 - 2015 within the 0-100, 100-200, and 200-400 foot buffers within the Thornton Creek watershed, respectively. Citywide there were 4862, 3149, and 4723 side sewer permits requested during the same time periods within buffers applied to all critical areas within the city limits. Once again, these numbers do not provide much information in themselves; therefore the number of permits was divided by the total land area within the buffer zones in order to obtain permits per square foot.

Within the 100-foot buffers of the Thornton Creek watershed requested 4.65 permits per 1,000,000 square feet while there were 7.87 per 1,000,000 square feet citywide. In the 200-foot buffers there were 4.75 and 8.94 per million square feet in Thornton and citywide, respectively, and within the 400-foot buffers there were 5.32 and 8.91. These numbers seem substantially closer to the number of permits for all permits requested in both the Thornton Creek watershed as well as citywide. They are also higher across the board implying that permits are requested more often in these critical areas than they are along streams. Additionally, trend lines indicate an R^2 value of 0.7284 (logarithmic) and 0.96 (linear) for citywide and Thornton Creek basin permit requests, respectively (Figure 14). However, with one trend logarithmic and the other linear, it is again difficult to establish a shared trend between the two areas.

Analysis by Built Area

Analysis by built area was performed in addition to by land area. Using land area it is possible to better compare two regions, but it should be noted that built area allows for a clearer analysis of permit densities because we can better account for lack of permits due to undeveloped land. Public mainlines were used to represent built area.

Table 5: Thornton Creek and City of Seattle repair and replacement numbers within 100, 200, and 400 foot stream buffers. Permit density was calculated by land area. Source: Author.

Buffer Feet	Thornton Creek Stream Buffer			City Wide Stream Buffer		
	# Permits	MLLinearFeet	Permits/MLft	# Permits	MLLinearFeet	Permits/MLft
0-100	59	74187.7	0.00079528	326	220460.8	0.001479
100-200	91	64857.6	0.001403074	248	159132.0	0.001558
200-400	155	103121.9	0.001503075	613	330504.7	0.001855

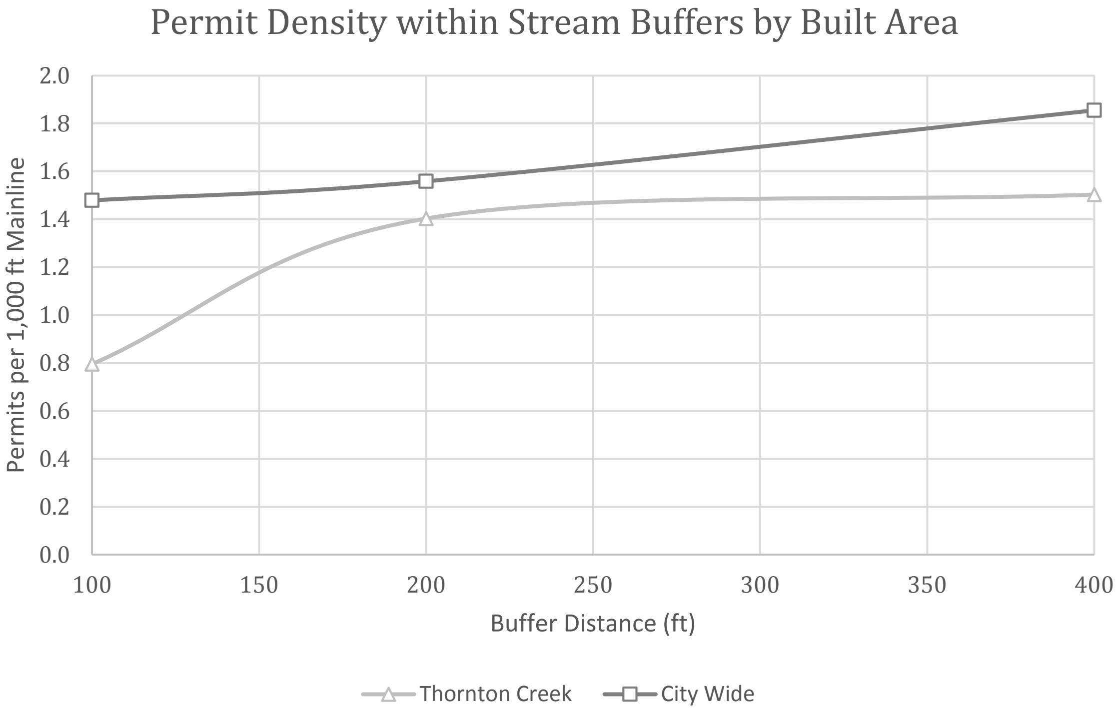

Figure 15: Thornton Creek and City of Seattle repair and replacement numbers within 100, 200, and 400 foot stream buffers. Permits found within buffers were counted and divided by total land area within buffers to determine density. Source: Author.

Within the 100-foot buffers Thornton Creek watershed there were 0.79 permits requested per 1,000 linear feet of mainline while there we 1.48 per 1,000 linear feet citywide. In the 200-foot buffers there were 1.40 and 1.56 per thousand feet in Thornton and citywide, respectively, and within the 400-foot buffers there were 1.50 and 1.86 (Table 5). Similar to

Figure 12, when these numbers are plotted as shown in Figure 15, it is difficult to find a trend shared among the two regions.

Table 6: Thornton Creek and City of Seattle repair and replacement numbers within 100, 200, and 400 foot critical area buffers by built area with SPU mainline length used to represent built area. Source: Author.

Buffer Feet	Thornton Creek Critical Areas			City Wide Critical Areas		
	# Permits	MLLinearFeet	Permits/MLft	# Permits	MLLinearFeet	Permits/MLft
0-100	198	186516.9	0.001061566	4862	2710751.4	0.001794
100-200	144	148748.1	0.00096808	3149	1809667.3	0.00174
200-400	265	206494.2	0.001283329	4723	2383288.7	0.001982

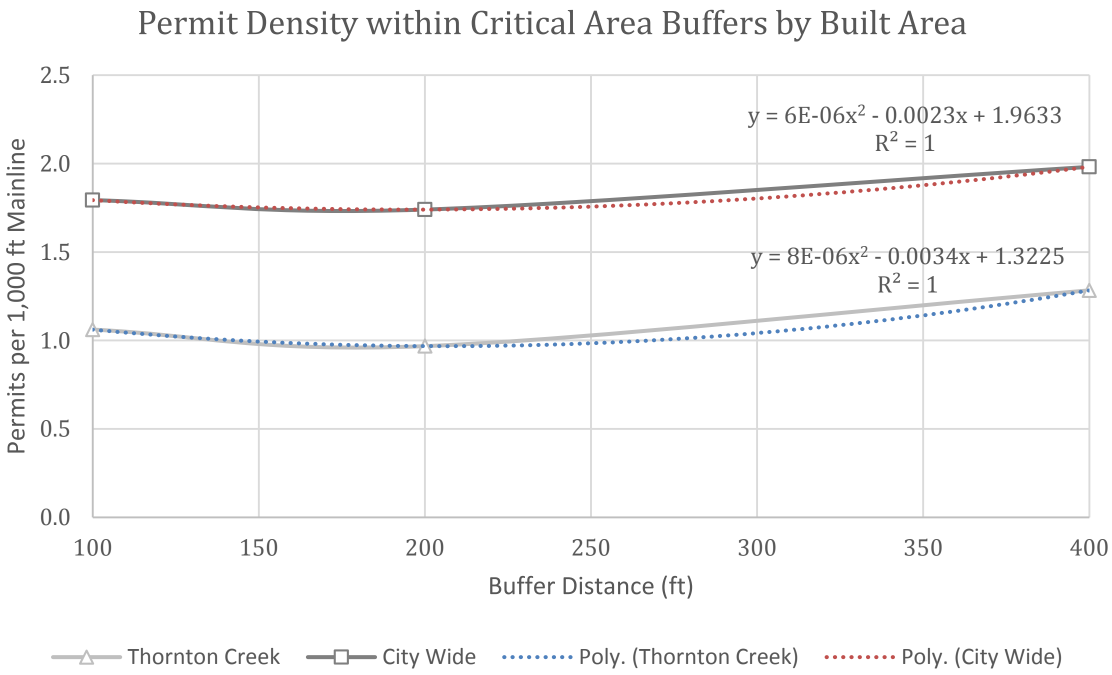

Figure 16: Thornton Creek and City of Seattle repair and replacement numbers within 100, 200, and 400 foot critical area buffers. Source: Author.

Within the 100-foot buffers Thornton Creek watershed there were 1.06 permits requested per 1,000 linear feet of mainline while there were 1.79 per 1,000 linear feet citywide. In the two hundred foot buffers there were 0.97 and 1.74 per thousand feet in Thornton and citywide, respectively, and within the 400-foot buffers there were 1.28 and 1.98 (Table 6).

When we compare the plotted lines for each area in Figure 16, we can visually detect a trend. Both lines show a polynomial trend with an R^2 value equal to 1.

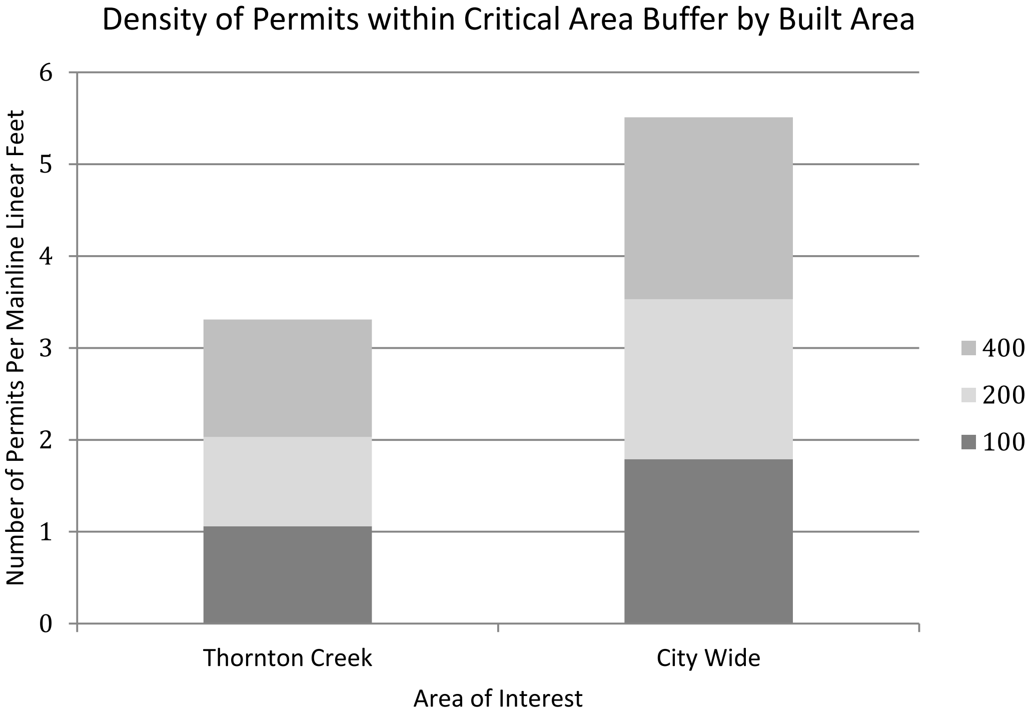

Figure 17: Bar graph representation of Thornton Creek and City of Seattle repair and replacement numbers per 1,000,000 square feet of land within 100, 200, and 400 foot stream buffers. Source: Author.

When examining the bar graph representing the data (Figure 17), a similar trend can again be seen in the data. In both the Thornton Creek watershed as well as in the citywide data, the highest density of permits are requested within the 200-400 foot buffer zones, followed by the 1-100 foot buffer zone, and the least density is found within the 100-200 foot buffer zone.

VI: Discussion

Current fecal coliform levels within Thornton Creek pose very serious health hazards to the surrounding human population as well as dozens of species of birds, amphibians, mammals, insects, and fish. Backyards, parks, and trails along Thornton Creek (such as Magnuson Park) serve as popular locations for outdoor activity bringing adults, children, and pets close to if not in contact with highly contaminated water. In order to determine the best way to mitigate this issue, we must determine the cause of the problem. With side sewer failure data remaining beyond the reach of the public utility, failure prediction models can be used to estimate how much side sewer failure is contributing to this dangerous contamination.

Study Findings

Seattle is an aging city with aging infrastructure. Based on the era of construction and the evidence of failure in the literature, there is little room for doubt about the failure of side sewers within the city and specifically within the Thornton Creek watershed. However, with the information currently available we lack the ability to make a definite statement regarding the influence that these failures have on fecal contamination within the stream. This thesis addressed three questions: (1) is there evidence of correlation between pipe age and the number of line repair/replacement permit requests (2) is there evidence of correlation between proximity of creek and the number of line repair/replacement permit requests, and (3) is there evidence of correlation between bed material slope and the number of line repair/replacement permit requests. From this study it was possible to detect:

- A correlation between pipe age and repair and replacement permit requests citywide, but not within the Thornton Creek watershed,
- No significant correlation between distance from creek and replacement permits requested citywide nor within the Thornton Creek watershed by land area nor built area
- Perhaps a negative correlation between the distance from critical areas and replacement permits requested within the Thornton Creek watershed by land area, but not citywide,
- Strong polynomial relationship between distance from critical areas and replacement permits within both the Thornton Creek watershed as well as city wide when density determined by built area.

While the results are not conclusive, they do provide a way for municipalities to begin determining the health of their existing side sewer systems in a way that has not been done historically. Many municipalities focus on infiltration and inflow rather than exfiltration because of the expense associated with treating excessive flows. In municipalities that struggle with surface water pollution similar to Seattle, commercial and public industries are most often targeted due to ease of detection and enforcement. This paper used easily accessible data to determine potential trends relating year of development to side sewer repair and replacement as well as a decrease in numbers of permits requested in areas of steep slope.

Limitations

Exfiltration Data

Exfiltration occurs within the conveyance system pipes, maintenance holes, joints, and pump stations due to construction practices as well as deterioration (Amick and Burgess, 2003). Within the Thornton Creek watershed, we know that there have been historical issues within the system that contributed to infiltration and inflow. Excessive flows from infiltration were noted as early as 1954 (Metropolitan Seattle Sewage and Drainage Survey, 1958). Hill and Ingman, consulting engineers within the Lake City district, submitted a report that indicated high variations in both wet and dry seasons. Analysis of records from the 1950's reveal that more than 60 percent of the total flow into the sewage treatment plant from the Lake City area was attributable to infiltration and inflow. Infiltration and inflow occurs when water flows into a pipe from the surrounding ground through cracks and holes. If infiltration and inflow occurs within a system, it is reasonable to assume that exfiltration is also occurring, however, little data exists to support this assumption.

System Condition Data

Davies et al. (2001) indicated that age of pipe, load transfer, standard of workmanship, sewer size, sewer depth, sewer bedding, sewer material, sewer joint type and material, sewer pipe section length, sewer connections, surface use, surface loading and surface type, water main bursts and leakage, ground disturbance, groundwater level, ground conditions, soil backfill type, root interference, sewage characteristics, and maintenance methods are all variables that influence the structural stability of sewer lines. Using the data available for this research, most of this information was not accounted for.

Seattle's side sewers, like those in Shoreline, have been overlooked by the local government due to private ownership. The municipality may realize benefits in repairing and replacing side sewers in an effort to reduce infiltration and inflow as well as exfiltration. The city of Shoreline received confirmation that municipal sewer districts have the authority to use public funds to repair and replace side sewers when it directly provides a significant benefit in the public interest (Pottinger et al. 2009).

Pollution Source Data

There are many sources of water pollution in urban areas. Runoff from impervious surfaces, lawns, and agriculture lands all contribute to fecal contamination. There is dumping that occurs every day, cross-connections that occur by accident and purposefully, homeless encampments, spills, and pet waste that all increase fecal coliform concentrations. While each one of these sources is important and needs to be dealt with, this paper has been focused on exfiltration from private side sewers. It seems likely that side sewers contribute to the pollution of the creek, but other sources should also be considered. Lake City Way is a major commercial corridor through Thornton Creek. There is a potential that commercial facilities in this area could provide food for urban wildlife or discharge food waste directly into the stormwater conveyance system such as what was experienced in Clear Creek (Fohn, 2009). Additionally, *E. coli* and other fecal derived bacteria may be stored and continuously breed within sediments, soils, seeps, stream pools, and stormwater conveyance systems throughout the watershed as was found in Dunes Creek (Whitman et al. 2006).

The City of Seattle does not currently have enough information to credibly determine the source(s) of contamination. The only way to move from speculation to understanding is by obtaining more data through continued testing.

Incomplete Data

It must be acknowledged that this study was unable to determine every side sewer leakage, break, collapse, or joint slip. This study was dependent on permit requests submitted by property owners through the Department of Planning and Development at the City of Seattle. A number of scenarios exist in which a property owner has an inadequate side sewer yet does not file for a repair or replacement permit. The first scenario is that the owner is simply unaware of the issue. Side sewer problems can occur without having a noticeable impact on the property tenant. Conditions that may lead to exfiltration may still allow conveyance of waste from the home. This paired with the fact that side sewers are located several feet under the property surface can lead to no reason for concern or investigation.

Another possible scenario is one in which the property owner is aware of the issue, but it is not directly impacting their current quality of life so they do not see the need to begin corrective action. For example, a side sewer on a steep ravine may experience a slip at the joint causing sewage to pour downhill with the help of gravity. Conveyance from the house is still occurring, potentially removing urgency to address the problem even if the homeowner is aware of the situation. Similarly, the homeowner may be aware of the failure, but simply cannot afford to begin corrective action. As was mentioned in a previous section, side sewer repair and replacement ranges between $5,000 and $15,000 making it difficult for many property owners to address the issue without great financial burden.

Another scenario is one in which a property owner is made aware of an issue with their side sewer and has it repaired without the appropriate permit. This could occur for a number of reasons including being unaware of the fact that a permit is required, not feeling that a permit is necessary, or skipping the step to save on project costs.

All of the scenarios described may, in combination, be contributing to an underrepresentation of sanitary side sewer repair and replacement rates across the city. Unfortunately, with the data that is available to the City of Seattle, this uncertainty of complete data is unavoidable.

Inaccurate data

Another issue that this study faced is a lack of accurate data. Side sewer age was calculated using the year of development as provided by the Assessor's Data maintained by the Department of Planning and Development at the City of Seattle. A more desirable way to calculate age is by using the precise install date. Unfortunately, attribute data such as install dates, pipe material, and pipe depth is typically missing from the feature class representing private side sewers. It is understood that this is because historical side sewer data was manually drawn from georeferenced as-builts and given attribute data over a short period of time during Seattle's effort to digitize spatial data. When this information is present, it is difficult to gauge the accuracy due to the City's inability to inspect the infrastructure to verify data.

Unavailable Data

As of 2016, the City has yet to develop an accessible feature class containing groundwater table data. Knowledge of where the water table level is in terms of elevation across the city as well as seasonal fluctuations would help us to better understand places more susceptible to exfiltration versus infiltration and inflow. Accurate side sewer depth information is desired for the same purpose.

Climatic Implications

As the climate continues to change in the Pacific Northwest, precipitation patterns are predicted to change. While the climate record on our planet has been dominated by variability, the natural cycles that have been recorded in the past cannot account for the rapid increase in global temperature that have occurred in the past 50 years (UW Climate Impacts Group 2009). Nearly every study conducted by scientists specializing in this phenomenon across the world has concluded that temperature rise is a product of increasing concentrations of greenhouse gases in our atmosphere.

Temperature records show that temperatures have increased 1.5^{o}F since 1920 within our immediate region and climate models indicate that this rise will continue to increase by an average of 2.0^{o}F by 2020, 3.2^{o}F by 2040, and 5.3^{o}F by 2080 (UW Climate Impacts Group 2009). While these increases will more than likely impact our local air pollution, human health, food production, coastlines, fisheries, and annual flooding, the focus of this paper will be on the changes in precipitation patterns that will have an impact on our water quality. Many models anticipate greater variations between wet and dry seasons as autumns and winters become wetter and summers become drier. As our sanitary and stormwater infrastructure continues to age it is likely that capacity issues will arise, infiltration and inflow may lead to an increase in CSO occurrences, and exfiltration could all have an impact on the fecal contamination within Thornton Creek, along with every other creek in the urbanized region.

City-wide Green Stormwater Infrastructure

Dealing with capacity issues will become increasingly urgent in the face of climate change. Many of the mitigation strategies within the Thornton system are instead being used to combat peak flows to prevent flooding and combined sewer overflows, rather than to address capacity issues related to the conveyance systems. Smaller systems on a larger scale can and should be implemented to reduce peak flows in order to reduce the risk of inflow and infiltration as well as exfiltration while also working to reduce flooding and enhance water quality. Green Stormwater Infrastructure (GSI) such as bioswales, rain gardens, permeable pavement, and green roofs treats stormwater runoff near deposit locations mimicking nature by allowing infiltration through an engineered medium to slow runoff velocity while reducing pollution. While many types of GSI exist, bioswales and rain gardens serve as the two models that the author suggests to be installed near downspouts and roadways to adapt to the increasingly severe seasonal precipitation that is likely to occur here in the Pacific Northwest.

Bioswales

Similar to a ditch, swales are generally sloped channels with flat bottoms. Unlike ditches, swales are always lined with grass or vegetation promoting water infiltration into the top layer of soil rather than just directing the water to the nearest culvert. Additionally, the grass and vegetation increase the removal of many pollutants including fine sediments, oils, and metals (Thornton Creek Characterization Report, 2000). Stormwater that would normally be collected by a ditch or conveyance pipe would instead flow into a swale in which water could be absorbed by a sandy, engineered top soil and infiltrate while being treated by vegetation (Figure 5).

Collected water that is absorbed by vegetation and soil is later released as water vapor and infiltrated water is released at a reduced velocity compared to what would flow into the system in typical urban conditions. If a bioswale reaches capacity, excess runoff may be directed into an overflow pipe that flows into and classic urban stormwater conveyance system.

A great way to take advantage of rainfall and stormwater is a rain garden, which is designed to contain native plants and planting materials that may withstand the high levels of nutrients and moisture characterized by urban precipitation runoff (The Low Impact Development Center 2007). Rain gardens are typically small areas of land sloped to accommodate the lowest elevation in a central area, allowing for water accumulation towards the middle. This design allows precipitation more time to infiltrate, losing its erosive momentum and peak volume. Like swales and retention ponds, these features can be made to infiltrate water directly into the ground of be collected through perforated pipes to be conveyed to an outfall. The rain garden, through biological processes, via engineered mediums and specifically selected plants, reduce nitrogen and phosphorus loads as well as reduce runoff volume while providing habitat for arachnids, insects, and birds.

VII: Conclusions

Clean water is necessary for the health of our economies, communities, and individuals (EPA Clean Water Rules). The water that feeds our streams and wetlands eventually flows to the rivers, lakes, and marine waterbodies that make up the landscapes by our homes. Additionally, this water recharges groundwater and provides crucial habitat for fish and wildlife. Every day we use water to keep our bodies hydrated, clean our bodies and possessions, appreciate its aesthetic power, and use it for recreation. It is our duty to protect our waters and mitigate the consequences of our urban lifestyles.

Future research

Due to the fact that side sewers are privately owned and not maintained by the Public Utility, very little information is known about the side sewer system condition in the Thornton Creek watershed. This study is intended to examine the potential correlations between side sewers and fecal contamination within surface water which may indicate failure within the side sewer system using Thornton Creek as a case study.

There are multiple data fields that could be gathered using a variety of projects in order to better understand the health of our side sewer system and the impact that this infrastructure could be having on the surrounding waterbodies.

Simultaneous Sampling

Between May 2013 and October 2014 Seattle Public Utilities acquired over 250 water quality samples. However, these samples were not taking simultaneously. Previous to writing this paper, the author had thought that it would be possible to begin exploring the theory that sewage is seeping from private side sewers through exfiltration and contaminating the stream with the obtained sample data. This study would assume that similar qualities of construction practices were used during the installation of these side sewers. Additionally, due to citywide regulations and standards, the study was also to operate under the assumption that climate and environmental conditions remain constant across sampling locations due to their closeness in proximity to one another. Because simultaneous sampling has not occurred, this second assumption does not seem realistic. The method in which samples have been collected are not ideal for the kinds of statistical testing that the author deems appropriate as these samples were not necessarily taken at the same time of year, day nor were they necessarily taken during the same weather conditions. The author suggests simultaneous water quality sampling within the Thornton Creek basin or a similar basin using GPS to track sample locations in order to use GIS to test if correlations can be made between age of side sewers and cumulative length of pipe surrounding sample location and fecal contamination levels using *E. coli* concentration as the fecal contamination indicator.

The following questions may be addressed:

Question 1: Is there a statistical correlation linking age of pipes surrounding water sample location and *E. coli* concentration of water sample?

To answer this question, the researcher may create a 50, 100, and 200-foot buffer around the sample locations to determine average pipe age. It could be determined whether a higher average pipe age corresponds to a higher contamination of the water. Unfortunately, the City of Seattle does not have ages recorded for the vast majority of these pipes, primarily because they are not City installed nor maintained. As was done in this paper, DPD parcel development data may be used to determine likely age assuming that the pipes were installed at the most recent parcel development.

Question 2: Is there a statistical correlation linking total length of pipe surrounding water sample location and *E. coli* concentration of water sample? To answer this question the researcher may create a 50, 100, and 200-foot buffer around the sample locations to determine average cumulative length of pipe surrounding the sample location. The buffers could then be used to clip the pipe segments, then add their length to determine total length within the buffers to determine if total length corresponds to a higher contamination of the water.

It should be understood and acknowledged that water travels downstream, so efforts will likely lead to inconclusive results.

This research would have some assumptions associated with it. Side sewer depth data does not exist, but some assumptions about this can be made (Amick and Burgess, 2013). The EPA has stated that the typical service lateral (side sewer) depth can be assumed to be 8 feet for building with basements and 2-4 feet for buildings built on slabs. Typical sewer main depth can be assumed to be 6-10 feet deep. Sewer depths are generally shallower in the western part of the country when compared to the middle and eastern states.

Groundwater data

It would also be beneficial for a future project to look into groundwater elevation data and compare it to our sanitary line elevations. What percentage of our sanitary lines are above the groundwater table (susceptible to exfiltration) and what percentage of them are below the groundwater table (more susceptible to infiltration and inflow)? Previously there has been a lack of groundwater table elevation data. This is something that should be researched and made available in the future.

Dye testing

A hands-on suggestion for future research in the Seattle is dye testing. Many cities across the country use dye testing as a means to trace sewage contamination within the stream systems. Dye testing technicians enter homes to place dye into sinks or toilets to do fine studies, or they can test larger areas at a time by placing dye directing into maintenance holes. Typically, the tests are conducted in pairs so that an observer is able to watch a drainage mainline and a sanitary mainline to observe where the dye appears. A sample selection of houses adjacent to the Thornton Creek system should be selected in order to introduce florescent dye to the sanitary system by way of interior plumbing or side sewer clean-outs to see if it can be traced to the stream by way of fluorometer or absorbents downstream.

CCTV

Similarly, a sample set of houses may be selected for side sewer CCTV. Due to the fact that side sewers are privately owned, the city does not have the authority to cross property boundaries in order to CCTV private sewer lines without the consent of the property owner. However, a sample set of houses selected anywhere throughout the city may provide the opportunity for the city to have a better understanding of how size, age, construction features, material, etc. play a role in failure and deterioration. Perhaps even more valuable, this type of study may help the city to understand a better approximation of a percentage of total side sewers that may be failing within the area.

Planning Implications

It is our job as planners to learn from past oversights and work to avoid similar problems in the future. In the case of fecal contamination within our urban stream systems, we are currently unable to determine the cause. However, it is unlikely that there is only one source of the pollution and we do have a fairly good grasp on potential factors contributing to the problem.

As the population within Seattle continues to grow and the age of our existing infrastructure continues to increase, the policies associated with the infrastructure should undergo adaptations in order to best preserve the integrity of the environment in which it exists. Historically, our impacts have and continue to possess the potential to bring mass destruction to the health of the environment and natural systems, which in turn degrades the quality of life for our community.

Changes in political ideologies and focus occur regularly, triggering changes that remain unknown. These shifts often result in direct negative impacts to the ecosystems in which they occur as well as indirect negative impacts to connected systems and the human economy and societal wellbeing.

While the serious repercussions that can arise due to these ideological shifts are largely under acknowledged, it is of great importance that we as planners err on the side of caution to sustain current regimes, simply because we do not yet know how dramatic and irreversible of an impact we could make. Due to our lack of knowledge pertaining to potential repercussions, it is wise to plan by considering a wide range of divergent but plausible futures including worst case scenarios. We must continue to research and promote the exchange of information between scientists, planners, and politicians while acknowledging the fact that change is inevitable and uncertainty is the only thing that we can be certain of.

In the case of side sewers within the City of Seattle, the wisdom to leave something as invisible as an underground pipe system within the ownership of the private sector is questionable. With most people unaware of a failure unless a backup on their property occurs, sewage leaks may very well be occurring throughout the city, contaminating our water systems with a variety of fecal derived bacteria. Perhaps it is time for Seattle to bear the burden of these systems to ensure the protection of our natural systems.

Closing Thoughts

It is a fallacy to think of our planet as a system with an endless supply of resources. In recent years we have focused an exceptional amount of time educating the public on renewable energy sources and climate change. While we may be able to make advances allowing us to desalinate water, filter air, and increase the density in urban areas, we will likely not see a future in which we invent new clean water, air, and land (Muskie, 1978). For this reason we are reaching a consensus in the idea that our planning process should take into consideration the environmental impacts of our growth and development.

This case study focused on Seattle, but this problem is not new and is not specific to the Seattle area. Infrastructure such as our sanitary system ages and fails just like our buildings, roads, drink water system, and bridges. One major difference between our sanitary system and these other examples is that the sanitary system is highly hidden and often times the impacts of failures are not directly felt by the human population unless the issue results in a surface overflow. While many creeks throughout the country and world are contaminated like those listed in this thesis, they flow through backyards and provide beautiful landscape without provoking suspicion among neighboring residents.

It is important to keep in mind that this study aimed to perform analysis on existing data. One major setback is that the information currently available is lacking. While the data currently obtained by the City allowed me to begin to explore the side sewer failure through repair and replacement permits obtained, it is important for the utility to begin working toward the collection of new data. While this is difficult because the pipes are located on private property and collection methods may be expensive, it should be taken into consideration that private line failures cost the City money to investigate even when the repair ultimately is the responsibility of the homeowner (Bhatt, 2016).

It is the responsibility of the inhabitants of this planet to maintain a healthy environment for this and future generations so that all species may be born with the same access to resources and quality of life that we have been gifted by our predecessors.

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