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At-Risk Wastewater Pipeline Identification Due to Flooding

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At-Risk Wastewater Pipeline Identification Due to Flooding

by

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DEDICATION

This thesis would not have been possible without my wonderful family, Sandy and David, and most of all, my loving husband William, and his recent duties as my chef, housekeeper, butler, personal shopper, and page number-fixer.

Special gratitude is due to my thesis committee.

ABSTRACT

At-Risk Wastewater Pipeline Identification Due to Flooding

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Corrosion is a risk to all ferrous pipelines, and the impact of moisture from major flood events in potentially corrosive soils upon the corrosion of sensitive pipeline materials has not yet been thoroughly studied. Rapidly accelerated corrosion from flooding can cause a pipeline break and lead to environmental hazards. This research seeks to quantify the risk of wastewater pipeline components to fracturing and damage from flooding to inform decision-makers.

The corrosion risk to Austin Water Utility's aged ferrous wastewater pipelines from surrounding soil through flooding is analyzed by establishing the relationships among pipeline material, age, and the surrounding soil type. First, aged ferrous wastewater pipelines in the network were isolated. Then, the Web Soil Survey from the United States Geological Survey (USGS) for Travis County and FEMA Flood Insurance Rate Maps (FIRM) were overlaid on the selected pipelines. USGS soil data was used to locate potentially corrosive soils surrounding the pipelines. Third, FIRM flood zones were overlaid on the selected soil and pipelines in order to examine the relationship between soil type, moisture, and increased corrosion potential. Three different flood zones were evaluated. The analysis shows a total of 386 pipelines, or 27.99 miles of pipelines, were identified to be at-risk.

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CHAPTER 1: INTRODUCTION

1. Problem Statement

Corrosion is a risk to all ferrous pipelines, but corrosion is a unique risk for municipal water and wastewater utilities, and remains an important, yet not fully resolved issue for many municipally owned utilities. Municipally owned utilities are faced with ever-changing budgets, and are often subject to the oversight of a city council, consisting of some dozen members, each of whom faces scarce resources in terms of budget constraints. City councils, utility managers, and mayors face numerous competing demands and programs that are in need of revenue. Given the political environment to which municipally owned utilities can be subject, corrosion of its ferrous wastewater pipelines only accelerates the depreciating life of a solid asset already in the ground and providing service. Corrosion is a costly situation for the manager: the National Association of Corrosion Engineers estimates that the cost of corrosion to the water and wastewater industries is $58.5 billion a year. Where corrosion can be mitigated or avoided, the manager of the municipally owned utility avoids the tension between the risk of decaying infrastructure leaking pollutants into the groundwater and that of making a request to a city council for an increase in funds; moreover, the manager reduces the need to upset the everyday lives of voters with repairs of corroded pipelines, taking lines out of service, and tearing up roads and grounds to repair or replace lines.

Unlike oil and gas infrastructure, which has invested extensively in anti-corrosion technologies due to the potential for highly hazardous waste spills and the resulting state, local, and federal regulations, the consequences for leakage from water and wastewater pipelines would seem to be relatively small by comparison (Romer and Passaro, 2007). While leakage from a corroded wastewater pipeline may not be as environmentally damaging as leakage from an oil and gas pipeline, and thus are subject to limited regulation and oversight, there are undoubtedly impacts and contaminants released into the water. Wastewater pipeline leaks can pollute both groundwater and surface water through recharge, as noted in one study that found steroidal hormones and pharmaceuticals in surface water (Standley et al., 2008). While there may be arguments that some quantity of pollutants or potential pollutants already pass through wastewater treatment plants, as noted by Schroder et al. (2016) in their study of painkillers and steroidal hormones passing through wastewater systems, a superior management approach for the wastewater manager is to control decisions regarding treatment of pollutants at the wastewater treatment plant site rather than beyond his or her control at the groundwater site. Fractures of the wastewater pipeline can consequentially result in groundwater entering the wastewater system, diminishing the groundwater resource and causing the pipelines to overflow, the contents of which can then enter local bodies of water (Chisolm and Matthews, 2012). Given these environmental concerns, the wastewater manager has an additional motivation to seek to mitigate corrosion of wastewater pipelines.

Figure 1: An example of external corrosion on a pipeline (source: InHabitat, June 2015)

External corrosion of ferrous pipelines is caused by several properties of the soil surrounding the pipeline. As will be discussed later in this paper, research has discussed extensively the issue of mitigating corrosion from perspective of increasing resilience to disaster – that is, placing encasements or cathodes on the pipelines themselves – rather than from a holistic disaster avoidance perspective – avoiding the need for any corrosion control strategies other than evaluating the choice of pipeline with respect not only to the surrounding soil, but also to the surrounding soil conditions. In addition to the other properties of soil that can increase the soil's corrosion potential, a significant increase in moisture content and prolonged exposure to water – such as would occur in a flood event – will also increase the corrosive properties of the soil. Through exposure to high moisture content in soils, flooding can rapidly accelerate corrosion, potentially causing a pipeline break (Chisolm and Matthews, 2012).

The municipal wastewater manager can expand their range of options in wastewater pipeline asset management by analyzing asset management from not only a disaster resilience perspective, but also from a disaster avoidance perspective. A disaster avoidance perspective would be framed around removing risk of pipeline failure from external corrosion by choosing non-ferrous pipelines for corrosive soils in high-risk floodplains, while a disaster resilience perspective would mitigate corrosion risk through add-on products such as cathodes and encasement, as will be discussed later in this paper. Contextualizing the risk of corrosion to ferrous wastewater pipelines with respect to soils and floodplains would assist the wastewater manager when selecting materials for wastewater pipelines, whether that be siting new wastewater pipelines or replacing existing wastewater pipelines. Such a perspective would not only enhance asset management, but would also reduce environmental hazards.

2. Research Purpose and Questions

The goal of this research is to investigate the risk of Austin Water Utility's aged ferrous wastewater pipelines to corrosion through flooding. Specifically, the thesis will analyze the risk of Austin's wastewater pipelines to corrosion through flooding by mapping the materials and age of pipeline to the soil type and flood risk surrounding the pipeline. Then, a level of risk is assessed by determining the number of components (in terms of pipe length and volume) of aged ferrous wastewater pipelines located in high-risk floodplains that also consist of potentially corrosive soils.

Specific questions and objectives for this research are outlined below:

- **Research Question 1**: Are there ferrous pipelines located in the flood zone under evaluation?

- **Research Question 2:** Are there aged ferrous pipelines located in the flood zone under evaluation?
- **Research Question 3:** For the flood zone under evaluation, are there aged ferrous pipelines located in a potentially corrosive soil?
- **Research Question 4:** What is the flood risk to Austin's wastewater pipeline network?

The goal of this research is to quantify the number of components of the Austin wastewater system that are located in high-risk floodplains and vulnerable to fractures and breaks caused by corrosion through exposure to higher soil moisture content in soils with low resistivity, and, in addition, provide a highlight of at-risk pipe located in an environmentally sensitive area where leakage from a pipeline fracture could infiltrate groundwater with potentially deleterious effects. The objective is to create a preliminary model and methodological approach for the wastewater manager to analyze and prioritize wastewater pipeline replacement and repair, with a focus on the material type, type of the surrounding soil, and the location of the anticipated pipeline with respect to flooding risk.

CHAPTER 2: PREVIOUS RESEARCH

1. Literature Review

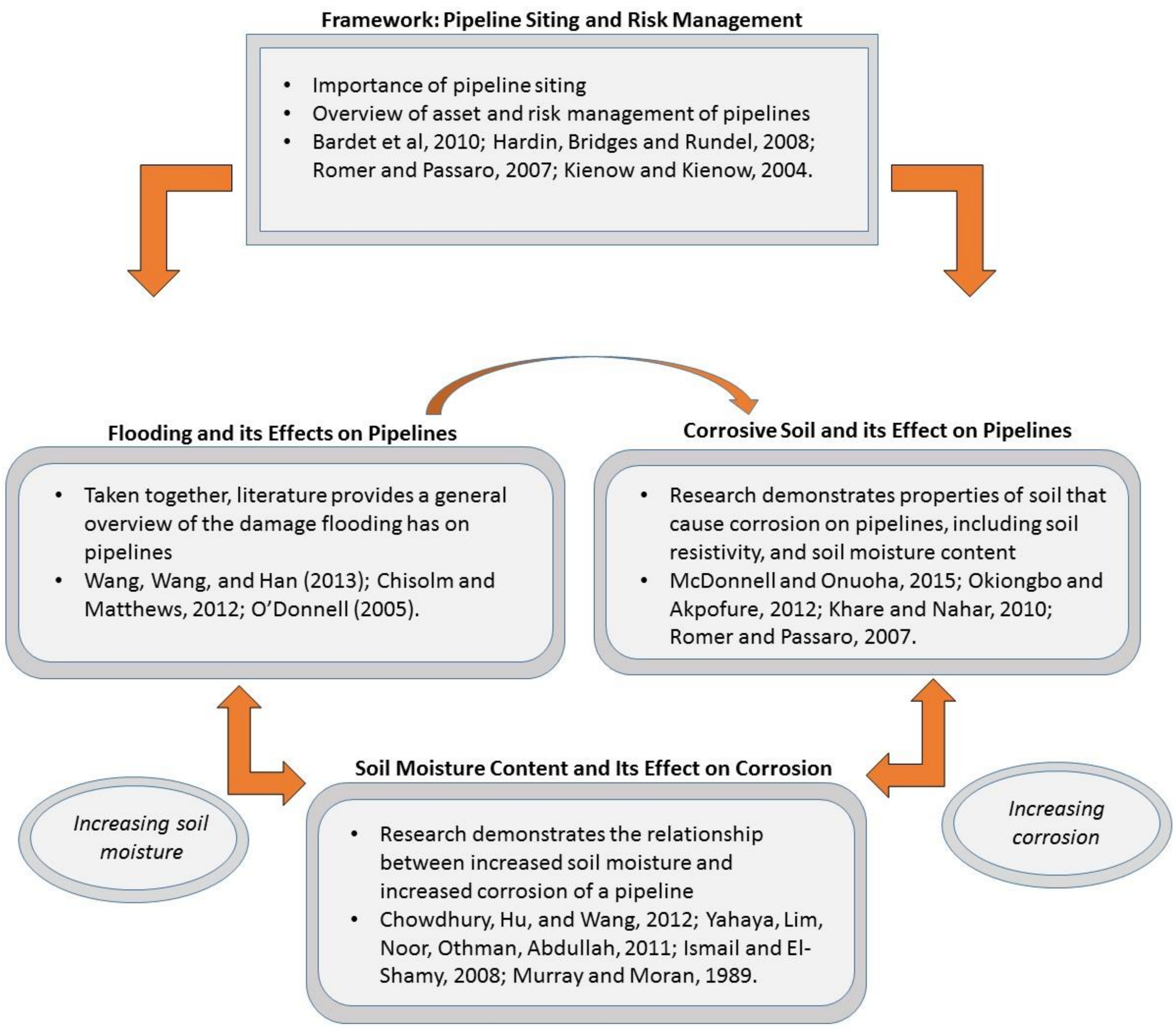

Figure 2: Existing literature

Given that this research endeavors to contextualize flooding, soils, and pipelines, the literature review drew from four distinct fields. Figure 2 above shows the relationship among the body of research, and demonstrates how it will be considered in this thesis.

Table 1. Literature review						
(1) Flooding and its Effects on Pipelines – The following studies demonstrate the effect of flooding events on pipelines. Together, the studies show a variety of manners in which flooding events can reduce the integrity of a pipeline.						
Researchers/ Year	**Title**	**Location and Time of Research**	**Tools Used**	**Area of Emphasis/ Issues Analyzed**	**Data Collected and Analysis Performed**	**Main Findings**
Wang, Wang, and Han, 2013.	Mechanical Response Analysis of Pipeline under the Action of Floods	China, 2013.	Static and quasi static mathematical model.	Mechanical behavior of pipes under flood and relationship to surrounding soil.	4 mechanical models under a strain-based safety assessment criteria.	Must consider impact of flood events to pipeline stress and interactions with surrounding soil.
Chisolm and Matthews, 2012.	Impacts of Hurricanes and Flooding on Buried Infrastructure	Louisiana and Mississippi, 2005 – 2012.	Interviews with water utility personnel, questionnaire studies.	New Orleans after Hurricane Katrina.	Systematic review of responses translated into analysis of network failures.	Flooding causing soils to become saturated, building shifts, breaks and fractures in pipe.
O'Donnell, 2005.	Investigation of Flood Induced Pipeline Failures on the Lower San Jacinto River	Harris County, Texas, 1994.	Computational analysis.	Failure of oil pipelines on the San Jacinto River (TX) after a major flood in October 1994.	Aerial photography showing changes in flood plain, oscillation of water current over pipe and soil.	Failure of pipelines due to fatigue of metal caused by oscillation of varying water current velocities and hydrodynamic loads flowing over pipeline.

(2) Corrosive Soil and its Effect on Pipelines – The following studies have analyzed the effects of soil on the integrity of a pipeline. The studies show that the resistivity of the surrounding soil is the most crucial component of determining the likelihood that corrosion will occur on the pipeline; one study (Khare and Nahar, 2010) in particular demonstrates that the increased presence of moisture contributes to increased likelihood of corrosion.

Researchers/ Year	**Title**	**Location and Time of Research**	**Tools Used**	**Area of Emphasis/ Issues Analyzed**	**Data Collected and Analysis Performed**	**Main Findings**
McDonnell and Onuoha, 2015.	Oil and Gas Pipeline Technology Finds Uses in the Water and Wastewater Industry	2015.	Case study of advanced inspection technology for water and wastewater pipelines.	Apply techniques learned from oil and gas industry to wastewater to protect from corrosion.	Applied different tests of corrosion to pipelines to improve outcomes and reduce costs.	Soil resistivity can give indication on corrosiveness.
Okiongbo and Akpofure, 2012.	Investigation of Soil Aggressiveness Toward Underground Fuel Storage Tanks and Water Pipelines in Parts of Bayelsa State, Southern Nigeria	Nigerian Delta, 2012.	25 Schlumberger Vertical Electrical Soundings and 1D inversion software.	Determining the corrosiveness of the soil to buried metallic structures in Baylesa State.	Some soils cause corrosion of buried cast/ductile iron water mains. Finer grained, easier conduction of current. Also depends on depth.	Design should mandate use of non-metallic piping product or cathodic protection system; predict potential corrosiveness of soil and apply appropriate measure.

Khare and Nahar, 2010.	Soil Aggressiveness Towards Buried Water Pipelines	Laboratory, Delhi, India, 2010.	Measurements of soil properties, physical observations.	Potential corrosiveness of soil validation using soil test parameters.	Applying a soil test method to tropical Indian conditions and corrosion in underground pipes.	Electrical resistivity found to be inversely proportional to moisture content of soil causing more corrosive environment.
(3) Soil Moisture and its Effect on Corrosion – The research below shows the effect of increased moisture on increased corrosion of a pipeline, focusing particularly on ferrous pipelines and the moisture in the surrounding soil.						
Researchers/ Year	**Title**	**Location and Time of Research**	**Tools Used**	**Area of Emphasis/ Issues Analyzed**	**Data Collected and Analysis Performed**	**Main Findings**
Chowdhury, Hu, and Wang, 2012.	Condition Evaluation of Asbestos Cement Water Mains	US and Canada, 2012.	Samples of asbestos cement pipe from U.S. and Canada, various methods used to examine condition.	Evaluating asbestos cement pipe for condition after testing.	155 samples of AC pipe visually inspected, physically and chemically tested.	AC pipes vulnerable in soils with high water content, and in high sulphate soils.
Yahaya, Lim, Noor, Othman, Abdullah, 2011.	Effects of Clay and Moisture Content on Soil-Corrosion Dynamic.	Malaysia, 2011.	160 pieces of steel installed underground in five location for 12 months, retrieved once	Effect of soil corrosion on buried underground structures.	Analyzed corrosion of different soils/locations on pipelines.	Rapid growth of corrosion correlated with high moisture content of soil as opposed to clay content.

			each 3 months to determine weight loss and corrosion growth rate.			
Ismail and El-Shamy, 2008.	Engineering behavior of soil materials on the corrosion of mild steel	Egypt, 2008.	Weight loss, soil texture, clay minerology, soil engineering.	Effect of different qualities of soil on pipeline corrosion and damage.	Unfavorable interaction between water and soil.	Increase in soil water content causes increased damage to surrounding pipelines.
Murray and Moran, 1989.	Influence of moisture on corrosion of pipeline steel in soils using in situ impedance spectroscopy	Laboratory study, 1984.	Electrochemical impedance spectroscopy (EIS).	Corrosion of steel pipes coated and exposed to clay and sandy loam soils in water-saturated and dry conditions.	Lab samples exposed to 9 wet/dry cycles over 1 year in two soil types: sandy loam and clay.	Corrosion rate of exposed steel increased with increased moisture content.

(4) Pipeline Siting and Risk Management – The following research demonstrates the importance of correct pipeline siting, particularly with respect to mitigating risk. The research also focuses on a variety of locales, including a location near the site of the research presented in this paper.

Researchers/ Year	**Title**	**Location and Time of Research**	**Tools Used**	**Area of Emphasis/ Issues Analyzed**	**Data Collected and Analysis Performed**	**Main Findings**
Bardet, Ballantyne, Bell, Donnellan, Foster, Fu, et al, 2010	LA Water Distribution System and Blowouts Report	Los Angeles, CA, 2009 – 2010.	Material sciences, geotechnical engineering, statistics and geo-statistics; measured pressure transients, remote sensing.	Water main breaks in LA in 2009. Discussion of different types of pipeline, small mention of cast iron & corrosive soil.	Breaks versus blowouts over period of time, location (geography and pressure zones), evaluated materials of pipes and age over system.	Avoid abrupt variations in water pressure, especially in corroded cast iron pipes. Steel pipes leak more per unit.
Hardin, Bridges and Rundel, 2008.	Selecting the Best Pipeline Route Based on Facts Not Feelings	Cedar Park, Leander, and Round Rock, TX, 2004.	Decision analysis software.	Route evaluation and selection process for a 78 inch diameter water pipeline in Brushy Creek, TX.	Evaluation of process for cost, construction, environmental impact, permits and easements.	Use quantifiable criteria and measurable data by assimilating data associated with competing impacts.

Romer and Passaro, 2007.	Risk Management of Pipeline Corrosion in the Water and Wastewater Industries	2006.	Review of risk management standards, 2006.	Reduce corrosion to improve public safety and health effect issues.	Review of standards and discussion of various ferrous pipelines susceptible to corrosion.	Risk assumed by utilities lie in assumption of life design extension of underground assets.
Kienow and Kienow, 2004.	Predicting Your Next Concrete Pipe Sewer Failure Before It Happens	2004.	Mathematical modeling given inputs of sulfide and corrosion.	Review of methods of employing sulfide and corrosion modeling.	Mathematical model used to determine priority of rehabilitation needed on pipelines.	Sulfide and corrosion modeling allows for improved sewer evaluation prioritization.

2. Gaps in Literature

A review of the previous research revealed several main gaps in the previous body of knowledge. First, within the literature review discussing flooding and its effect on pipelines, the research focuses on the more mechanical aspects of the pipeline-soil interaction. Wang, Wang, and Han (2013) analyze models under a mathematical flood strain assessment, and conclude that the relevant decision makers must consider the impact of flood events to the pipeline. While it is informative, a mathematical model may not be the most holistic consideration of flood events. Moreover, the mathematical model does not account for the *degree* of flood events, nor consider the flood event within the context of a pipeline network. The wastewater manager may not find it as desirable to avoid or mitigate a flood event that affects only 1% of their wastewater network as compared to a flood event that impacts 2% of their wastewater network. Similarly, O'Donnell (2005) provides a computational model overview after a flood event affecting oil and gas pipelines near Houston, Texas, while O'Donnell (2005) provides a holistic overview of a specific flood event and its impacts on the fracturing of oil and gas pipelines. However, like Wang, Wang, and Han (2013), O'Donnell (2005) does not provide any strategies for making a wastewater network more resilient, or mitigating it, but simply verifies his computational model of the mechanical stress of the flood event on the pipeline with the actual results. Chisolm and Matthews (2012) provide a comprehensive overview of flooding impacts on pipeline networks in recent post-hurricane environments, and while their paper provides extensive discussion of disaster resilience strategies, there is limited discussion of disaster avoidance – that is, ensuring that infrastructure is at low risk of facing the stress of flood events.

McDonnell and Onuoha (2015) provide an engineering-oriented overview of corrosion control strategies currently utilized in the oil and gas industry, and how those strategies could be applied to water and wastewater networks. Their study recognizes that data regarding soil properties are important to understanding the appropriate corrosion control measures, and also recognizes the need for water and wastewater industries to engage in corrosion control. Okiongbo and Akpofure (2012) state that the appropriate corrective action to prevent corrosion of water mains accounts for the degree of the corrosiveness of the soil, and establishes the relationship between aggressiveness of the surrounding soil and the corrosion; moreover, they recommend predicting potential corrosiveness of the soil and mandating the use of a non-metallic pipeline product or cathodic protection on soils that have been determined to be aggressively corrosive. However, to the wastewater manager, the benefit of replacing *all* ferrous pipelines in aggressive soils with non-ferrous pipelines may be far diminished by the cost of doing so, and the wastewater manager may desire a framework that identifies the most at-risk ferrous pipelines in corrosive soil in order to maximize the net benefit of, or to prioritize, replacement. Khare and Nahar (2010) investigated the soil aggressiveness toward buried water pipelines, and found that electrical resistivity was found to be inversely proportional to the moisture content of the soil, and thus that moisture contributes to a more corrosive environment toward the pipeline. Similarly, Murray and Moran (1989) found that increased soil moisture content was strongly correlated with increased corrosion of steel pipelines, but neither literature made any recommendations for the wastewater manager as to how to mitigate corrosion in light of this information.

Romer and Passaro (2007) go further, and recommend selecting a pipeline material responsive to *in situ* corrosive soil environments to reduce the probability of failure, and strongly recommend that pipeline operators be proactive about corrosion control. However, their recommendation to evaluate pipeline materials with respect to soil environments is limited only to a disaster resilient perspective of installing linings, anodes, or bagging in order to mitigate corrosion. In addition, Romer and Passaro (2007) do not evaluate the pipeline network as a whole in the framework that the wastewater manager faces. Yahaya et al. (2011) observe that soil moisture content has a significant effect on the corrosion of steel pipe, but do not provide a solution to mitigating corrosion. Ismail and El-Shamy (2009) establish that finer soil particles are more corrosive for steel pipeline, and that the presence of water is a prerequisite for corrosion cells, and do recommend that the soil be investigated and risk of corrosion be estimated before installing susceptible pipelines; again, however, the authors take a forward perspective of pipelines to be installed in the future, rather than a network perspective to assist the wastewater manager not only on a foregoing basis for new pipeline siting, but also on a retrospective basis to select which pipelines are most at risk and should be prioritized for replacement.

Bardet et al. (2009) provided a comprehensive, network-oriented overview of water system pipeline breaks in Los Angeles, and recommended that the city decision makers prioritize replacing cast iron water mains. While that paper analyzed a single summer of pipeline breaks, this thesis aims to provide a somewhat similar perspective for the Austin wastewater network on a more holistic scale. Very close to the area studied in this thesis, Hardin et al. (2008) provided a case study for selecting a pipeline route just north of Austin. Political, environmental, and economic criteria are considered in the model in terms of capital cost, pipeline length, mitigating impacts on an undisturbed preserve, and property lines, but ensuring a sound investment in terms of mitigating potential future damage to the capital investment – the pipeline – is not a consideration. In their discussion of concrete pipeline wastewater failure, Kienow and Kienow (2004) recommend that, given scarce resources, rehabilitative attention needs to be paid to wastewater pipelines at the greatest risk of failure, and they provide a corrosion model to support this prioritization. However, the model provided by Kienow and Kienow (2004) is limited to the internal corrosion by wastewater on the concrete pipeline, and does not discuss the effects of external corrosion by certain soil properties and how these can accelerate corrosion.

Finally, there is no unitive framework for understanding the soil – corrosion relationship with respect to pipeline siting. While some literature addresses some disaster resilient and disaster avoidant behavior such as better design standards and better adherence to higher design standards (Bianchetti and Perry, 2009), the literature does not discuss the consideration of preventing placement of ferrous pipelines in environments conducive to corrosion – such as soils with a high corrosion potential that are in a high-risk flood environment. The literature lacks a template for pipeline replacement with respect to corrosive soil environments. This thesis seeks to contribute to a robust, unitive framework for avoiding corrosion risk.

3. Background and Context

A. Asset Management

Corrosion is a risk the wastewater manager faces, and is a threat to healthy asset management; while corrosion control is a crucial component of asset management, it is not a well-established one, as observed by Bianchetti and Perry (2009). As noted by the National Association of Corrosion Engineers, the estimated cost of corrosion to the state of Texas (the state in which the location of this research takes place) is $4.60 billion to the water and wastewater industries. Across the United States, corrosion is most costly to water and wastewater systems, as shown in Figure 3 below:

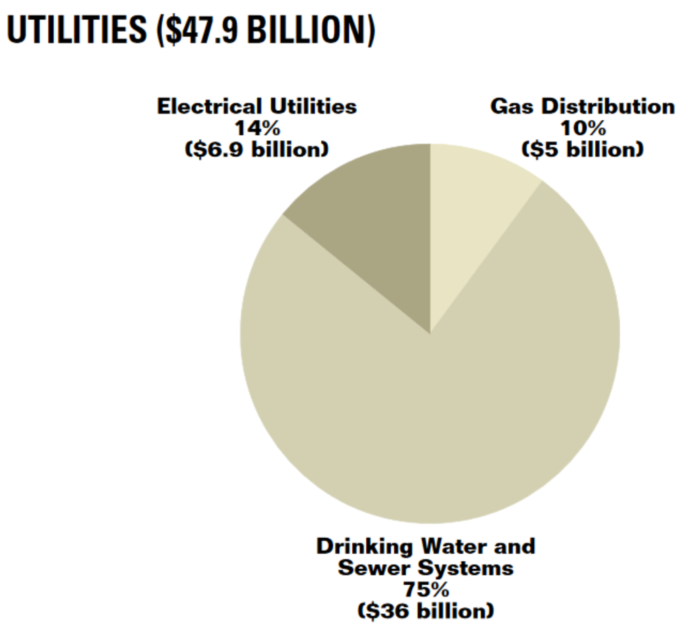

Figure 3: Cost of corrosion to utilities sector (source: National Association of Corrosion Engineers)

Though Austin Water Utility is municipally owned and therefore does not pay taxes, it must contribute a certain amount of its revenue to the City of Austin in what is called the “General Fund Transfer” and functions akin to a tax:

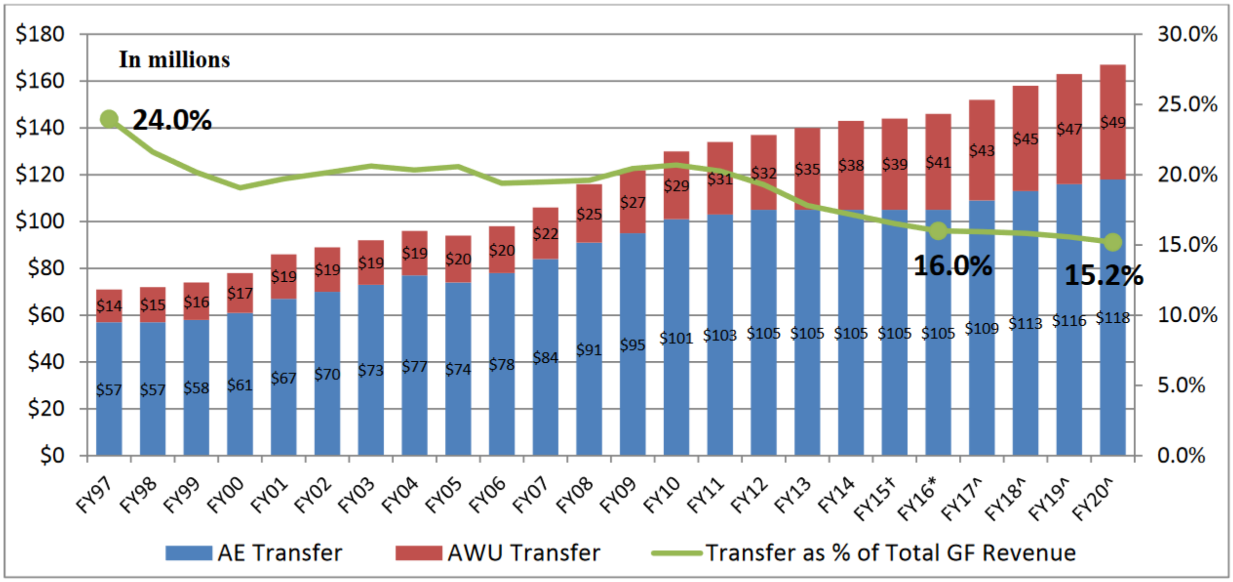

Figure 4: General Fund Transfer from Austin Water Utility (AWU) to the City of Austin (source: City of Austin, 2015-2016 Approved Budget)

Beginning in fiscal year 2012, the City of Austin set the General Fund Transfer for Austin Water Utility at 8.2% of average gross revenue. Austin Water Utility is a relatively modest share of total city expenditures at 12%:

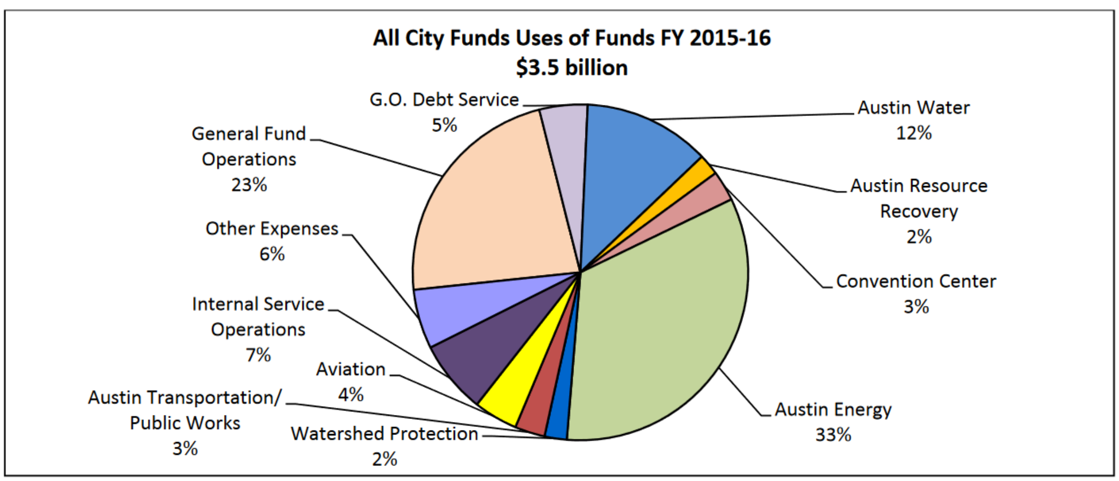

Figure 5: Total city expenditures as a percentage of operating budget (source: City of Austin, 2015-2016 Approved Budget)

For the 2015 – 2016 fiscal year, Austin Water Utility will have a budget of approximately $524 million, with the wastewater utility division claiming $238 million of that share. In the City of Austin's 2015 – 2016 Approved Budget, Austin Water lists its numerous goals for the utility: minimizing water loss, reducing customer service complaints, protecting the water supply and quality, protecting public health, maintaining a strong financial position, and optimizing life cycle cost. There are many competing needs and goals for the municipally owned utility, and only a limited amount of revenue from year to year.

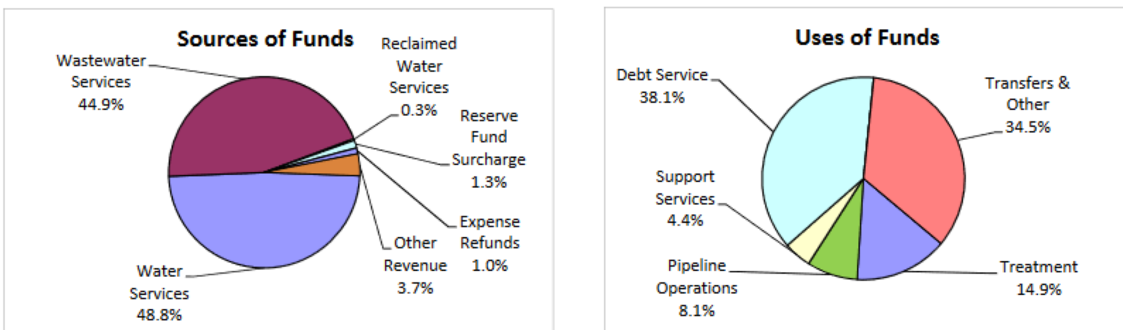

Figure 6: Total expenditures for Austin Water Utility as a percentage of a $524 million operating budget (source: City of Austin, 2015-2016 Approved Budget)

In addition, Austin Water Utility is engaging in a Capital Improvement Plan for the 2015 – 2016 fiscal year, which also sees competition for projects:

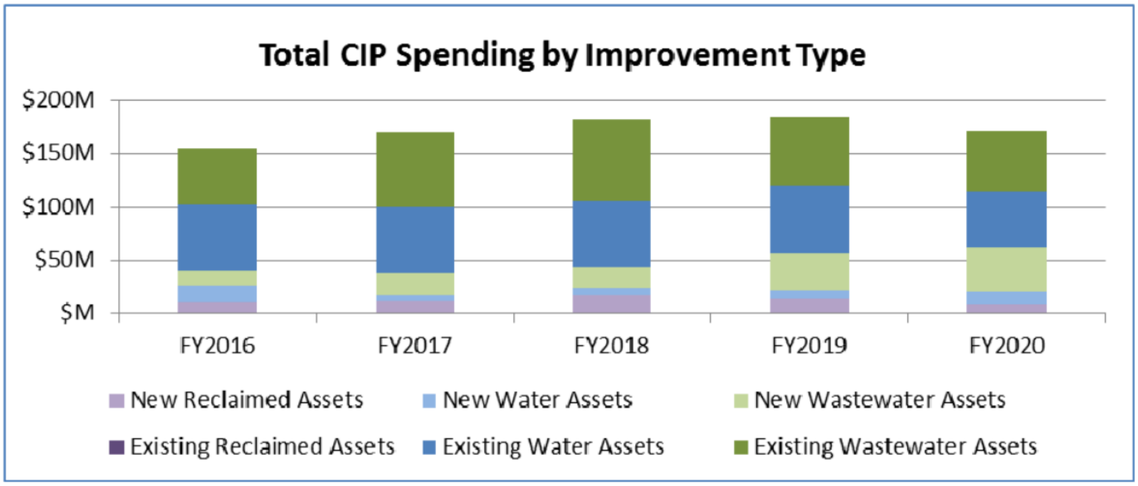

Figure 7: Spending on the Capital Improvement Plan for Austin Water Utility (source: City of Austin, 2015-2016 Approved Budget)

All of the goals listed above compete for the wastewater manager's budget, and reducing pipeline loss from corrosion can only assist in the latter three goals. Selectively upgrading pipelines based on the methodological approach here will only improve public health by minimizing the risk of wastewater entering groundwater, improve the financial position of the utility for the future by reducing pipeline loss to corrosion, and optimize the life cycle of assets. In addition, by strategically upgrading pipelines that are most at risk for failure, the municipal wastewater manager reduces the need to endure a lengthy and public process to raise its revenue through higher rates, which can result in an increase in complaints from citizen customers.

B. Wastewater Pipelines

Wastewater pipelines in particular were selected as an area of focus for this thesis due to the risk of environmental contamination from wastewater. Wastewater pipeline leaks can pollute both groundwater and surface water through recharge, as Standley et al. (2008) noted in one study that found steroidal hormones and pharmaceuticals in surface water, originating from wastewater. Fractures of the wastewater pipeline can also consequentially result in groundwater entering the wastewater system, diminishing the groundwater resource and causing the pipelines to overflow, which could easily enter local bodies of water (Chisolm and Matthews, 2012). The pollution of surface waters and groundwater is a particularly sensitive issue given the recharge zones of the Edwards

Aquifer in the Austin area, as well as the Colorado River which snakes through the center of Austin, as shown in Figure 8 below:

Figure 8: City of Austin, Texas municipal boundaries and environs (source: Google Maps)

The GIS data for Austin Water Utility shows over 70,000 wastewater main pipelines in its service territory. As ferrous materials are particularly susceptible to corrosion from the surrounding soil, this thesis isolated three ferrous materials from the wastewater network: ductile iron (DI), cast iron (CI), and steel. Previous research has demonstrated that corrosion occurs to concrete pipes, as well, but discussion has been limited to the internal corrosion from hydrogen sulfide and acidic wastewater (Zhaohui et al., 2003). Another paper discussed some internal and external corrosion effects from asbestos cement pipeline (Chowdhury et al., 2012); however, given the limited research on external corrosion of asbestos cement pipelines, this thesis focuses solely on ferrous pipelines. In addition, the Austin Water Utility GIS data showed a number of pipelines whose materials are categorized as "unknown". Out of an abundance of caution, this thesis included in its analysis the pipeline materials categorized as "unknown". Notably, a review of the Austin Water Utility GIS data determines that there are no wastewater pipelines categorized as consisting of steel. While steel will be discussed for purposes of a holistic review of ferrous wastewater pipelines, steel will not be directly included in the analysis of the Austin Water Utility wastewater network; it may be indirectly included through the analysis of the "unknown" pipeline materials, if any of those should be steel material.

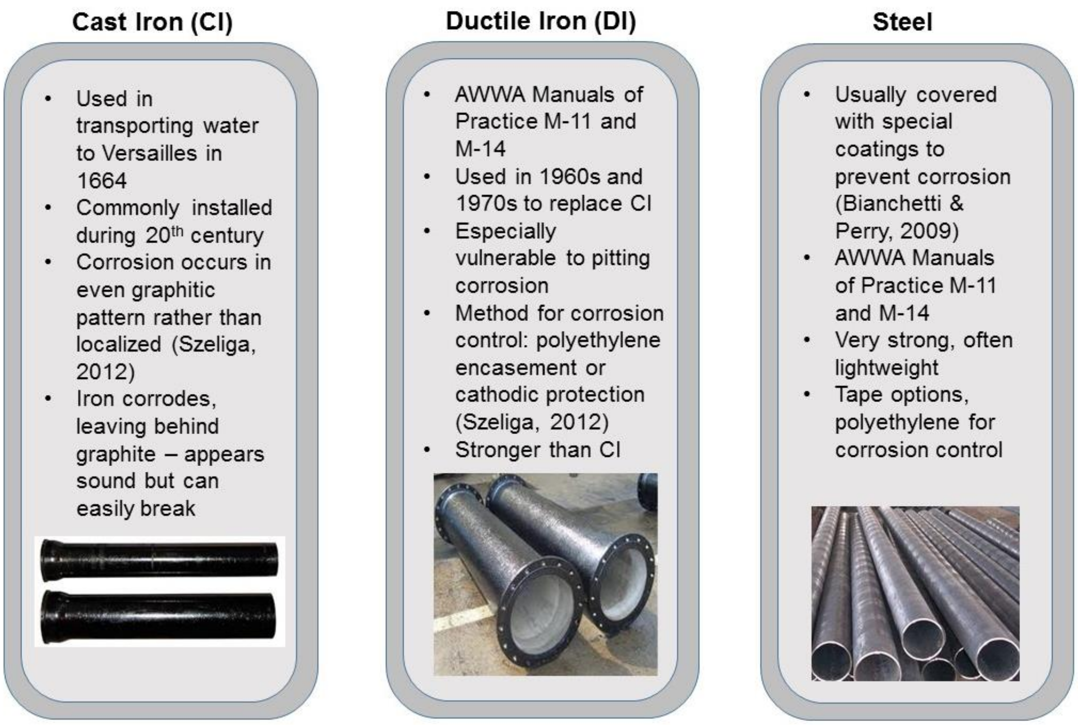

Figure 9: Overview of ferrous pipelines (Source: EngineeringToolbox, Ductile Iron Pipe Fittings, ERW Steel Pipe Company)

An important observation about cast iron and ductile iron pipes to note is that of corrosion patterns. Figure 10 below shows a detailed view of ductile and cast iron pipes. Due to its structure, ductile iron pipe is much more prone to "pitting" corrosion, and cast iron prone to "graphitic" corrosion, where the iron corrodes and leaves behind the graphite. The structures can be observed in Figure 10 below, where the cast iron tends to have increased degree of lateral matrices, and the ductile iron has small, round, localized points of weakness. While both graphitic and pitting corrosion are harmful to the pipe, graphitic corrosion occurs more evenly. A cast iron pipe experiencing graphitic corrosion will likely sustain a higher duration of corrosion before experiencing a break, whereas a ductile iron pipe will likely corrode around one node, potentially causing a hole or break at that location (Szeliga, 2012). However, when a cast iron pipe experiences sustained exposure to corrosion, it will likely fracture laterally and experience a significant break or collapse.

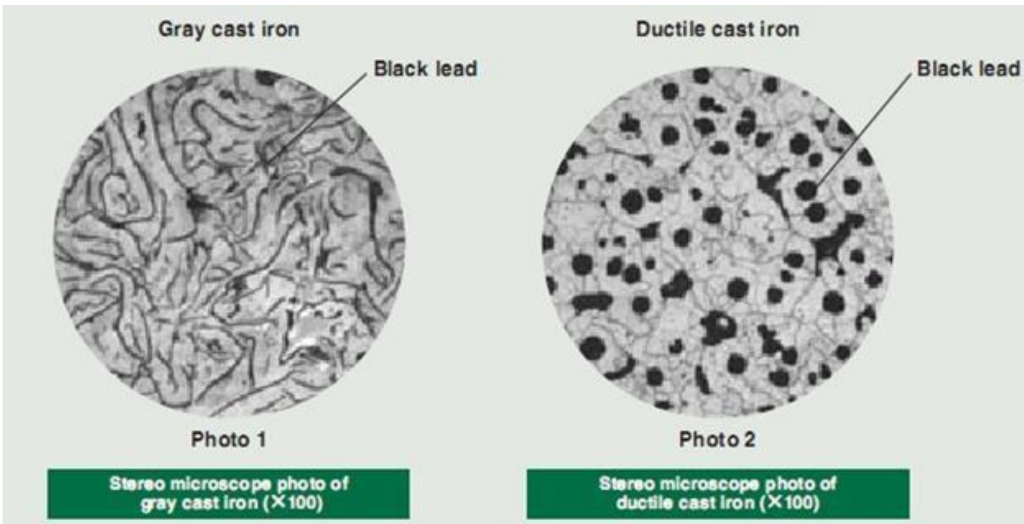

Figure 10: Ductile iron and cast iron pipe surface, microscope view at 100 magnification (source: Iron Foundry)

As discussed in Figure 9, there have been a number of attempts to mitigate the effects of external corrosion on ferrous pipelines, with varying degrees of success. First, bonded coatings have been applied to ductile iron. According to Szeliga (2012), for a time in the 1970s, bonded coatings for ductile iron became unavailable, and cathodic protection for uncoated ductile iron pipe became common, where the pipe size and soil resistivity made it feasible and cost-effective. Design criteria in the United States has mandated cathodic protection on oil and gas pipelines since the 1970s (Lary, 2000). Cathodic protection is a disaster hardening technique, essentially consisting of a "sacrificial anode" made of zinc or a similar material that is more easily corroded than the material of the pipe, in order to reduce the corrosion on the pipe material. However, cathodic protections require regular monitoring, whether in the field or more remotely, as the sacrificial anodes corrode. Another alternative to cathodic protection is polyethylene encasement of ductile iron pipe. The polyethylene is applied as a coat around the ductile iron pipe and prevents the pipe from coming into contact with the surrounding soil (DIPRA, 2000). However, Szeliga notes that polyethylene encasement reduces, but does not prevent, the corrosion of ductile iron pipe, and that pipes typically cannot be installed without some damage to the polyethylene coat. In addition, polyethylene is a plastic, and without additional protection, is not biodegradable, potentially resulting in environmental issues. To date, no corrosion control methodology for ferrous pipelines has been perfected.

Aged pipelines were chosen to assist in prioritization of ferrous wastewater pipeline replacement and assets that may be nearing the end of useful life. In addition, research by Bardet et al. (2010) analyzing a summer of record pipeline blowouts in Los Angeles suggests a significant increase in breaks and blowouts for pipes greater than 40 years old:

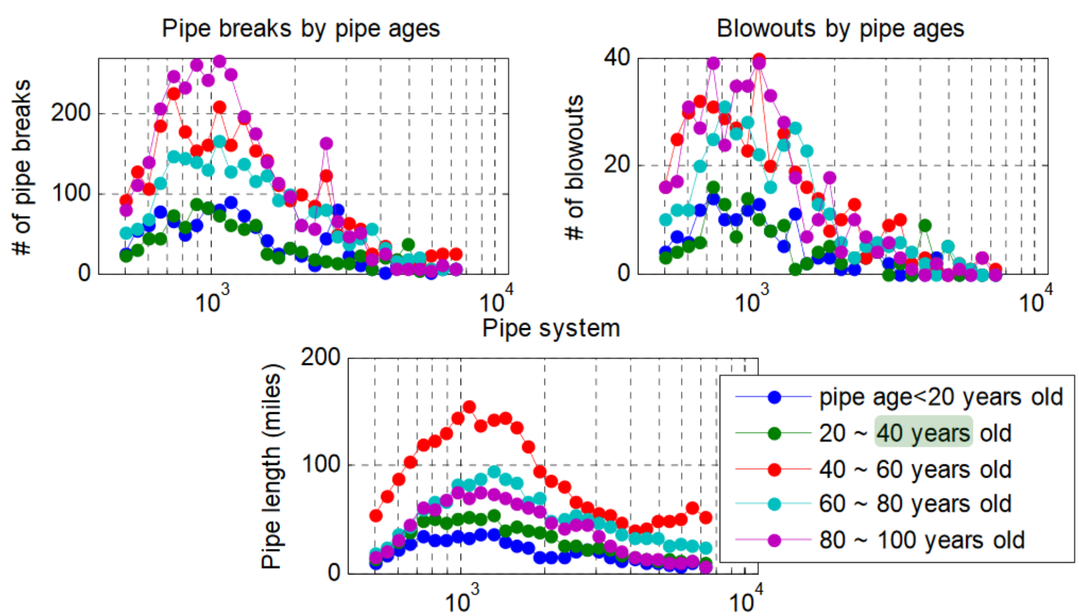

Figure 11: Pipe breaks by age and soil resistivity, with a higher value on the x-axis indicating increased soil resistivity in om-centimeters, and by extension decreased corrosion potential (source: Bardet et al., 2010)

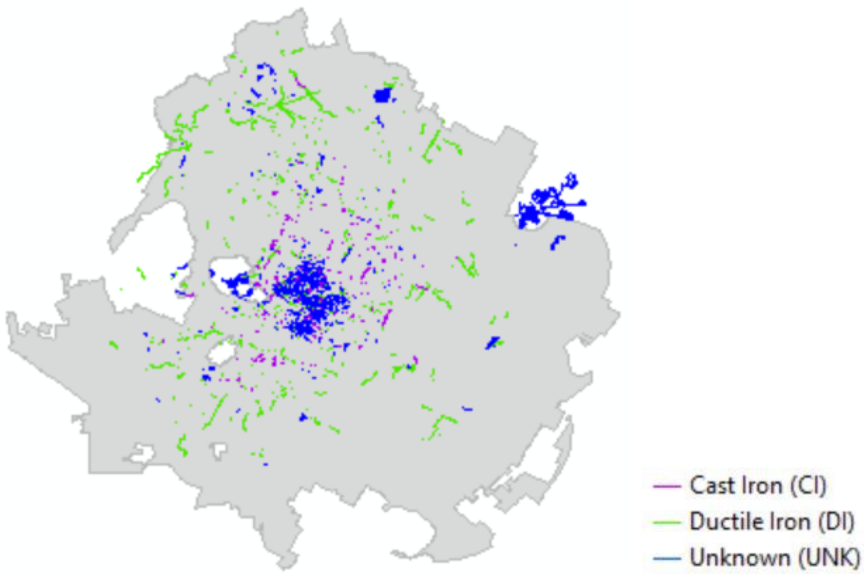

Figure 12: Ferrous wastewater mains overlaid on the Austin Water Utility service territory

While there may be a reasonable argument to isolate pipelines with higher flow rates as well, the economic cost of corrosion on the basis of pipe flow rate has not been well established in the existing literature. A larger corroded pit in a ductile iron pipe with a lower flow rate could result in larger wastewater leakage than a smaller corroded pit in a ductile iron pipe with a higher flow rate. Therefore, for purposes of this analysis, flow rate is not considered. Volume is, however, calculated as a proxy to potentially assist the wastewater manager in prioritizing the replacement of pipelines. In addition, such an analysis may also benefit from discriminating by pipe material. As discussed, cast iron pipe corrodes more evenly, and therefore, a higher flow rate pipe may be expected to suffer more corrosion and wastewater leakage than a lower rate pipe when the pipe fully corrodes. However, the same pattern may not be true for ductile iron pipes, which are much more prone to pitting or localized corroded spots. Future research could determine if there are methods appropriate for assessing the rate of corrosion on certain pipe materials in a given environment. In addition, future research could consider applying Tafel's law of corrosion to the framework presented here that accounts for soil and flooding dynamics.

C. Corrosion Potential

Per the National Association of Corrosion Engineers, corrosion is "a naturally occurring phenomenon commonly defined as the deterioration of a material (usually a metal) that results from a chemical or electrochemical reaction with its environment." With respect to pipelines, corrosion can occur in two forms: external, generally from the surrounding soil, and internally, from the materials and chemicals that travel through the pipeline. Both forms of corrosion reduce the efficiency of the pipeline. This thesis focuses only on external corrosion; that is, the corrosion of the pipeline's exterior. This external corrosion is caused by multiple factors present in the environment of the surrounding soil, as an extensive body of research has investigated, including soil resistivity, acidity (pH), chlorides, moisture, sulfates, redox, and stray current.

Bardet et al. (2010) found that breaks and blowouts in the Los Angeles Water System were most strongly correlated with a combination of the effects of soil conductivity to corrosion and pipe age, concluding that the longer a pipe is exposed to corrosive soils, the more likely it is to break. Many factors contribute to corrosion and it is a complex science.

External corrosion to a pipeline occurs as a result of the properties of the surrounding soil. Ferrous pipelines are, by definition, comprised of metal. Given certain properties of the surrounding soil environment, an electrical cell is created. Soil varies by "resistivity", or how resistant it is to a flow of electrical current. A higher resistivity in the surrounding soil translates to an increased *resistance* to an electrical current, resulting in less corrosion to a ferrous pipeline. By contrast, a *lower* soil resistivity results in *increased* corrosion to a ferrous pipeline, all other factors being equal. Any property that affects the electrical current of the surrounding soil will affect the corrosion on a pipeline. For example, water increases the electrical conductivity of a soil environment that is in the presence of iron, causing iron to disintegrate into iron oxide, or rust.

Taken as a whole, the research seems to agree that soil moisture content and soil resistivity are two of the most crucial soil properties factoring into the likelihood of corrosion of ferrous pipelines. In addition, while it is not an exact measurement of the corrosion potential, certain soil types are more likely to possess properties that facilitate corrosion than others, such as decreased soil resistivity. Silts and clays tend to have the lowest soil resistivity, all other things being equal in the soil environment, with silts being measured at a resistivity of 1,000 – 2000 Ω-centimeters, and clays being measured at resistivity of 500 to 2,000 Ω-centimeters (Cunat, 2002).

Table 3: Soil resistivity by soil type in ohm-cm (source: Cunat, 2002)

Type of Soil	Physical Properties (Particle size, plasticity, moisture, ...)	Chemical Composition (Main constituents and contaminants)	Resistivity (Ω · cm)
Sand	Particle sizes: Fine : 0.02 / 0.06 mm Medium : 0.06 / 0.2 mm Coarse : 0.2 / 0.6mm Good drainage	SiO_2, ...	10,000 to 500,000
Gravel	Particle sizes: Fine : 2 / 6 mm Medium : 6 / 20 mm Coarse : 20 / 60 mm Excellent drainage	SiO_2, ...	20,000 to 400,000
Loam	Plastic mixture High moisture	SiO_2, Al_2O_3, ... Dissolved species: H^+, Cl^-, SO_4^{2-}, HCO^-_3, ...	3,000 to 20,000
Clay	Very plastic mixture High moisture	SiO_2, Al_2O_3, ... Dissolved species: H^+, Cl^-, SO_4^{2-}, HCO^-_3,	500 to 2,000
Silt	Coarse clay High moisture	SiO_2, Al_2O_3, ... Dissolved species: H^+, Cl^-, SO_4^{2-}, HCO^-_3,	1,000 to 2,000

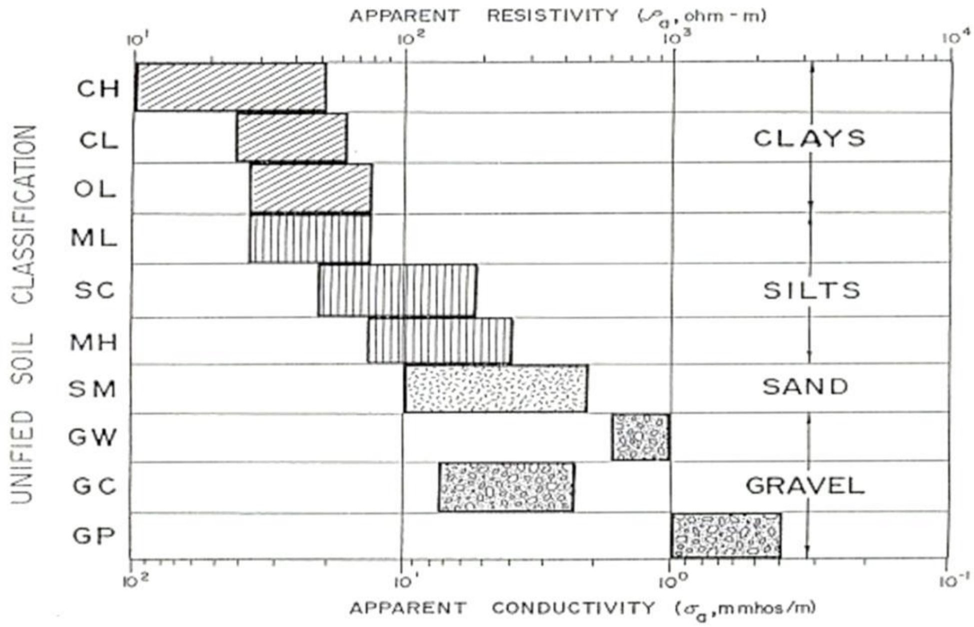

Figure 13: Soil resistivity in ohm-meters by soil classification (source: Recorder)

Therefore, regarding the corrosion potential of surrounding soil on pipeline, this analysis focuses on the relatively more corrosive soils, clays and silts, which are isolated in this thesis.

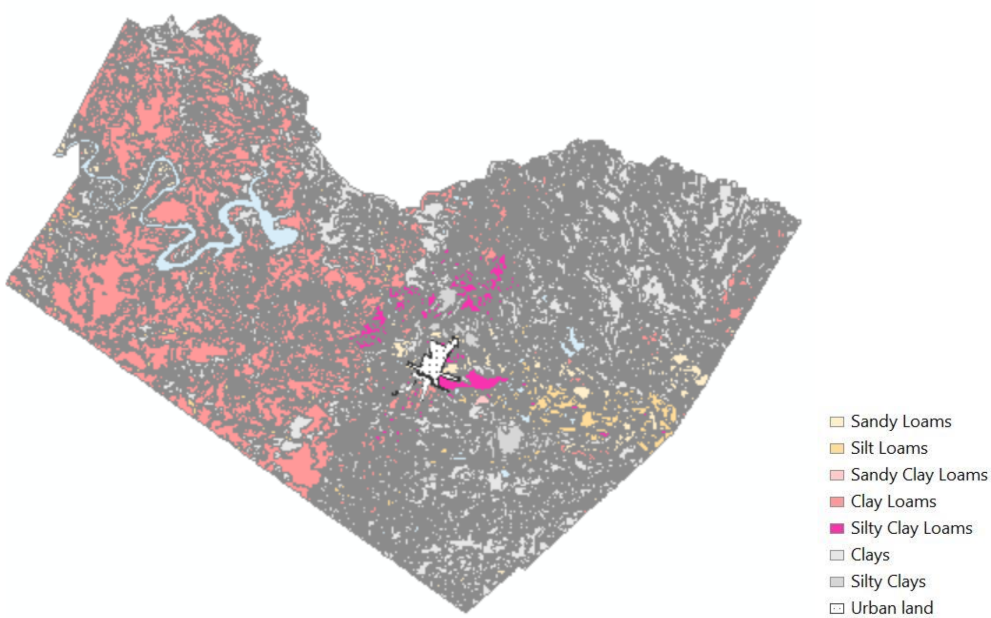

Figure 14: Soil Profile of Travis County (source: USGS, 2016)

Figure 14 shows a soil profile of Travis County, in which the City of Austin is located. This soil profile is utilized in this thesis. The western portion of Travis County is primarily dominated by sandy clay loams, and the eastern dominated by silty clays and clays. The demarcation appears to be consistent with the Balcones Fault, the boundary between the Edwards Plateau on the western side of Travis County, and the Blackland Prairie to the east. The land around the Colorado River on the eastern side of the county is predominantly silt loams and sandy loams.

D. Flooding Risk

Austin has a storied flooding history. Lightning may seldom strike in the same place twice, but landmark flood events do not seem bound by the same axiom. Around the end of October in both 2013 and 2015, there was historic flooding of Onion Creek, a residential neighborhood sited on the eponymous creek 10 miles south of the Colorado River. The 2013 "Halloween flood" of Onion Creek saw floodwaters rise 22 feet in 3 hours, eventually cresting more than 40 feet; more than 660 structures were destroyed. The second "Halloween flood" of Onion Creek just two years later, combined with the earlier flood, was so devastating that it resulted in displaced residents and city-initiated buyouts of homes. In the 2015 Halloween flood, storm water over flooded the wastewater system and wastewater surged out of a manhole. Another unique flood anniversary is the "Memorial Day Flood" of both 2015 and 1981. The Memorial Day Flood of 1981 cost 13 lives and damages of $35.5 million; its 2015 twin was so historic the Blanco River southeast of Travis County rose to a new record over 44 feet and Shoal Creek, part of which is shown in Figure 15 below, reached its 1981 flood peak.

Figure 15: Floodwaters at 9th and Lamar Streets on the 2015 Memorial Day Flood, Austin, Texas (source: Jorge Sanhueza-Lyon/KUT)

Figure 16: The 1981 Memorial Day Flood at Whole Foods Market (source: Bob Daemmrich/American-Statesman)

Figure 17: The Onion Creek flood of 2013 (source: AP Photo/Tamir Kalifa)

Historic and reoccurring major flood events are a reality in Austin. These major flood events have caused significant damages to infrastructure and structures aboveground, and this thesis seeks to examine the potential effects of these more historic, high-risk floods on infrastructure belowground. Chisolm and Matthews (2012) investigated the effects of flooding upon the water and wastewater systems in New Orleans after Hurricanes Katrina and Rita, hurricanes that resulted in major flood events. The authors discuss how the flooding associated with the hurricane caused major ground shifts, and then fractures in the wastewater infrastructure. They also noted that aged cast iron pipes were particularly at risk for fractures due to extensive corrosion from the surrounding soil, which then absorbed water from the flood, resulting in pipeline breaks from ground shifts. In addition, flooding – especially repeated floods in the same site – causes an increase in soil moisture, which increases the corrosion potential of the surrounding soil environment, stressing the ferrous pipeline and potentially resulting in a fracture.

The Federal Emergency Management Agency (FEMA) defines a flood as “a general and temporary condition of partial or complete inundation of normally dry land areas from: (1) The overflow of inland or tidal waters; (2) The unusual and rapid accumulation or runoff of surface waters from any source; (3) Mudslides (i.e., mudflows) which are proximately caused by flooding and are akin to a river of liquid and flowing mud on the surfaces of normally dry land areas, as when earth is carried by a current of water and deposited along the path of the current." FEMA further notes that "a flood inundates a floodplain". Therefore, in a flood event, the soil is oversaturated with water, causing the water to inundate dry land surface.

To provide a guide for flood insurance, FEMA creates a Flood Insurance Rate Map (FIRM) on a community-wide basis. FIRMs are colloquially called "flood maps", and show the risk of flooding in a community on a zonal basis. In developing FIRMs, FEMA considers hydrology, infrastructure, hydraulics, land use, and existing maps. The figure below shows the flood zones for Travis County, the location of this research:

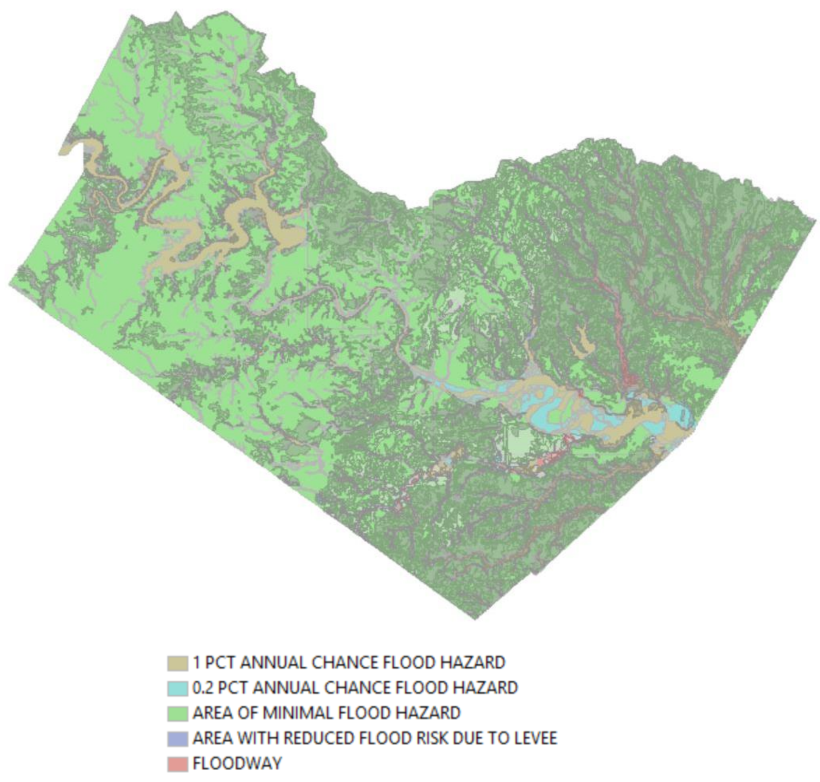

Figure 18: FEMA Flood Insurance Rate Maps (FIRM) for Travis County (source: FEMA, 2016)

As shown above, there are several different categories of flood risk. These categories of flood risk are grouped into zones defined by FEMA. For Travis County, the zones are:

- **Zone A**: Commonly called the "100-year flood", or a 1% annual chance of such a flood event. This is the base floodplain – defined as the 100-year flood – mapped by approximate methods. There are six categories within Zone A, two of which are in Travis County:
  - **Zone AE**: Considered a subpart of the Zone A category, this zone is the base floodplain where base flood elevations are provided. In the figure shown above, some portions of Zone AE are marked as "floodways", or the channel of a river and the adjacent land areas reserved to discharge the base flood.
  - **Zone AO**: Considered another subpart of the Zone A category, this zone is an area that is at risk of a 1% annual chance of "shallow flooding" where average depths are one to three feet, generally as a result of man-made runoff.
- **Zone X (shaded)**: The "100-500 year flood", or a 1% to 0.2% annual chance of a flood event. Zone X also contains the areas marked "Reduced Flood Risk due to Levee" in the figure above.
- **Zone X (unshaded)**: Flood events that occur at a probability less than 0.2% per year.

E. The Edwards Aquifer Recharge Zone

Finally, this thesis also seeks to examine the possibility that there are at-risk wastewater pipelines in the Austin Water Utility that could also pose an environmental risk to the Edwards Aquifer Recharge Zone were these pipes to break or leak from corrosion through flooding. The Edwards Aquifer Recharge Zone stretches across multiple counties for 1,250 square miles. Figure 19 shows the environs of Austin that contribute to the Edwards Aquifer:

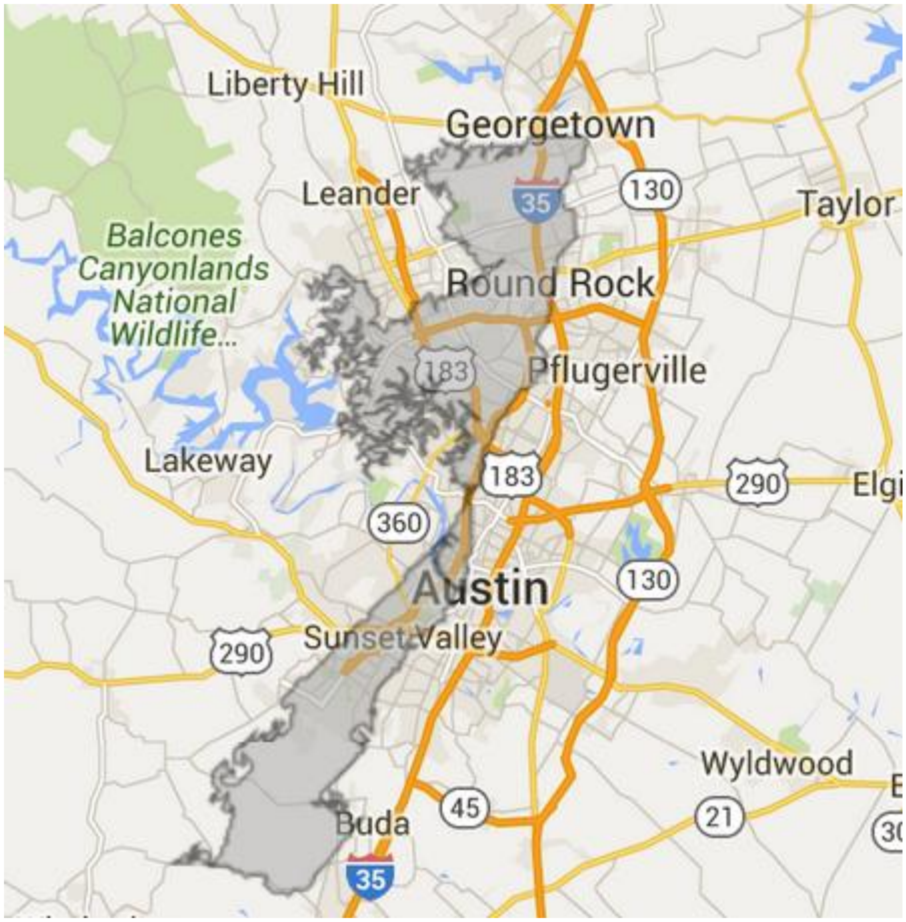

Figure 19: The contribution of Austin and its environs to the Edwards Aquifer recharge zone (source: City of Austin)

The Edwards Aquifer is a layer of water-bearing rock, and its recharge zone is the area where faulted and fracture limestones interface with the land surface, and water from the recharge zone flows down into the Edwards Aquifer itself.

CHAPTER 3: RESEARCH DESIGN

1. Overview of Methodology

A. Research Goals and Questions

This research is categorized into four parts, as demonstrated in the figure below:

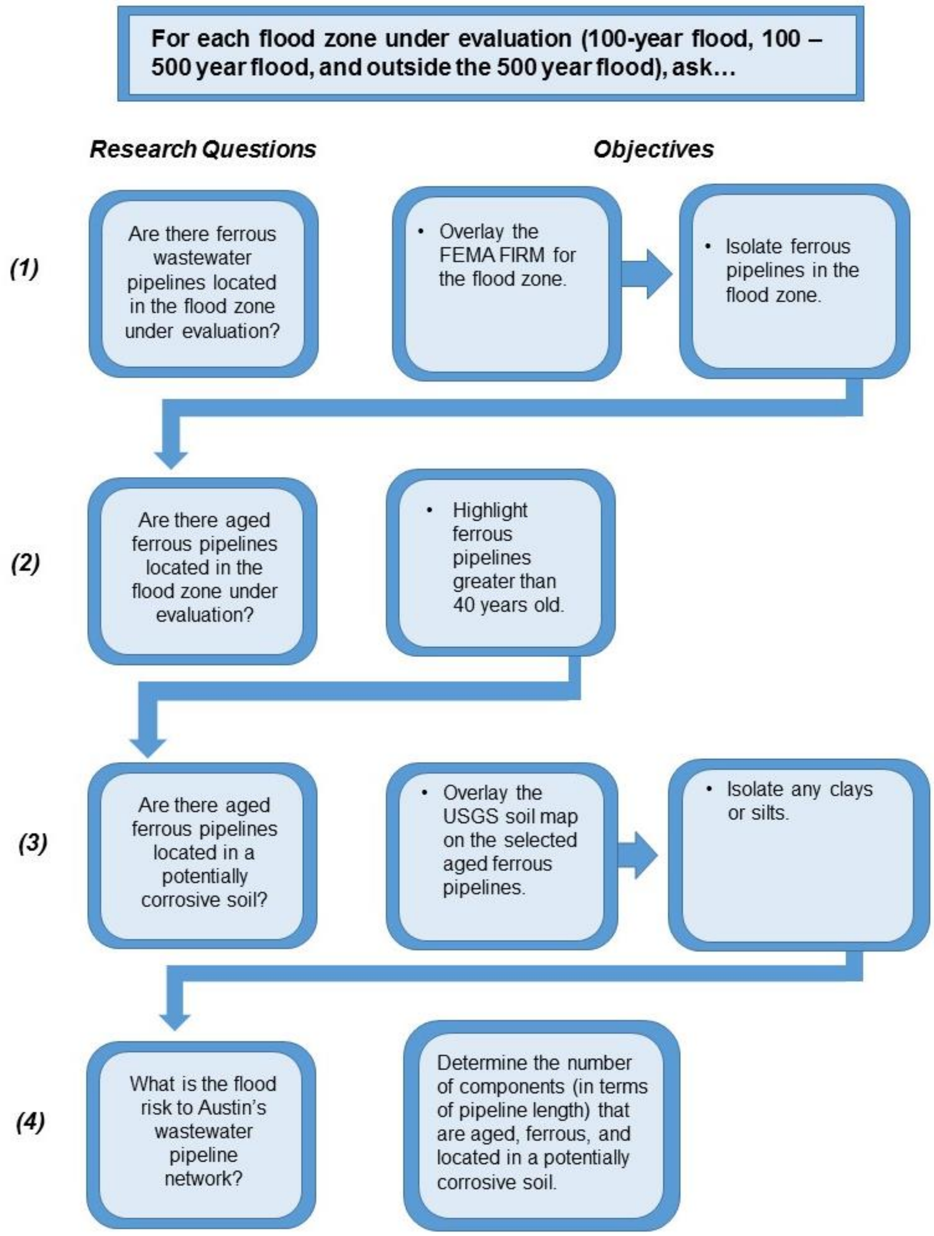

Figure 20: Research questions and objectives

Figure 20 demonstrates the relationship between the research questions and objectives, as the research seeks to unify each aspect of the analysis (flood zones, aged ferrous wastewater pipelines, and corrosive soils) by contextualizing each component in relationship to each other. The research questions and objectives are further discussed below:

- **Research Question 1**: Are there ferrous pipelines located in the flood zone under evaluation?
    - ***Objective*****:** Overlay the FEMA FIRM for the flood zone under evaluation (the High Risk or 100 year floodplain, Moderate Risk or the 100 – 500 year floodplain, and Low Risk flood zone or areas outside the 500 year flood plain) with the Austin Water Utility wastewater network. Isolate ferrous pipelines in the flood zone.

Prior to positing this series of research questions, a flood zone will be selected: the 100-year floodplain ("High Risk"), the moderate risk 100 – 500 year floodplain ("Moderate Risk"), and the areas outside the 500 year floodplain ("Low Risk"). The series of four research questions will be answered for each of the three flood zones. The purpose of this question is to examine the pipelines within the flood zone under evaluation and determine if that flood zone has any ferrous pipelines contained within it.

- **Research Question 2:** Are there aged ferrous pipelines located in the flood zone under evaluation?
    - ***Objective:*** For the flood zone under evaluation, highlight ferrous pipelines greater than 40 years old.

The purpose of this research question is to determine if there are any *aged* ferrous pipelines in the flood zone under consideration. For the purposes of this study, aged is defined as greater than 40 years old. Aged pipelines will be highlighted from among the ferrous pipelines that are in the flood zone under evaluation.

- **Research Question 3:** For the flood zone under evaluation, are there aged ferrous pipelines located in a potentially corrosive soil?
    - ***Objective:*** Overlay the USGS soil map for Travis County on the selected aged ferrous pipelines for the flood zone under evaluation and isolate any clays and silts.

The purpose of this research question is to determine if the selected aged ferrous wastewater pipelines in a flood zone are also located in any corrosive soil environments: clays and silty clays. The USGS soil map for Travis County will be overlaid on the selected pipelines from Research Question 2 and aged pipelines in corrosive soils selected and isolated.

- **Research Question 4:** What is the flood risk to Austin's wastewater pipeline network?
    - ***Objective:*** Determine the number of components (in terms of pipeline length and volume) that are aged, ferrous, and located in a potentially corrosive soil for that FIRM flood zone category.

The purpose of this research question is to determine the final level of risk exposure to present to the wastewater manager. The risk exposure of the wastewater pipeline network for that flood zone will be measured by the number of components, in terms of length, that meet the criteria outlined in the objective above: aged, ferrous, and located in a potentially corrosive soil. After concluding the review of all three of the flood zones, the length and volume of pipeline exposed to the risk of corrosion through flooding will be calculated. In addition, at-risk wastewater pipeline in the High Risk flood zone and in the Edwards Aquifer recharge zone will be identified and the length and volume of the pipeline at risk in the recharge zone calculated.

B. Hypothesis

The hypothesis aids with the organization of research methods and creates an aim for the thesis. This thesis constructs its hypothesis based on the research questions outlined above. This thesis assumes that:

- There is more than one flood zone for the Austin Water Utility service area;
- There are ferrous pipelines in Austin Water Utility's wastewater network;
- There are aged ferrous pipelines in Austin Water Utility's wastewater network located in a high-risk flood zone;
- There are corrosive soils located around the aged ferrous pipelines; and that
- There are corrosive soils located around the aged ferrous pipelines in a high-risk flood zone.

The hypothesis of this thesis is that there are wastewater pipelines in the Austin Water Utility network greater than 40 years old, comprised of a ferrous material, that are in a soil corrosive to that material, in a high-risk flood zone in Austin.

C. Methodology

To complete the objectives outlined above and answer the research questions posited in order to test the hypothesis, the following methodological approach will be used (see Figure 21):

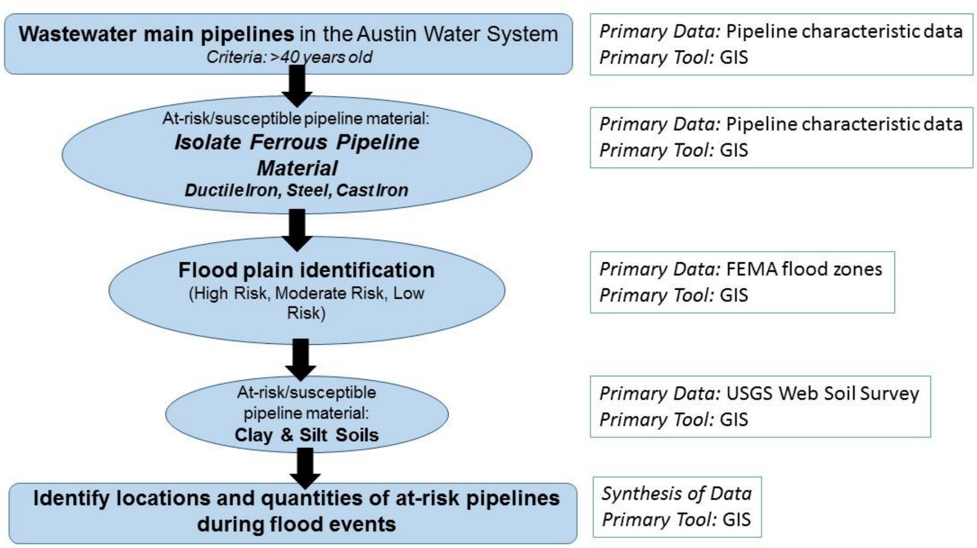

Figure 21: Methodological approach

The methodological approach will be carried out through the following steps:

Step 1: Isolate ferrous wastewater pipelines in the Austin Water Utility network: ductile iron, cast iron, and steel. In addition, isolate "unknown" wastewater pipelines for this analysis.

The methodology begins with narrowing the scope of the wastewater infrastructure network to ferrous pipelines, as discussed above. The ductile iron, cast iron, and steel pipelines are isolated in the Austin Water Utility GIS data, so that only those ferrous pipelines could be overlaid on soil and floodplain maps. Notably, Austin Water Utility GIS data did not record any entries for pipelines made from a steel material. In addition to these ferrous pipelines, to ensure the broadest scope of this data, pipelines that are categorized within the Austin Water Utility GIS tables with "unknown" materials are included in this analysis as well. Therefore, all wastewater mains pipelines that are categorized as "unknown" are treated as ferrous pipelines for the purposes of this thesis.

Step 2: Overlay the FEMA Flood Insurance Rate Map (FIRM) on the layer created in Step 1.

The FEMA FIRMs are downloaded in the form of GIS data from the FEMA website. The FIRMs are on a county-wide basis, so the FIRM for Travis County, Texas, in which the city of Austin is located, was downloaded.

First, the FIRM panels were transformed into the parameters and coordinates of the of the Austin Water Utility GIS data. After the FIRM GIS data was loaded, the spatial file with location information representing the flood zones where incorporated into the GIS map. There were four categories for Travis County: Zone A, Zone AE, Zone AO, Zone X (0.2% annual chance of a flood event, referred to by FEMA as "Zone X Shaded") and Zone X (area of minimal flood risk, referred to by FEMA as "Zone X Unshaded"). For purposes of this analysis, all flood zones under "Zone A" (Zone AE and Zone AO) were considered as one group under the "Zone A" flood zone, as this analysis is focused on risk: defined by the 100-year floodplain, rather than the evolving history of flood zone changes or measured versus estimated base flood elevation. Therefore, the other Zone A subcategories in the Travis County FEMA data, Zone AE and Zone AO, were combined with Zone A. The combined Zone A is referred to as the "High Risk" flood zone for purposes of this thesis.

In addition, the FEMA GIS data for Zone X had to be further analyzed; while FEMA utilizes the term "Zone X Shaded" to refer to the 0.2% annual chance of a flood event or the "500-year flood" and the term "Zone X Unshaded" to refer to an area with a risk less than 0.2% of a flood event, this distinction was not made in its GIS data, and instead, in its category specifying flood zones, grouped both zones together under the label "Zone X". However, FEMA GIS data had an additional category further describing each Zone X flood zones. In this additional category, Zone X flood zones were labeled as either "area of minimal flood hazard" or "0.2% annual chance of flood hazard" in this additional category. These category descriptions were used to separate flood zones "Zone X (shaded)" and "Zone X (unshaded)", as these labels were consistent with FEMA's definitions of "Zone X (shaded)" and "Zone X (unshaded)". For ease, this thesis refers to the "0.2% annual chance of flood hazard" component of Zone X as the "Moderate Risk Flood Zone", as it marks the probability of the "500-year flood" event, and refers to the "Zone X (unshaded)" flood zone for areas of minimal flood hazard as simply the "Low Risk Flood Zone". In sum, this thesis analyzed three flood zone categories on the basis of risk: the 100-year flood in the "High Risk Flood Zone", the 100 – 500 year flood in the "Moderate Risk Flood Zone" and the areas outside the 100- and 500-year floodplains in the "Low Risk Flood Zone".

Figure 22 shows the FEMA flood zone categories for Travis County:

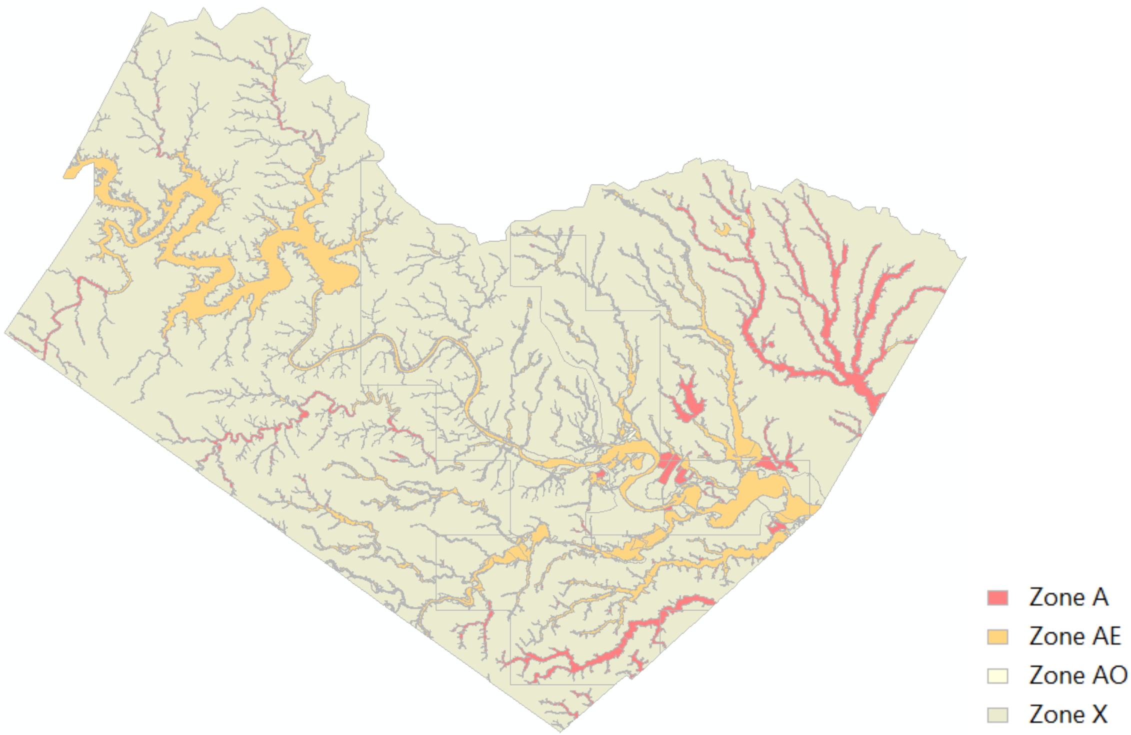

Figure 22: Flood zones for Travis County (source: FEMA)

Figure 23 shows the FEMA GIS data for Travis County after Zone A, Zone AE, and Zone AO have been combined, and the Zone X (0.2% annual chance of a flood event) and Zone X (area of minimal flood hazard) have been segregated out. This revised FIRM will be used for this analysis.

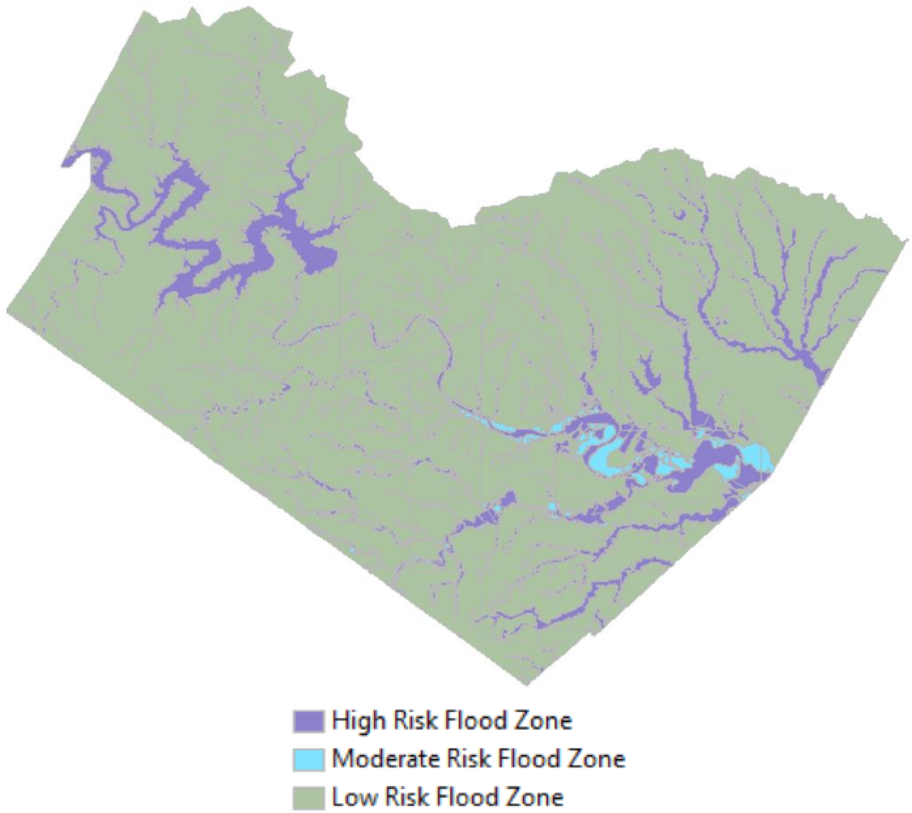

Figure 23: Revised FEMA flood zones for Travis County (source: FEMA)

Step 3: Evaluate the High Risk zone (100 year flood or 0.1% annual chance flood event).

The purpose of this step is to evaluate one flood zone in isolation. As discussed in Step 2 above, all categories within Zone A were combined for purposes of this analysis to arrive at information based on risk – that is, a 0.1% annual chance of a flood event, for example – rather than the history of the floodplain designation, and are considered to be the High Risk flood zone.

Step 4: Clip map to only show the High Risk flood zone overlaying the isolated ferrous wastewater infrastructure.

The purpose of this step is to isolate the flood zone under evaluation – the High Risk flood zone – and overlay it on the previously isolated ferrous wastewater pipelines from Step 1.

Step 5: Select ferrous wastewater pipelines aged greater than 40 years, and create a new layer with only aged ferrous wastewater pipelines.

In this step, ferrous wastewater pipelines in the flood zone under evaluation greater than 40 years old are selected and a new layer created, in order to determine the ferrous pipelines in the flood zone under evaluation. As Austin Water Utility GIS data for the year the pipeline was installed is largely incomplete, the "year proposed" category, which was more complete, was instead used to calculate age as of the publication of this research. As pipelines are proposed prior to installation, this will result in a more conservative estimate of age. Where there is no data for the year the pipeline was proposed, this thesis assumes that such pipelines are also aged.

Step 6: Categorize the USGS soil data for Travis County.

The United States Geographic Survey (USGS) Web Soil Survey for Travis County was downloaded into GIS. Within the USGS Web Soil Survey Data was a Microsoft Access Database containing more specific information. From the database, the field "mukey", a numerical key unique to each soil series and used to join tabular data and spatial data, was joined to "musym" (a short text value used to denote a soil strata), based on "mukey", creating the new field "muname" within the USGS GIS data, which translates the "mukey" into broader categories of about 50 strata of soil. First, strata not relevant to the scope of this thesis were removed: "pits, gravel", "quarry", "misc water", and "cut and fill land". These strata were a very small component of the total soil strata. Second, the remaining strata were further simplified for the purpose of this research into eight categories: sandy loams, silt loams, sandy clay loams, clay loams, silty clay loams, clays, silty clays, and urban land. The figures below show the classification of the soil strata given in "muname" into the eight larger categories. The soils were classified into these categories using descriptions from the Travis County Soil Survey, where the pedon, or the smallest component of soil that can be recognized, fell into one of these categories. Where strata were classified as a soil type and urban land, that soil type was classified into the larger category. The following figures below show the classification of the USGS Web Soil Survey soil strata into the seven larger soil categories:

Sandy Loams

- Chaney fine sandy loam, 1-2% slopes
- Chaney fine sandy loam, 2-5% slopes, moderately eroded
- Crockett soils, 2-5% slopes, eroded
- Fett gravelly soils, 1-4% slopes
- Gaddy loamy fine sand, 0-1% slopes, frequently flooded
- Gaddy soils and Urban land, 0-1% slopes, occasionally flooded
- Hardeman soils and Urban land, 3-12% slopes
- Hardeman fine sandy loam, 2-5% slopes
- Hardeman fine sandy loam, 5-12% slopes
- Heaton loamy fine sand, 0-2% slopes
- Hornsby gravelly loamy sand, 1-5% slopes
- Orif soils, 0-1% slopes, frequently flooded
- Pedernales fine sandy loam, 1-5% slopes
- Pedernales fine sandy loam, 5-8% slopes, moderately eroded
- Travis soils and urban land, 1-8% slopes
- Travis soils, 1-5% slopes
- Travis soils, 1-5% slopes
- Travis gravelly soils, 1-8% slopes
- Yahola very fine sandy loams, 0-1% slopes, occasionally flooded

Figure 24: Soil strata classified as sandy loam

Sandy Clay Loams

- Heaton soils and urban land, 0-2% slopes

Figure 25: Soil strata classified as sandy clay loam

Silt Loams

- Bergstrom silt loam, 0-1% slopes
- Bergstrom silt loam, 1-3% slopes
- Bergstrom silty clay loam, 0-1% slopes
- Bergstrom silty clay loam, 1-3% slopes
- Castephen silty clay loam, 1-3% slopes
- Castephen silty clay loam, 3-5% slopes
- Oakalla silty clay loam, 0-2% slopes, frequently flooded
- Oakalla silty clay loam, 0-2% slopes, occasionally flooded
- Volente silty clay loam, 1-8% slopes
- Volente silty clay loam, 1-8% slopes, moderately eroded
- Westwood silty clay loam, 0-1% slopes, occasionally flooded

Figure 26: Soil strata classified as silt loam

Clay Loams

- Brackett-Rock outcrop complex, 1-12% slopes
- Brackett-Rock outcrop-Real complex, 8-30% slopes
- Eddy gravelly loam, 0-3% slopes
- Eddy gravelly loam, 3-6% slopes
- Eddy soils and Urban land, 0-6% slopes
- Speck clay loam, 1-3% slopes;
- Speck stony clay loam, 1-5% slopes
- Urban land and Brackett soils, 1-12% slopes
- Whitewright clay loam, 1-5% slopes
- Wilson clay loam, 0-1% slopes
- Wilson clay loam, 1-3% slopes

Figure 27: Soil strata classified as clay loam

Silty Clay Loams

- Bergstrom soils and Urban land, 0-2% slopes
- Brackett soils and Urban land, 12-30% slopes
- Mixed alluvial land, 0-1% slopes, frequently flooded
- Oakalla soils, 0-1% slopes, channeled, frequently flooded
- Urban land, Austin, and Whitewright soils, 1-8% slopes
- Volente soils and Urban land, 1-8% slopes
- Westwood soils, 0-1% slopes, channeled, occasionally flooded

Figure 28: Soil strata classified as silty clay loams

Silty Clays

- Altoga silty clay, 1-3% slopes
- Altoga silty clay, 3-6% slopes, moderately eroded
- Altoga soils and urban land, 2-8% slopes
- Austin silty clay, 1-3% slopes
- Austin silty clay, 2-5% slopes, eroded
- Austin urban land complex, 2-5% slopes
- Austin-Whitewright complex, 3-5% slopes, moderately eroded
- Austin-Whitewright complex, 5-8% slopes, moderately eroded
- Denton silty clay, 1-3% slopes
- Denton silty clay, 3-5% slopes
- Lewisville silty clay, 0-1% slopes
- Lewisville silty clay, 1-3% slopes
- Lewisville soils and urban land, 0-2% slopes
- Purves silty clay, 1-5% slopes

Figure 29: Soil strata classified as silty clay

Clays

- Behring clay, 1-3% slopes
- Behring clay, 3-5% slopes
- Burleson clay, 0-1% slopes
- Burleson clay, 1-3% slopes
- Burleson gravelly clay, 1-3% slopes
- Burleson gravelly clay, 3-5% slopes
- Crawford clay, 0-1% slopes
- Crawford clay, 1-3% slopes
- Ferris-Heiden complex, 8-20% slopes, severely eroded
- Heiden clay, 1-4% slopes
- Heiden clay, 3-5% slopes
- Heiden clay, 5-8% slopes, eroded
- Heiden gravelly clay, 8-20 slopes, moderately eroded
- Houston Black clay, 0-1% slopes
- Houston Black clay, 1-3% slopes
- Houston Black clay, 3-5% slopes, moderately eroded
- Houston Black soils and Urban land, 0-8% slopes
- Houston Black gravelly clay, 2-8% slopes, moderately eroded
- Patrick soils and urban land, 1-10% slopes
- Patrick soils, 2-5% slopes
- Patrick soils, 5-10% slopes
- San Saba clay, 1-2% slopes
- San Saba soils and Urban Land, 0-2% slopes
- Ships clay, 0-1% slopes, rarely flooded
- Tarrant and Speck soils, 0-2% slopes
- Tarrant soils and Urban land, 0-2% slopes
- Tarrant soils and Urban land, 18-40% slopes
- Tarrant soils and Urban land, 5-18% slopes
- Tarrant soils, 5-18% slopes
- Tarrant-Rock outcrop complex, 18-50% slopes
- Tinn clay, 0-1% slopes, frequently flooded
- Tinn clay, 0-1% slopes, occasionally flooded
- Urban Land and Ferris soils, 10-15% slopes

Figure 30: Soil strata classified as clays

Finally, the single strata classified as "urban land" was classified as such, as there was no corresponding soil information available for that strata.

Step 7: Select clay and silty clay soils in the USGS soil data, and isolate them against the aged ferrous wastewater pipelines that are in the flood zone under evaluation, as completed in Step 6.

In GIS, soils potentially corrosive to ferrous pipelines – clay and silty clay – are selected from the USGS soil data into a new layer containing only clays and silty clays. Then, the layer containing the aged ferrous wastewater pipelines in the High Risk flood zone was clipped with the layer containing the clays and silty clays.

Step 8: Calculate the total length and volume of the aged ferrous pipelines identified in Step 5 that are at risk.

The purpose of this step is to arrive at a quantitative assessment of risk that is meaningful to the municipal wastewater manager. If there is a great length or volume of aged ferrous pipeline at risk in one high-risk flood zone, the wastewater manager may wish to prioritize replacement of those pipelines in that zone.

Step 9: Repeat Steps 3 – 8 for the Moderate Risk flood zone (0.2% annual chance flood event, or "500 year flood") and the Low Risk flood zone (area of minimal flood hazard, or less than 0.2% chance of flood).

In this step, the above process is repeated to achieve the objectives accompanying the four research questions for each floodplain zone. Analyzing all three major flood zones provides a useful context for understanding the risk to the wastewater network.

Step 10: Overlay the at-risk pipeline in the High Risk flood zone on the Edwards Aquifer recharge zone and identify any at-risk pipe that are also in the recharge zone.

The purpose of this step to identify any at-risk pipeline that should be especially prioritized for replacement, given the possibility of environmental damage to the aquifer and groundwater should the at-risk pipe corrode and leak into the aquifer.

2. Data Sources, Characteristics, and Limitation of Data Set

With respect to data sources, this study relies primarily on GIS data. First, to identify the ferrous pipelines in the wastewater network, GIS data from Austin Water Utility was used. This data has Austin Water Utility's reuse and water mains, as well as all supporting infrastructure. For purpose of this study, only the wastewater mains pipelines were selected. Second, to identify the floodplains, GIS data for Travis County was downloaded from FEMA.gov; the most recent flood map study was effective as of January 2016. Third, to identify the soils, data from the United States Geological Survey Web Soil Survey was downloaded in 2016 for Travis County. Fourth, to identify an area of particular environmental sensitivity, data for the Edwards Aquifer recharge zone was downloaded from the City of Austin. The primary limitation of the data set presented in this thesis is that two sets – the FEMA flood insurance maps and the soil survey – are specific to Travis County, while the wastewater network of Austin Water Utility is specific to its service area, the city of Austin and its environs.

Table 4: Data sources

	Data	Source	
GIS Data	Austin Water Utility wastewater network	Austin Water Utility, 2015.	Provided under confidentiality agreement
	FEMA Flood Insurance Rate Maps	FEMA, 2016.	https://msc.fema.gov/portal/advanceSearch
	Travis County soil survey	USGS, 2016.	http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm
	Edwards Aquifer recharge zone	City of Austin, 2016	https://data.austintexas.gov/Environmental/Recharge-Zones/fkk6-3s95

3. Data Rationales

A. Soil Survey

As discussed earlier, certain soil properties significantly contribute to the corrosion of ferrous wastewater pipelines: soil resistivity, pH, chlorides, moisture, sulfates, redox, and stray current. Certain soils, such as clays and silty clays as studied here, have decreased soil resistivity and therefore, in the correct environment, are more corrosive to ferrous pipelines, so the USGS soil survey for Travis County was used to approximate corrosive soil properties.

B. Flood Insurance Rate Maps

FIRMs from FEMA were used to locate environments that may be aggressively corrosive toward ferrous wastewater pipelines in a corrosive soil. In addition, FIRMs were utilized in this study as the three major flood zones provide a useful metric of analyzing risk for the municipal wastewater manager.

C. Edwards Aquifer Recharge Zone

The Edwards Aquifer Recharge Zone map from the City of Austin was used to provide an example of an environmentally sensitive area in which wastewater discharge should be particularly avoided, as such leakage could cause harm to the aquifer.

CHAPTER 4: FINDINGS

1. Overview

The following figure provides an overview of the analysis conducted and an outline of the presentation of the findings:

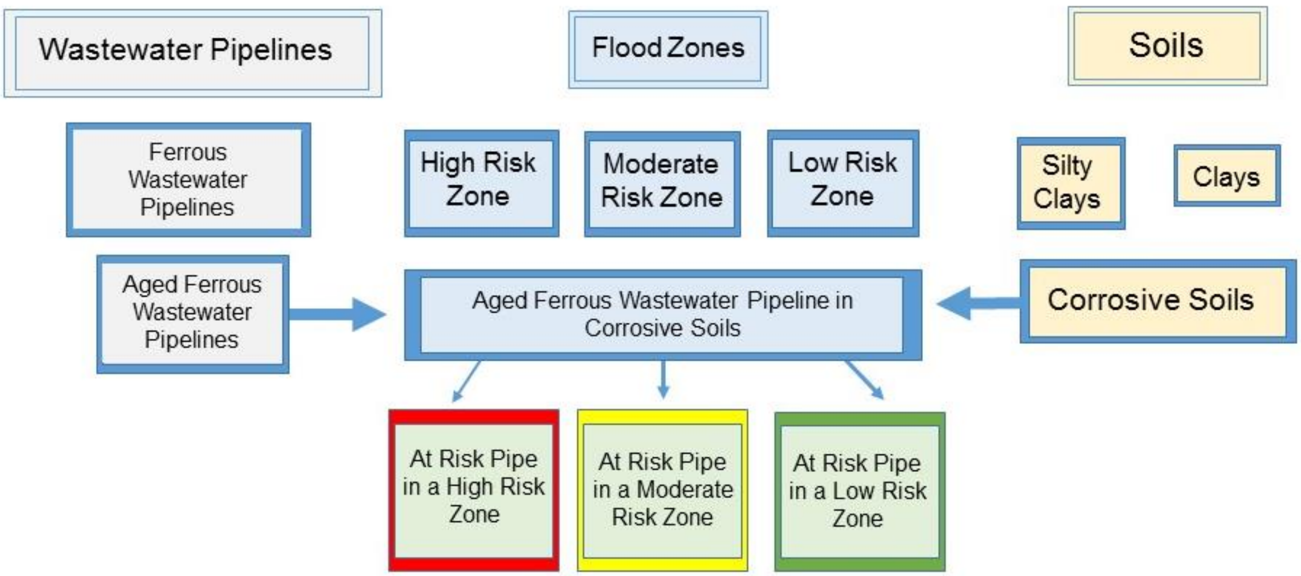

Figure 31: Overview of research conducted and findings

Per Figure 31, this section will present findings by the research questions outlined in Chapter 3: ferrous wastewater pipelines by flood zone, aged ferrous wastewater pipelines by flood zone, and, finally, aged wastewater pipelines in corrosive soils, by flood zone – those that are most at risk for corrosion through flooding. In addition, this section will also provide an overview of the pipelines most at risk that are located in the Edwards Aquifer recharge zone.

As discussed previously, the Austin Water Utility GIS data includes a number of pipes for which an age of “0” is given. These pipes are included in the analysis that follows, as these pipes could be aged. Where such pipes are discussed, the term “no-age” will be used to denote these pipes.

2. Ferrous Wastewater Pipelines by Flood Zone

This section will present the results of the following research question and objective, by flood zone:

- **Research Question 1**: Are there ferrous pipelines located in the flood zone under evaluation?
    - ***Objective*:** Overlay the FEMA FIRM for the flood zone under evaluation (High Risk, Moderate Risk, and Low Risk) with the Austin Water Utility wastewater network. Isolate ferrous pipelines in the flood zone.

A. Ferrous Wastewater Pipes in the High Risk Zone

First, the High Risk flood zone will be evaluated for ferrous wastewater pipes within the zone. Figure 32 below shows the High Risk flood zone under evaluation:

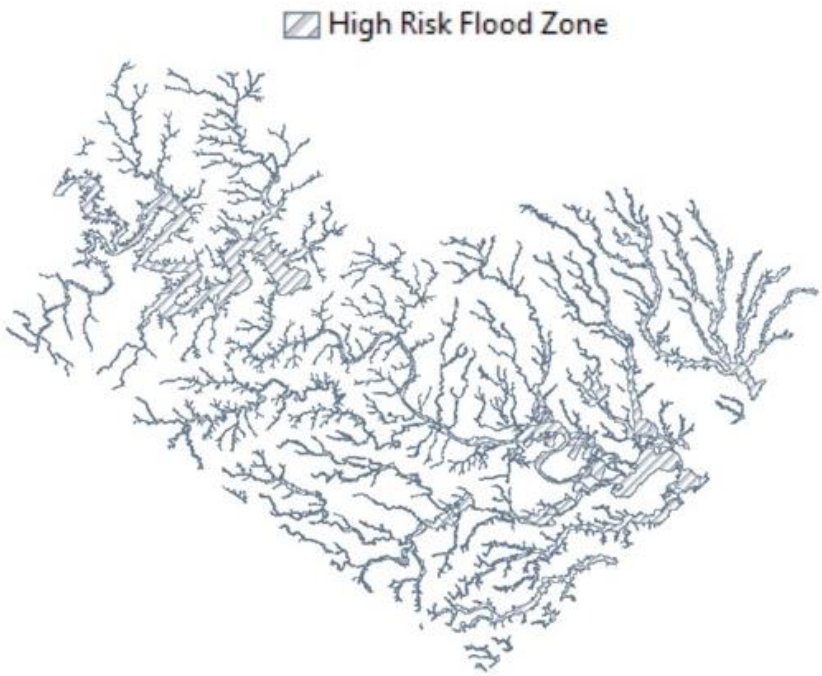

Figure 32: High Risk flood zone, isolated (source: FEMA)

The ferrous wastewater pipelines that had been previously isolated from the Austin Water Utility network were then overlaid on the High Risk flood zone:

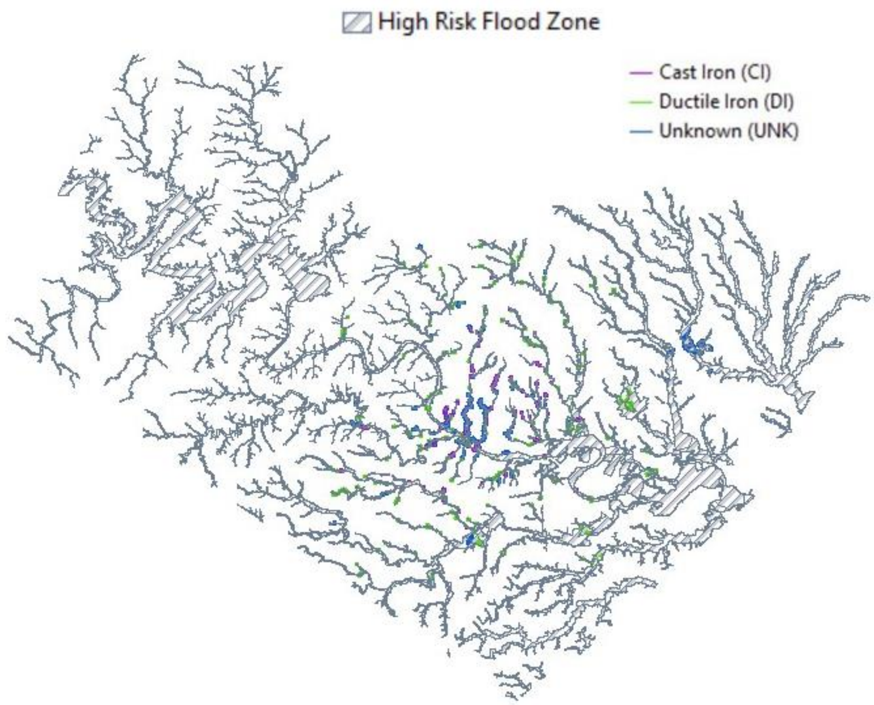

Figure 33: High Risk flood zone with ferrous wastewater pipeline overlay (source: FEMA, Austin Water Utility)

Figure 34 shows the age distribution for the ferrous wastewater pipelines in the High Risk zone:

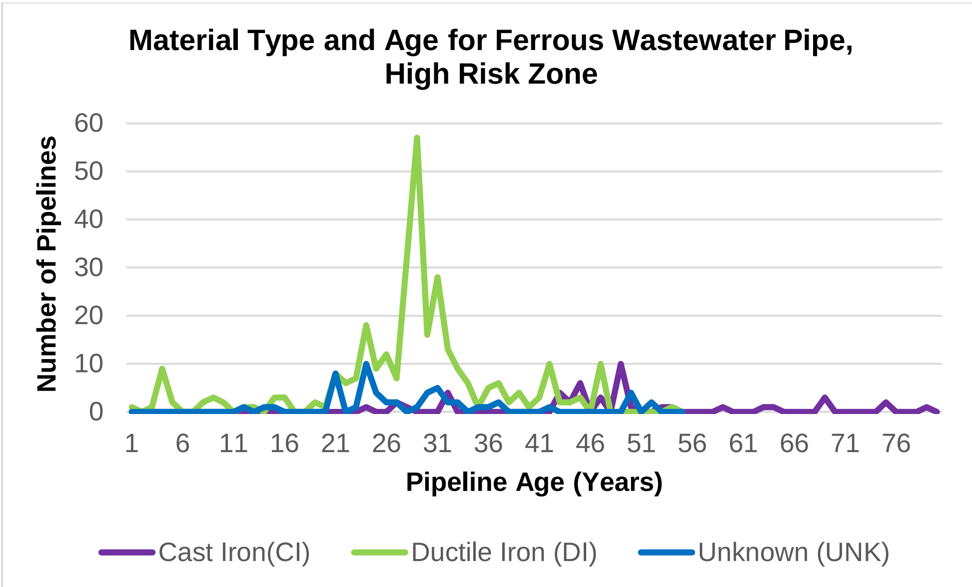

Figure 34: Material type and age for ferrous wastewater pipe in the High Risk zone, excluding "no-age" ferrous pipelines

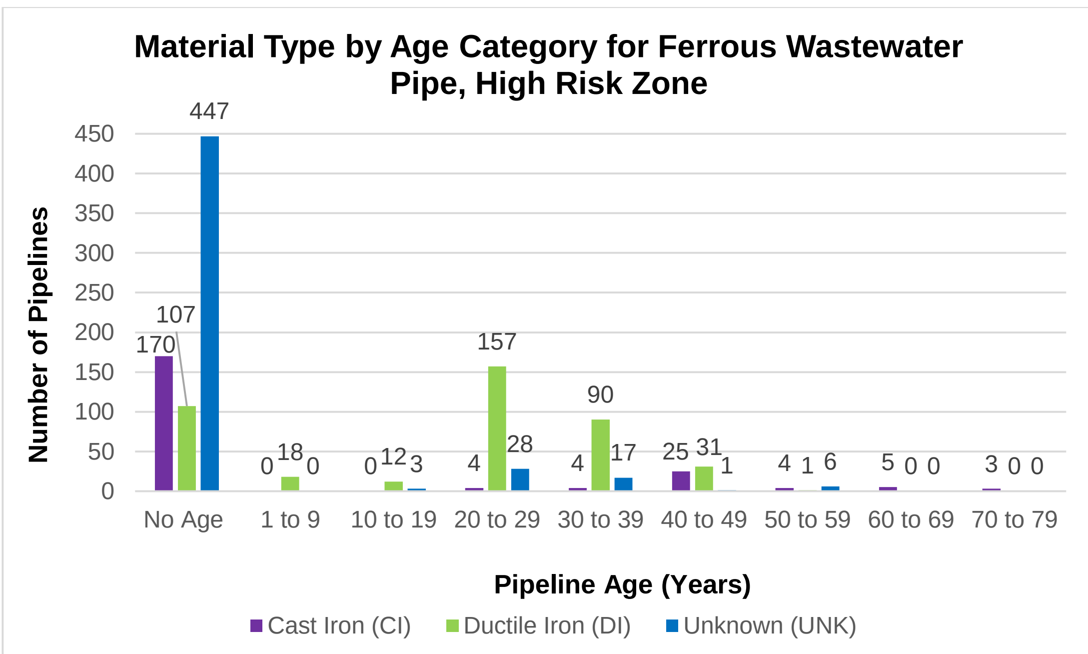

Figure 35: Material type by age category for ferrous wastewater pipe in the High Risk Zone

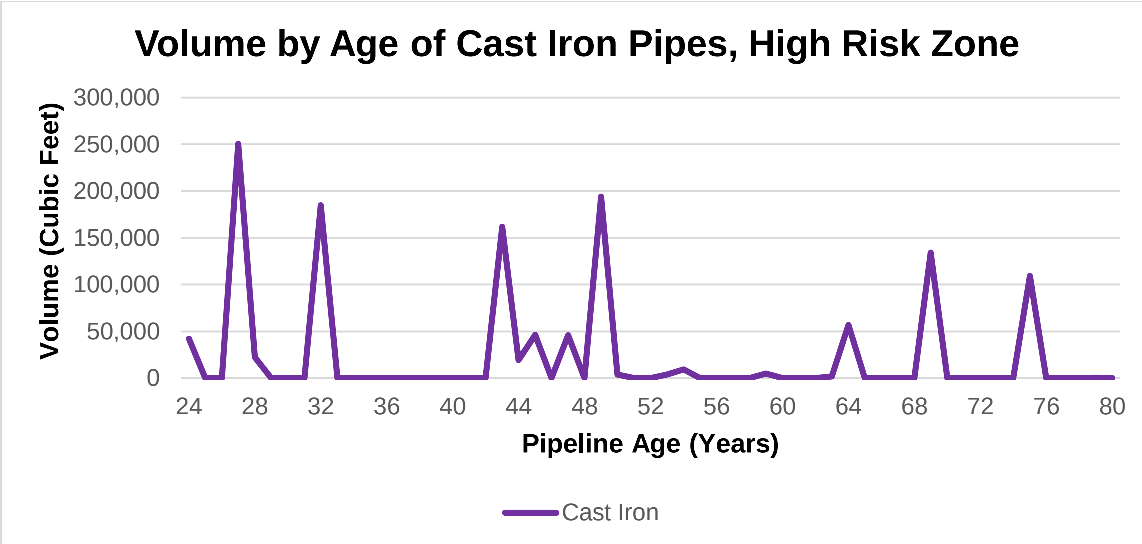

Figure 36: Volume by age of cast iron pipes in the High Risk flood zone, excluding no-age pipe

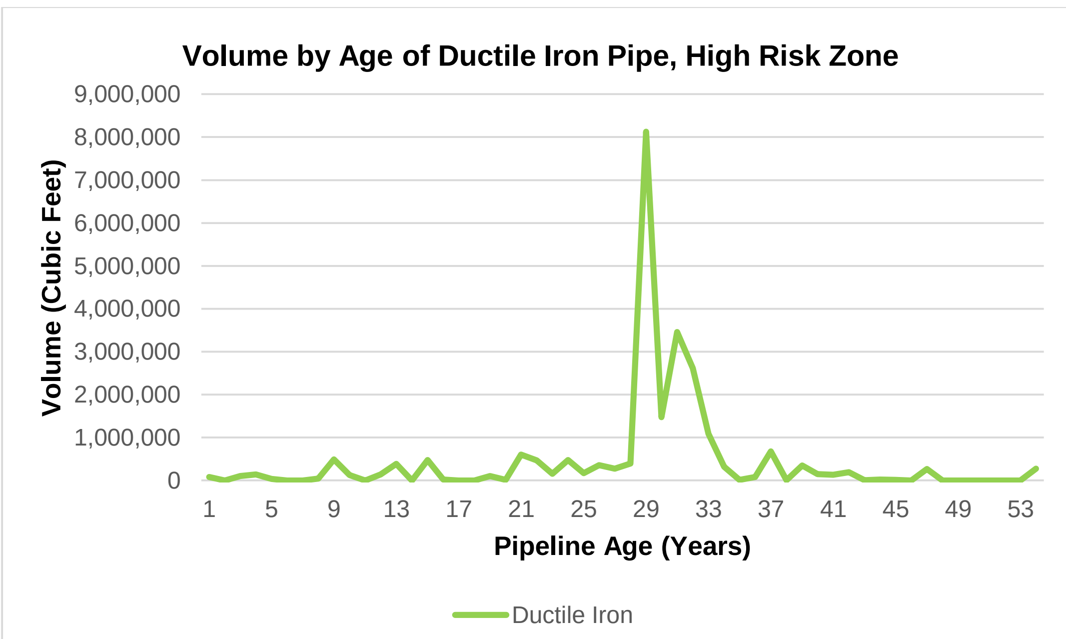

Figure 37: Volume by age of ductile iron pipes in the High Risk flood zone, excluding no-age pipe

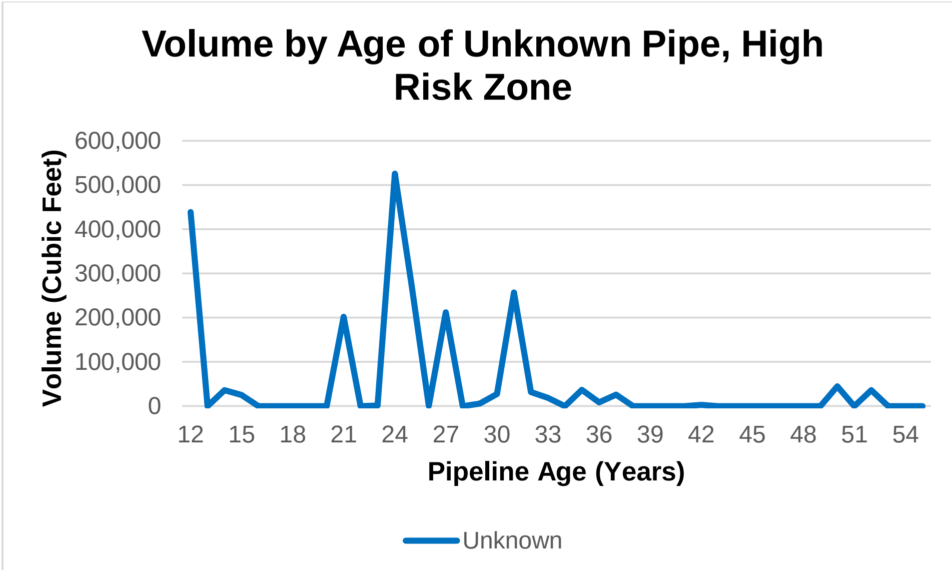

Figure 38: Volume by age of unknown pipes in the High Risk flood zone, excluding no-age pipe

A review of the figures above reveal several salient observations for the ferrous pipelines in the High Risk flood zone:

- **Young Ductile Iron Pipe.** Consistent with industry trend, ductile iron pipe appears to be younger than the other ferrous pipe, and has also been more recently installed.
- **Trend to Ductile Iron Pipe**. Consistent with industry literature, ductile iron appears to have functioned as a replacement for older cast iron pipeline.
- **Ductile Iron Pipe as the Workhorse**. The volume of ductile iron pipe examined here far exceeds the cast iron pipe and the unknown pipe: there appears to be a large ductile iron pipe that moves 8,000,000 cubic feet of wastewater, and another large ductile iron pipe that moves approximately 350,000 cubic feet of wastewater.
- **Aged Cast Iron Pipes**. Also consistent with industry trends, cast iron pipes appear to make up a majority of the older pipe in the system.
- **Limited Very Aged Cast Iron Pipe**. Interestingly, the cast iron pipelines that are in the High Risk flood zone and are also very aged (greater than 60 years) appear to be somewhat limited in number.

- **Unknown Pipe, Unknown Age.** Data for pipes labeled as "unknown" also appear to have an unknown age.

B. Ferrous Wastewater Pipe in the Moderate Risk Zone

Next, the Moderate Risk flood zone, or the 0.2% annual percent chance of a flood event, was evaluated for ferrous wastewater pipelines. Figure 39 shows the Moderate Risk flood zone:

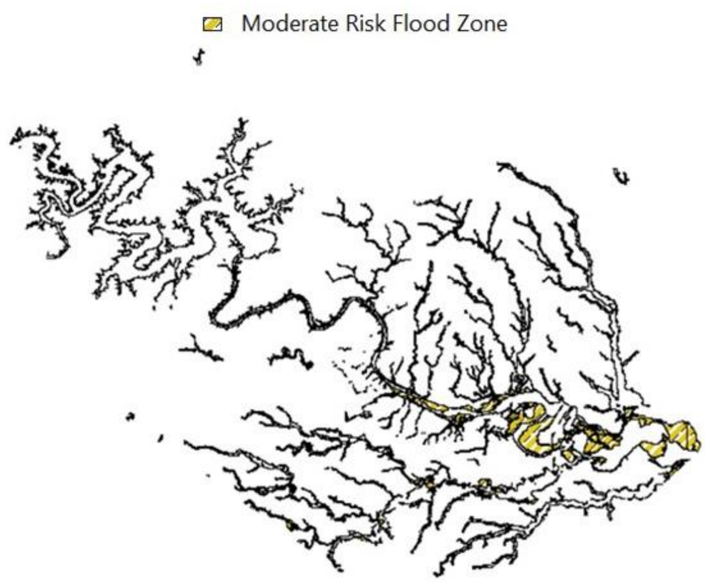

Figure 39: Moderate Risk flood zone (source: FEMA)

Figure 40 shows the ferrous wastewater pipelines overlaid on the Moderate Risk flood zone:

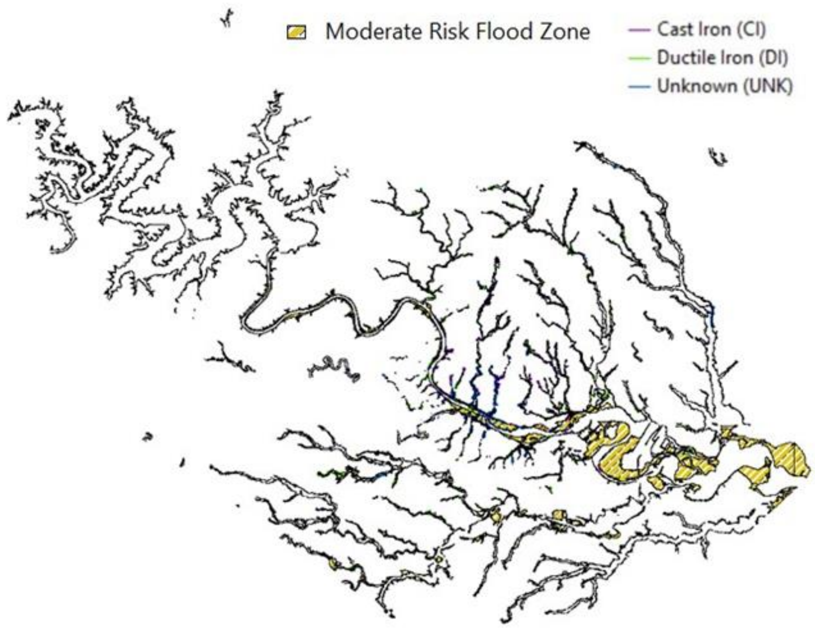

Figure 40: Ferrous wastewater pipelines in the Moderate Risk flood zone (source: FEMA, Austin Water Utility)

Figure 41 shows more detail of the ferrous wastewater pipelines in the Moderate Risk flood zone:

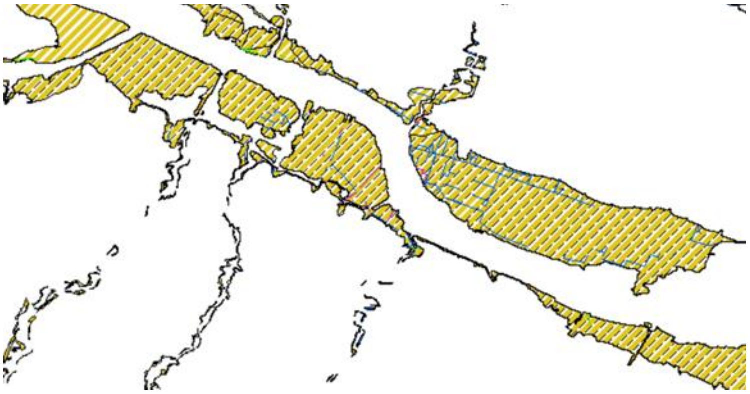

Figure 41: Detail of ferrous wastewater pipelines in the Moderate Risk flood zone (source: FEMA, Austin Water Utility)

Figure 42 below shows the age profile for the three ferrous wastewater pipeline materials in the Moderate Risk flood zone:

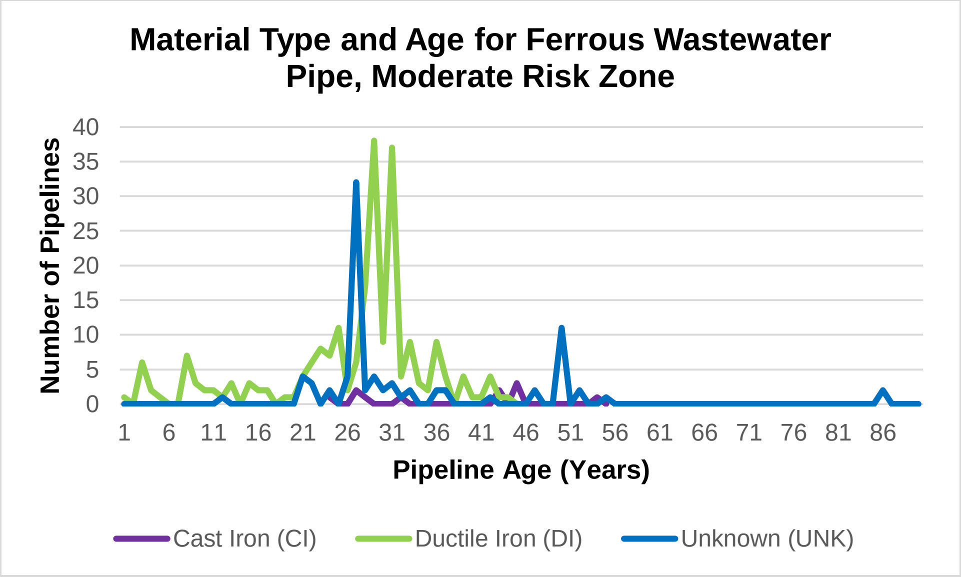

Figure 42: Material type and age for ferrous wastewater pipe in the Moderate Risk flood zone, excluding no-age pipe

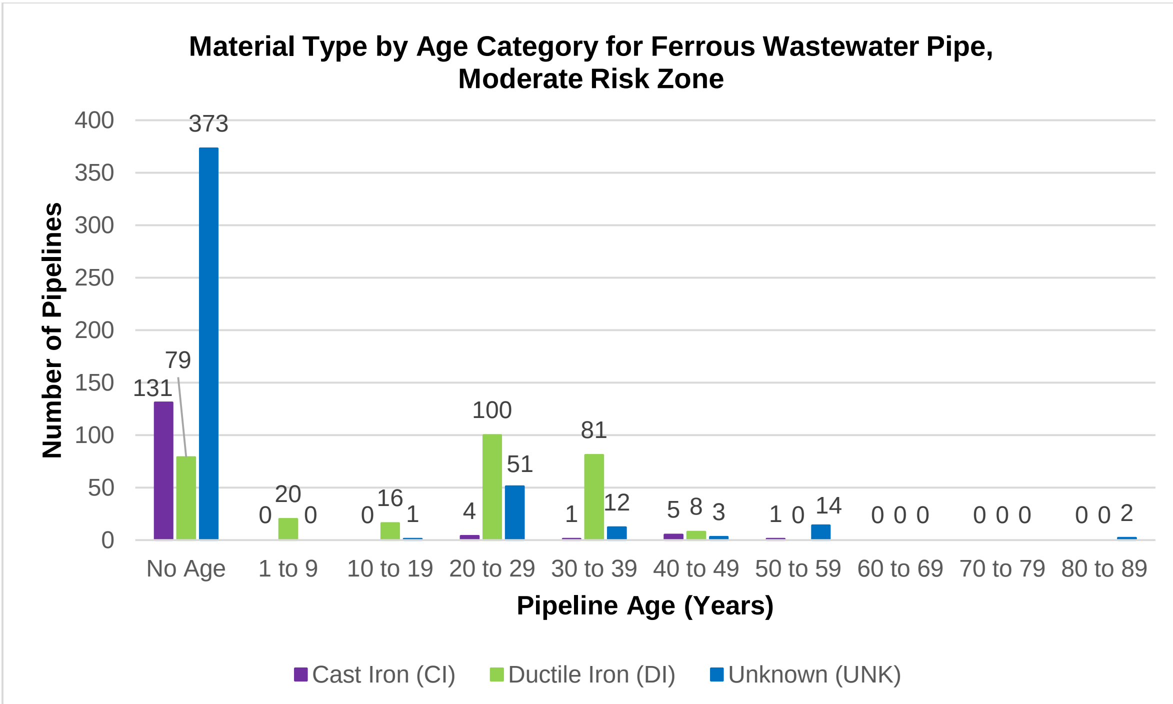

Figure 43: Material type by age category for ferrous wastewater pipe in the Moderate Risk flood zone

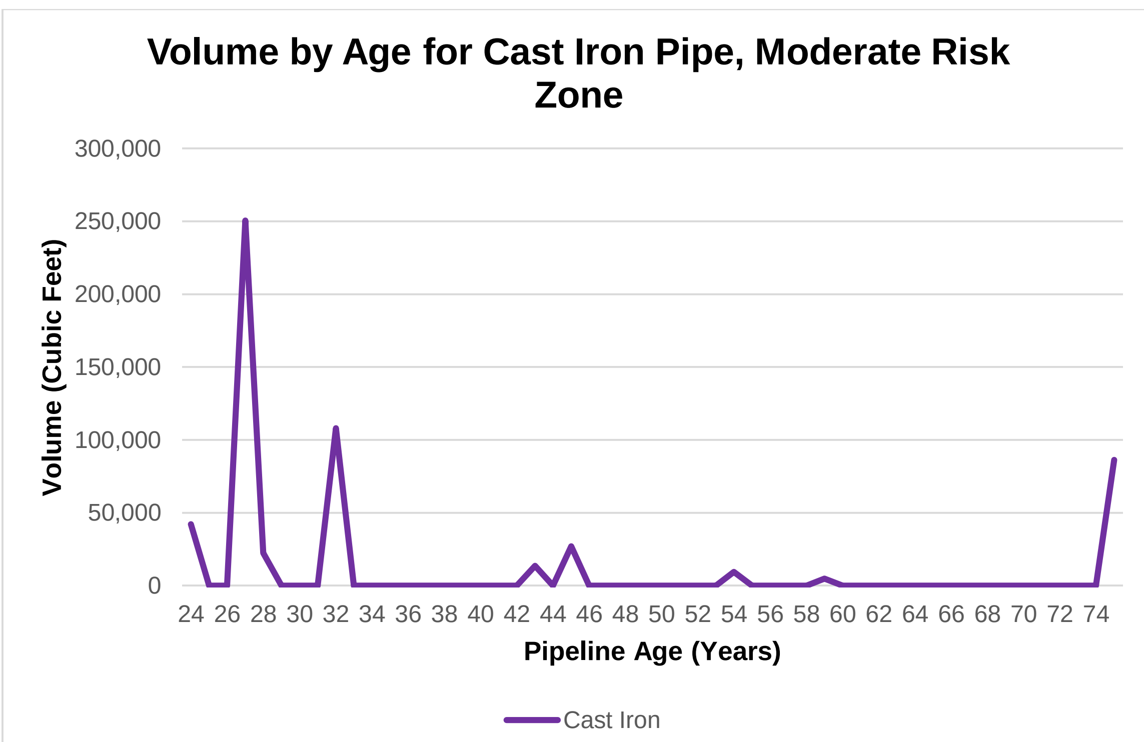

Figure 44: Volume by age for cast iron pipe in the Moderate Risk zone, excluding no-age pipe

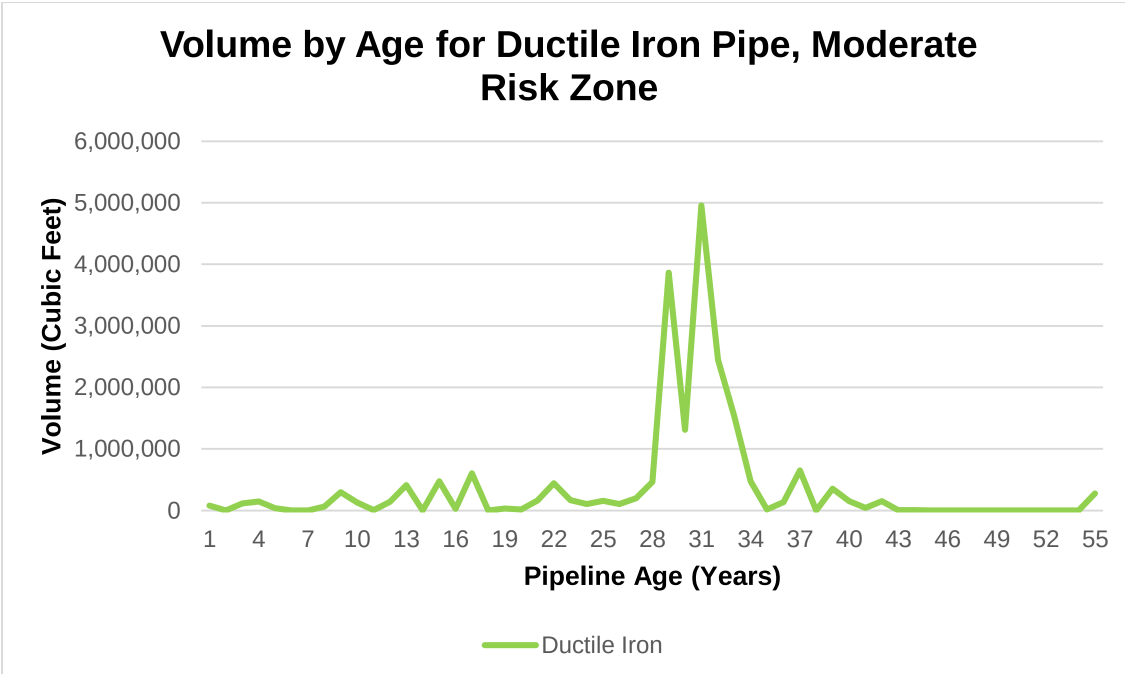

Figure 45: Volume by age for ductile iron pipe in the Moderate Risk zone, excluding no-age pipe

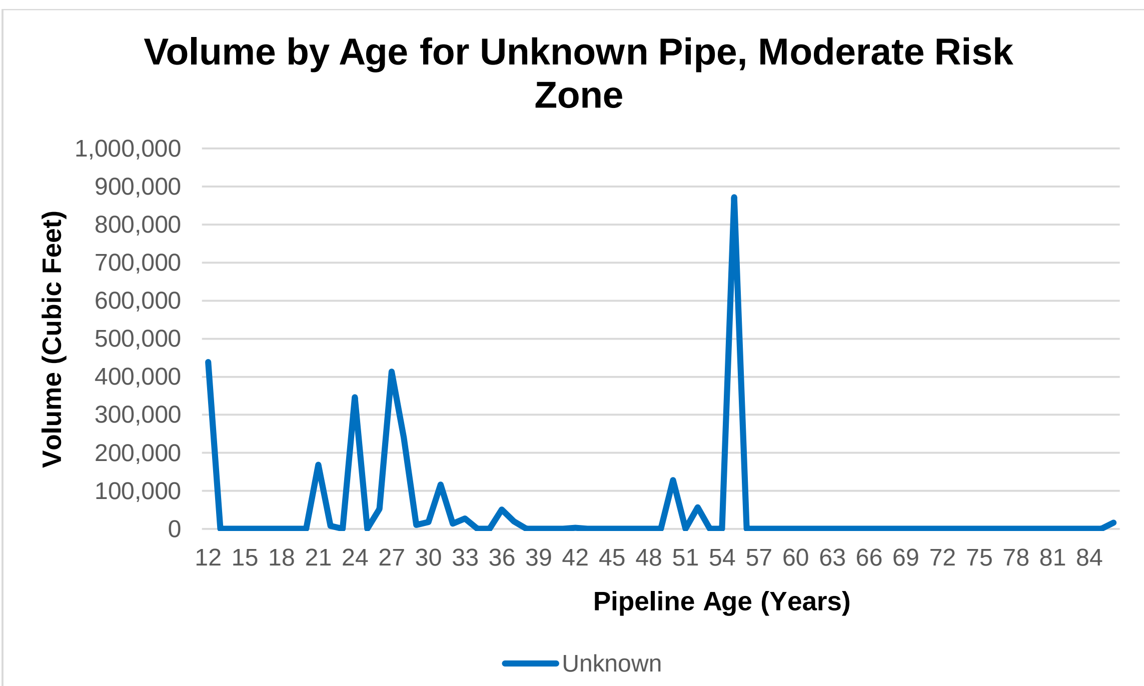

Figure 46: Volume by age for unknown pipe in the Moderate Risk zone, excluding no-age pipe

A review of the figures above reveal several observations for ferrous pipelines in the Moderate Risk flood zone:

- **Young Ductile Iron Pipe.** Consistent with industry trend, ductile iron pipe appears to be younger than the other ferrous pipe, and has also been more recently installed.
- **Ductile Iron Pipe as the Workhorse**. The volume of ductile iron pipe examined here far exceeds the cast iron pipe and the unknown pipe: there appears to be two ductile iron pipes within 4 years of age of each other transporting together nearly 9,000,000 cubic feet of wastewater. The vintage and volume pattern is similar to what was observed in the High Risk flood zone.
- **Working Young Cast Iron Pipe.** Interestingly, there is a young cast iron pipe, 27 years old, which is transporting 250,000 cubic feet of wastewater, and 32 year old cast iron pipe transporting approximately 108,000 cubic feet of wastewater.
- **A Workhorse Aged Cast Iron Pipe**. There is a workhorse 75 year old cast iron pipe transporting approximately 100,000 cubic feet of wastewater.
- **Unknown Pipe, Unknown Age.** As in the High Risk flood zone, data for pipes labeled as "unknown" also appear to frequently have an unknown age.

C. Ferrous Wastewater Pipe in the Low Risk Zone

Finally, the Low Risk flood zone, which has a less than 0.2% annual chance of a flood event, was evaluated for ferrous wastewater pipelines.

Figure 47 shows the Low Risk flood zone:

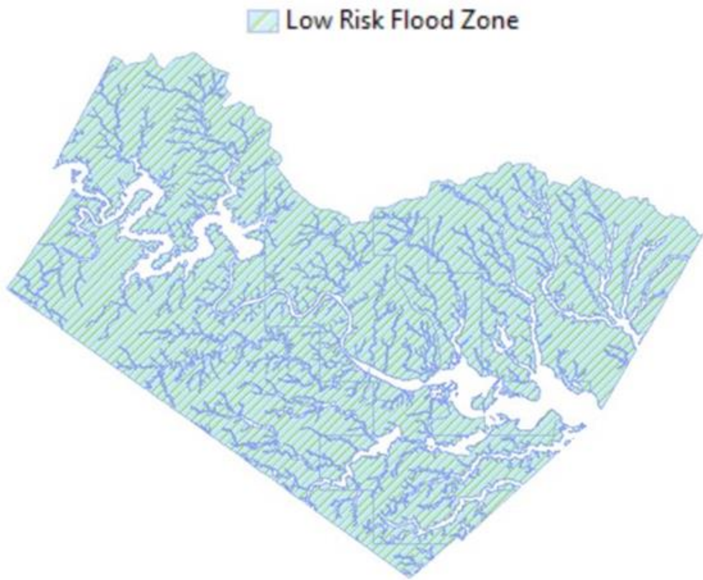

Figure 47: The Low Risk flood zone (source: FEMA)

Figure 48 below shows the ferrous wastewater pipelines in the Low Risk zone:

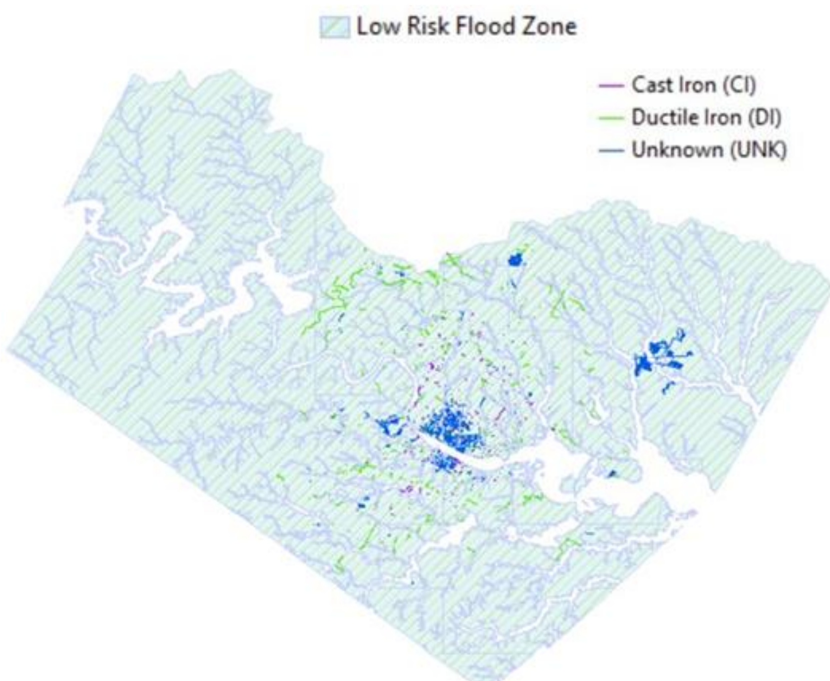

Figure 48: Ferrous wastewater pipelines in the Low Risk flood zone (source: FEMA, Austin Water Utility)

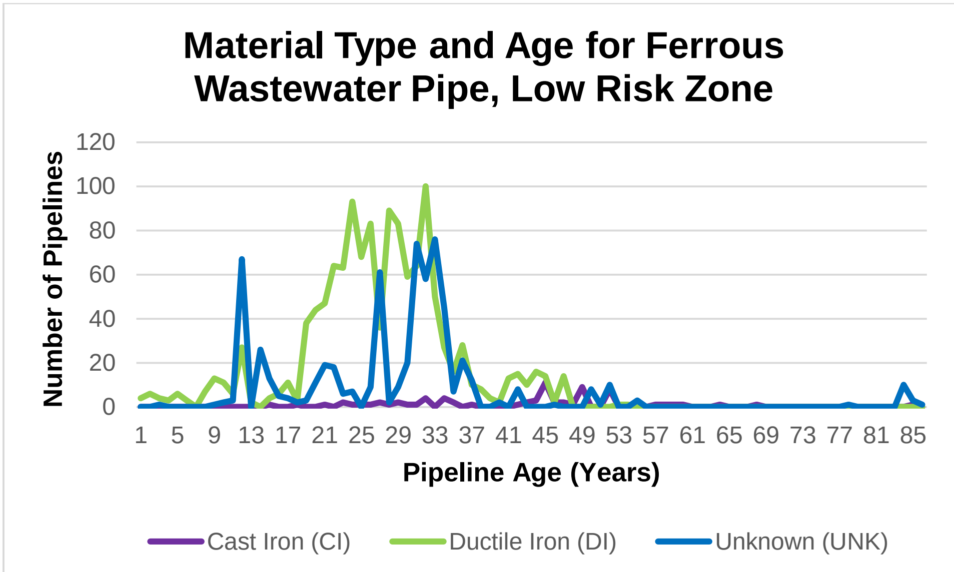

Figure 49: Material type and age for ferrous wastewater pipe located in the Low Risk flood zone, excluding no-age pipe

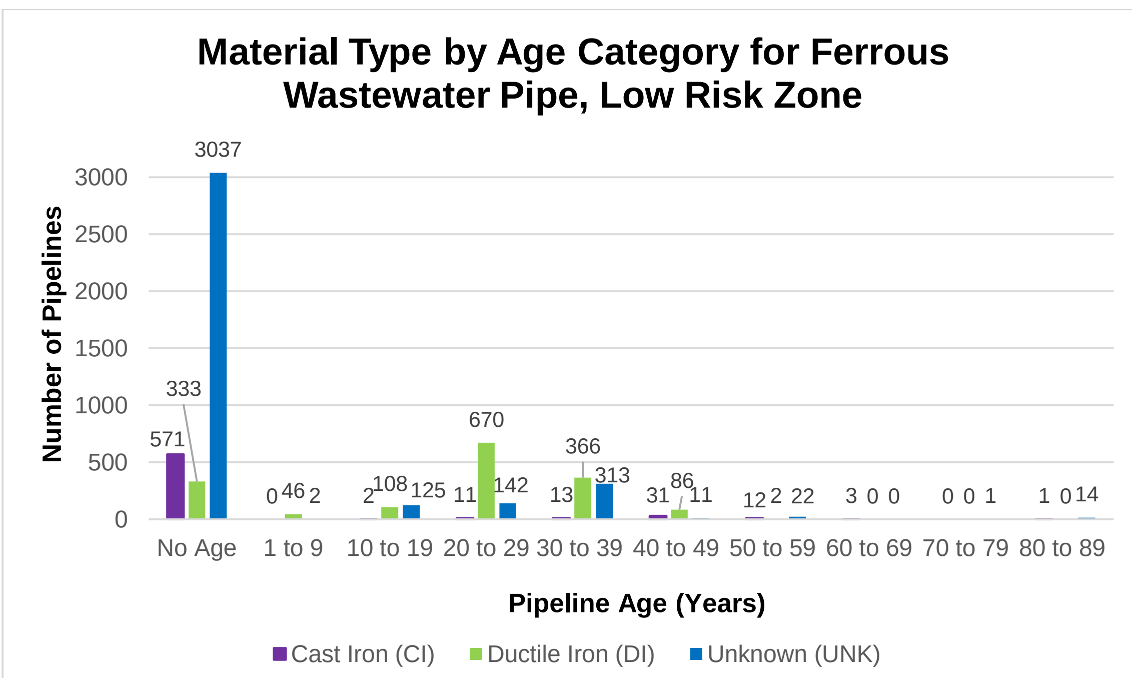

Figure 50: Material type by age category of ferrous wastewater pipe in the Low Risk flood zone

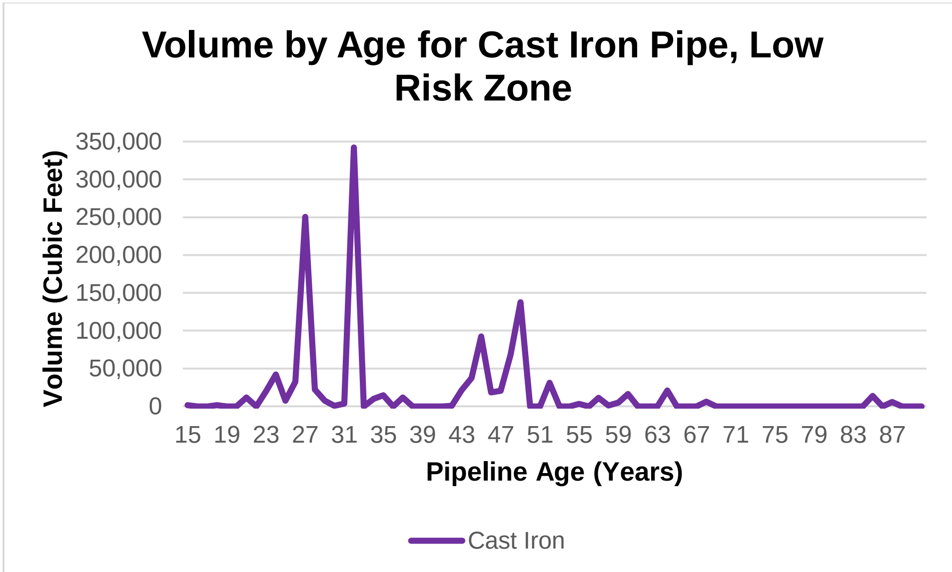

Figure 51: Volume by age for cast iron pipe in the Low Risk flood zone, excluding no-age pipelines

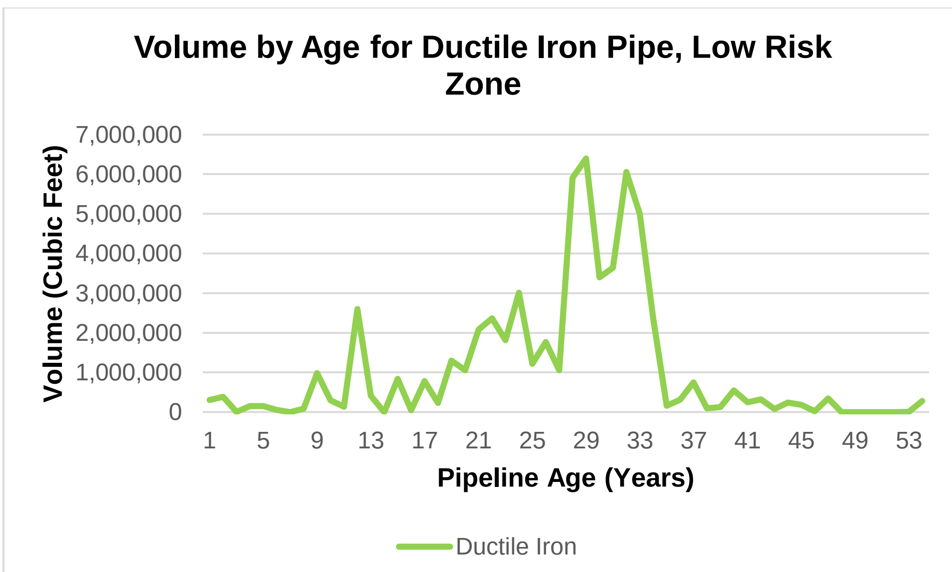

Figure 52: Volume by age for ductile iron pipe in the Low Risk flood zone, excluding no-age pipelines

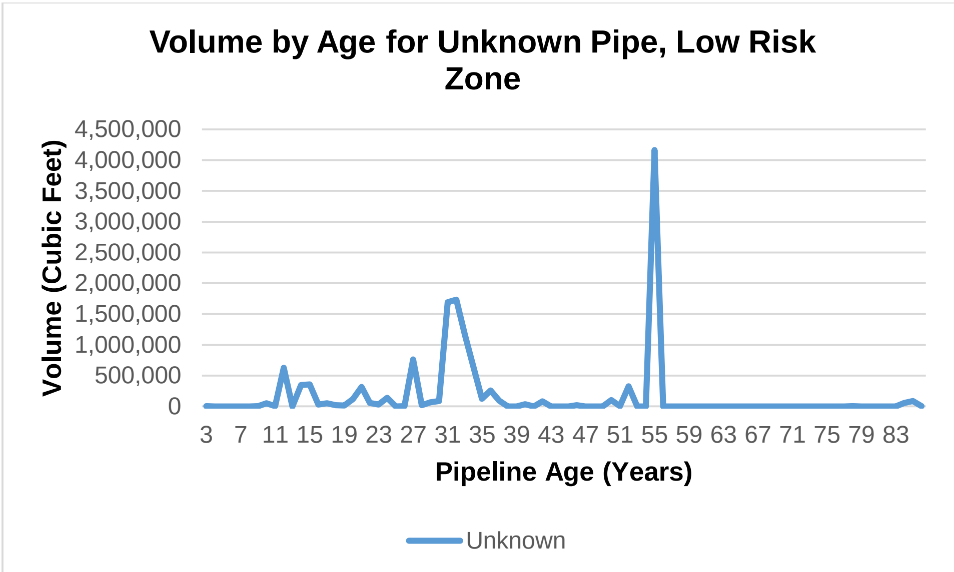

Figure 53: Volume by age for unknown pipelines in the Low Risk flood zone, excluding no-age pipe

A review of the figures above reveal several observations for ferrous pipelines in the Low Risk flood zone:

- **Ductile Iron Pipe Shines Again as the Workhorse**. As observed in the High Risk flood zone and the Moderate Risk flood zone, young ductile iron pipe is a workhorse: pipes installed within 7 years of each other have a volume of 31 million cubic feet of water.
- **Large Number of Ductile Iron Pipe.** There is a large number of ductile iron pipe in the Low Risk flood zone, especially relative to cast iron pipe and unknown pipe.
- **A Number of Aged Cast Iron Pipe**. There are approximately 10 very aged cast iron pipe, older than 80 years old; the volume carried by these is rather small. However, on the whole, the number of cast iron pipe is very small relative to ductile iron and unknown pipes.
- **Large Number of Unknown Pipe.** There is a large number of unknown pipe, over 3,000, in the Low Risk flood zone, which is expected due to the larger geographical area the Low Risk flood zone represents.

- **Small Number of Cast Iron Pipe Carrying Decent Work.** As observed in the Moderate Risk flood zone, there is a small number of young cast iron pipe carrying approximately 250,000 to 300,000 cubic feet of wastewater.

3. Aged Ferrous Wastewater Pipelines by Flood Zone

This section will address the following research question:

- **Research Question 2:** Are there aged ferrous pipelines located in the flood zone under evaluation?
  - ***Objective:*** For the flood zone under evaluation, highlight ferrous pipelines greater than 40 years old.

This section will evaluate the more narrow criteria of aged ferrous pipelines in each flood zone under evaluation, defined as greater than 40 years old. It is important to note that this section will be a narrowing of the information presented in the previous section, as the previous section showed *all* ferrous wastewater pipelines in the flood zones under evaluation; this section will explore the more narrow criteria of the aged ferrous pipelines in each flood zone.

A. Aged Ferrous Wastewater Pipe in the High Risk Zone

First, the High Risk flood zone was evaluated for aged ferrous wastewater pipelines.

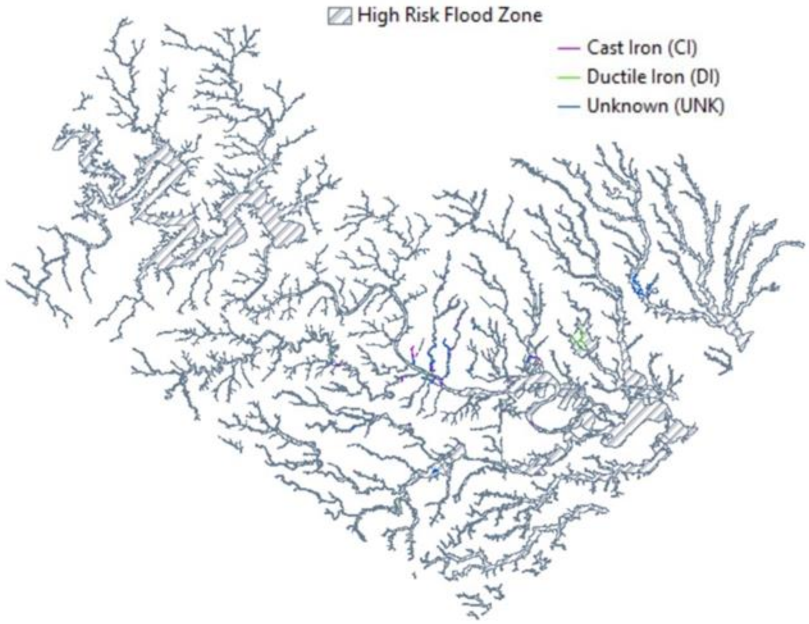

Figure 54: Aged ferrous wastewater pipeline overlay on the High Risk flood zone

The data for the aged ferrous wastewater pipeline were analyzed by material type in order to gain an age profile for the High Risk flood zone:

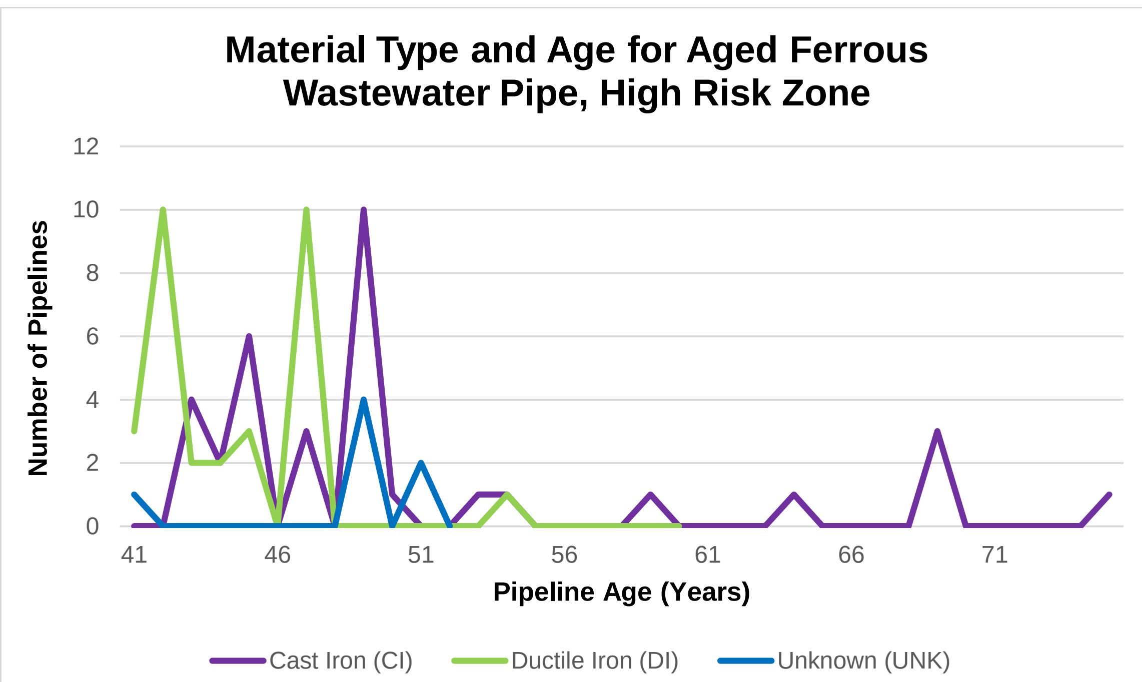

Figure 55: Material type and age for aged ferrous wastewater pipe in the High Risk flood zone, excluding no-age pipe

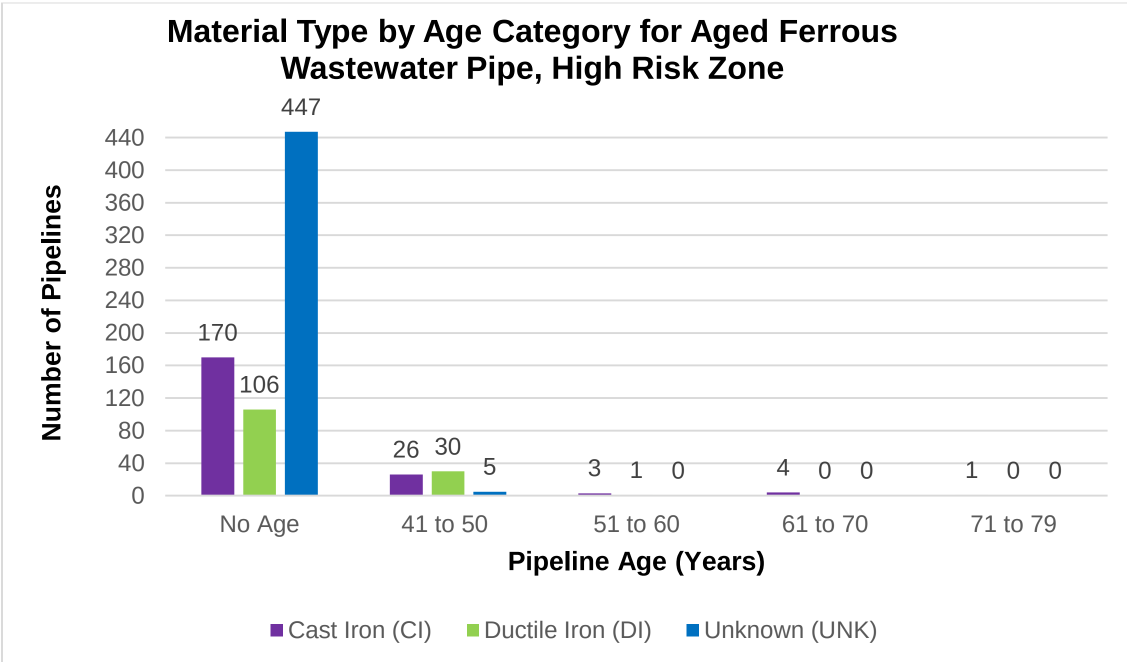

Figure 56: Material type and age for aged ferrous wastewater pipe in the High Risk flood zone

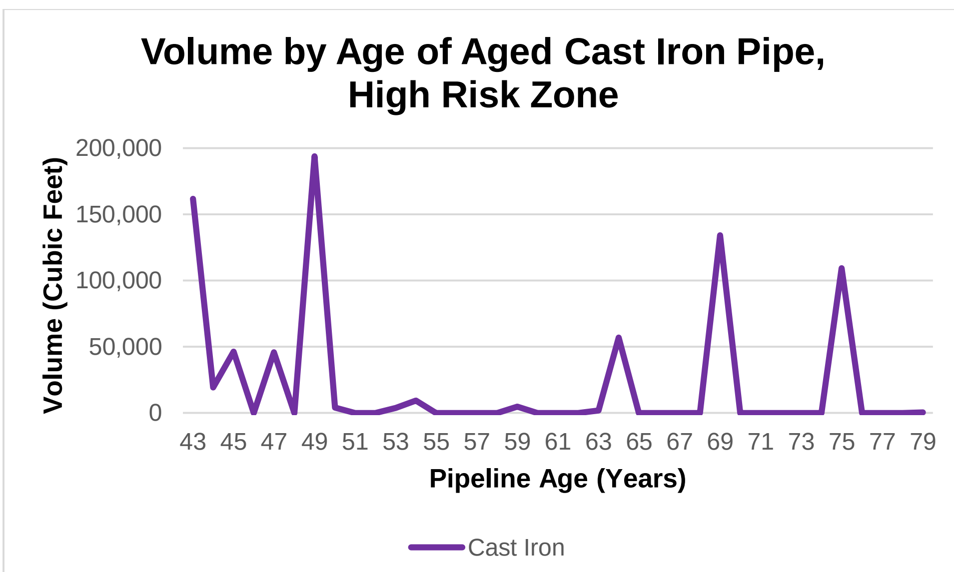

Figure 57: Volume by age of aged cast iron pipe in the High Risk flood zone, excluding no-age pipe

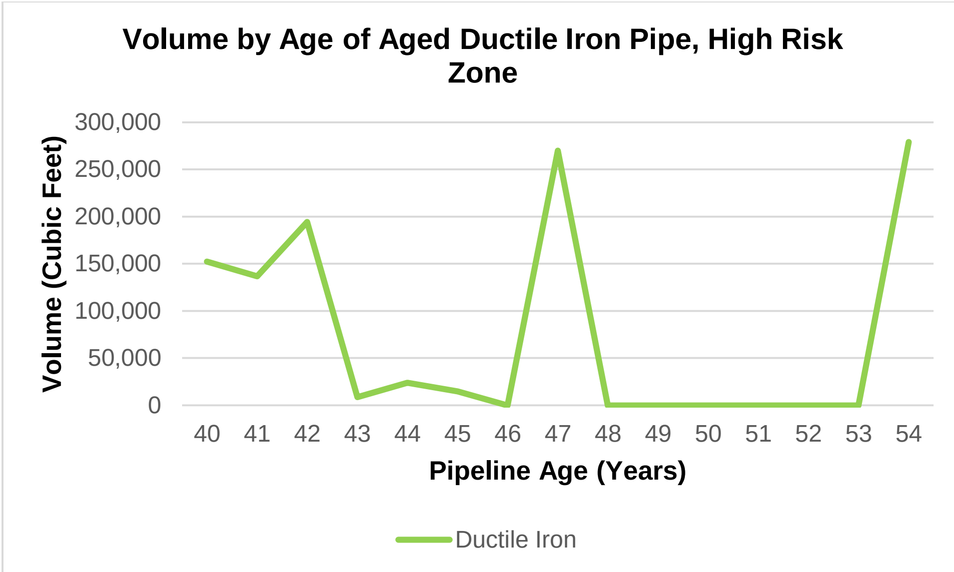

Figure 58: Volume by age of aged ductile iron pipe in the High Risk flood zone, excluding no-age pipe

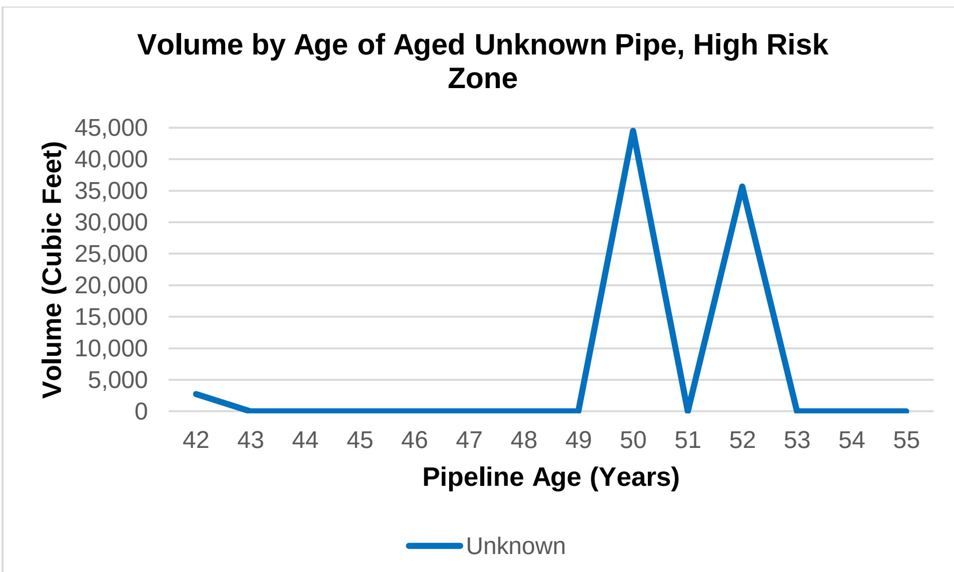

Figure 59: Volume by age of aged unknown pipelines in the High Risk flood zone, excluding no-age pipe

There are several observations to be made for these aged ferrous wastewater pipes in the High Risk flood zone. Again, this section is a narrowing of the analysis performed in the prior section, selecting only those wastewater pipelines that are aged, so these observations represent a narrowing of scope and a closer look at the trends observed in aged pipelines:

- **Relatively Young Ductile Iron Pipe**. The ductile iron pipe that are aged and in the High Risk flood zone appear to be largely 41 to 50 years old.
- **Small Number of Very Aged Cast Iron Pipe.** There is only one very aged cast iron pipe, 75 years old, in the High Risk flood zone; however, this pipe has a volume of 110,000 cubic feet of wastewater – not insignificant given its age.
- **Scale of Ductile Iron Volume Consistent with Cast Iron Pipe.** Interestingly, the volume of ductile iron is much more on scale to that of cast iron pipe than was observed in the previous analysis of the ferrous wastewater pipe, where young ductile iron had high volumes.
- **Small Volumes for Unknown Pipe.** Compared to the cast iron and ductile iron pipes, the aged unknown pipes have a relatively small volume.

B. Aged Ferrous Wastewater Pipe in the Moderate Risk Zone

Then, the moderate risk flood zone was evaluated for the presence of aged ferrous wastewater pipelines within the zone:

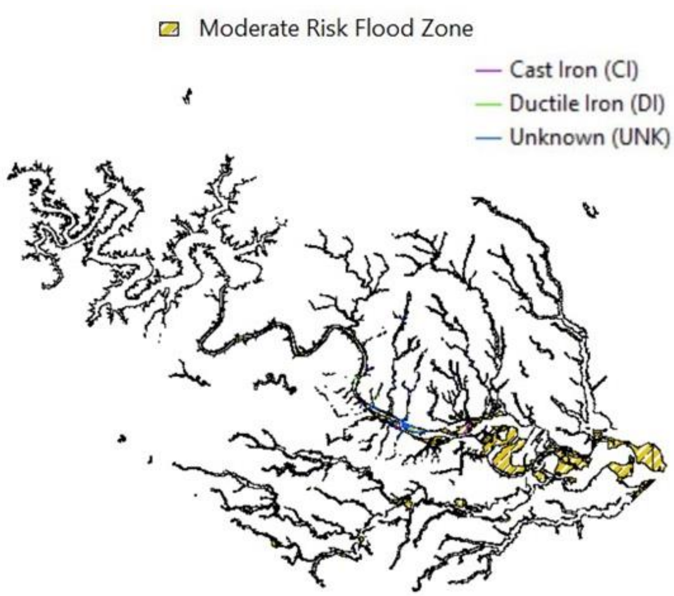

Figure 60: Aged wastewater pipelines in the Moderate Risk flood zone (source: FEMA, Austin Water Utility)

The data for the aged ferrous wastewater pipelines within the Moderate Risk flood zone were evaluated for an age profile:

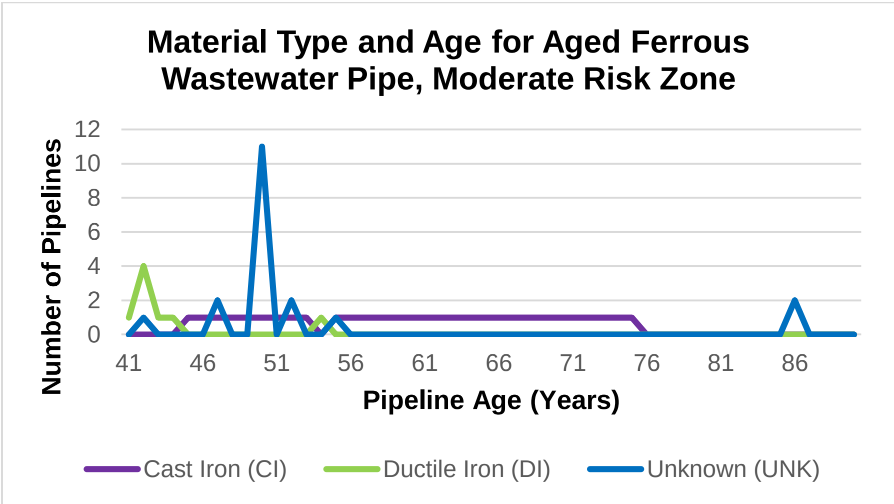

Figure 61: Material type and age for aged ferrous wastewater pipelines in the Moderate Risk flood zone, excluding no-age pipe

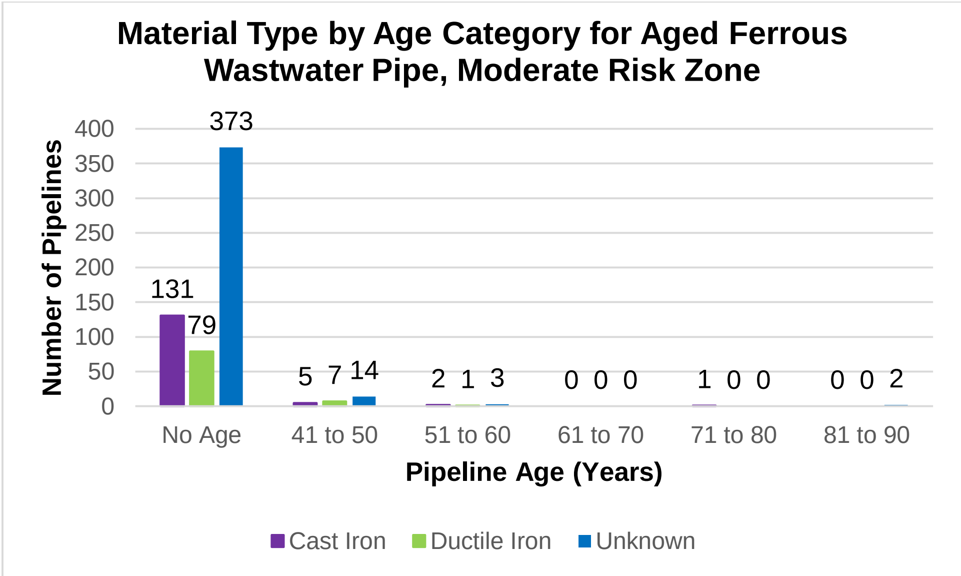

Figure 62: Material type by age category for aged ferrous wastewater pipe in the Moderate Risk flood zone

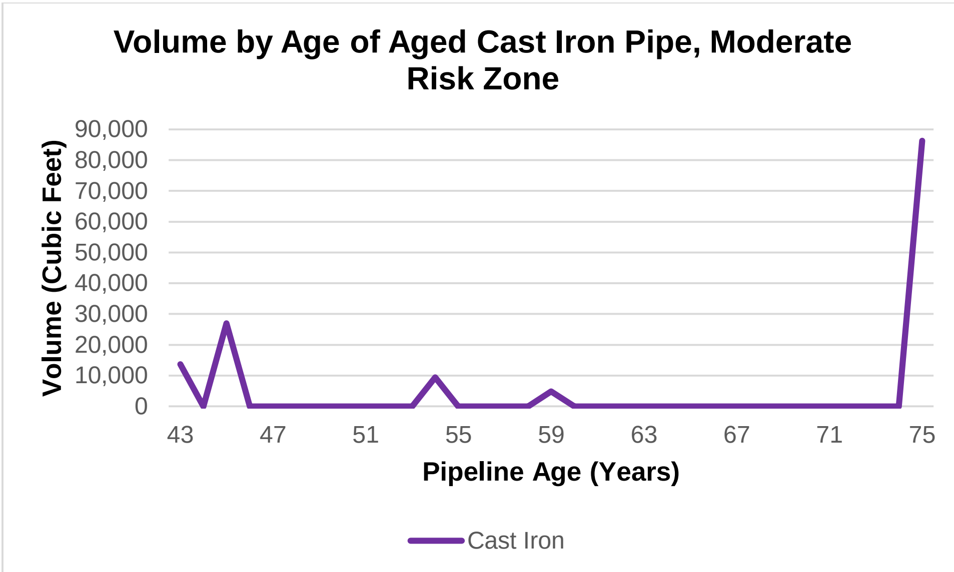

Figure 63: Volume by age of aged cast iron pipe in the Moderate Risk flood zone, excluding no-age pipe

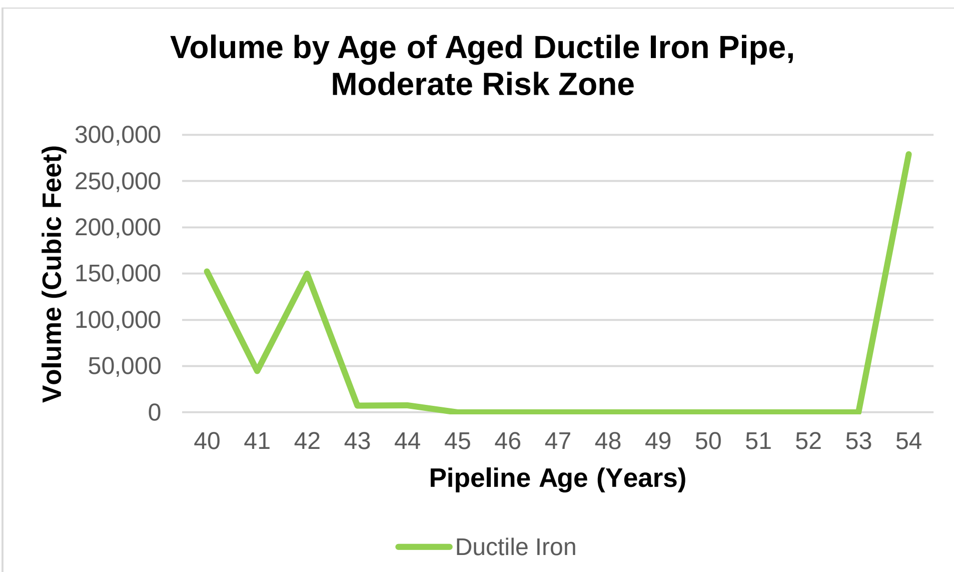

Figure 64: Volume by age of aged ductile iron pipe in a Moderate Risk flood zone, excluding no-age pipe

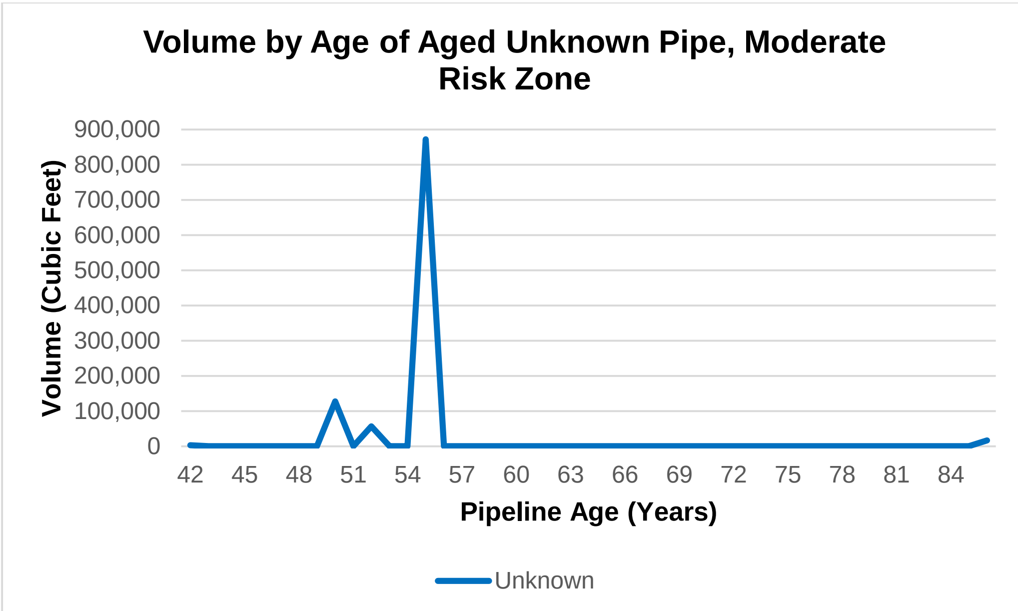

Figure 65: Volume by age of aged unknown pipelines in the Moderate Risk flood zone, excluding no-age pipe

There are several observations to be made for these aged ferrous wastewater pipes in the Moderate Risk flood zone:

- **Flat Level of Installing Cast Iron Pipe**. There appears to have been a trend of consistently installing a small number of cast iron pipe over a period of nearly thirty years.
- **Very Aged Unknown Pipe.** There are two pipes in the Moderate Risk flood zone older than 80 years that are very likely to be cast iron pipes. However, the volume carried by these pipes looks to be very small.
- **Workhorse Very Aged Cast Iron Pipe.** There is a single cast iron pipe older than 70 years; however, that cast iron pipe has a volume of nearly 90,000 cubic feet of wastewater.
- **Unknown Pipe Carrying Large Volume.** Unknown pipe 55 years of age have a volume of 900,000 cubic feet.

C. Aged Ferrous Wastewater Pipe in the Low Risk Zone

Finally, the Low Risk flood zone was evaluated for aged ferrous wastewater pipelines. The following figure shows the Low Risk flood zone with the aged ferrous wastewater pipeline overlay:

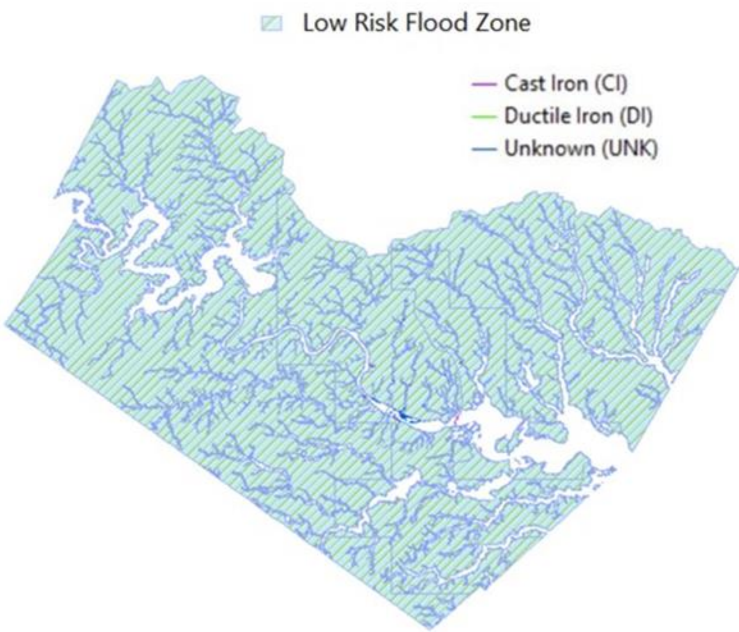

Figure 66: Aged ferrous wastewater pipelines in the Low Risk flood zone (source: FEMA, Austin Water Utility)

The aged ferrous wastewater pipelines within the Low Risk flood zone were isolated and their age profile assessed:

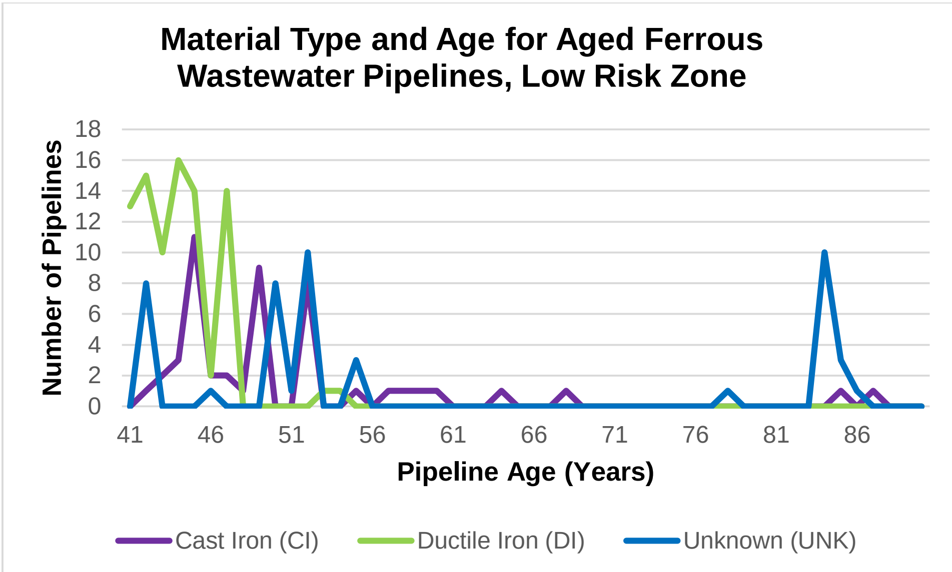

Figure 67: Material type and age for aged ferrous wastewater pipelines in the Low Risk flood zone, excluding no-age pipe

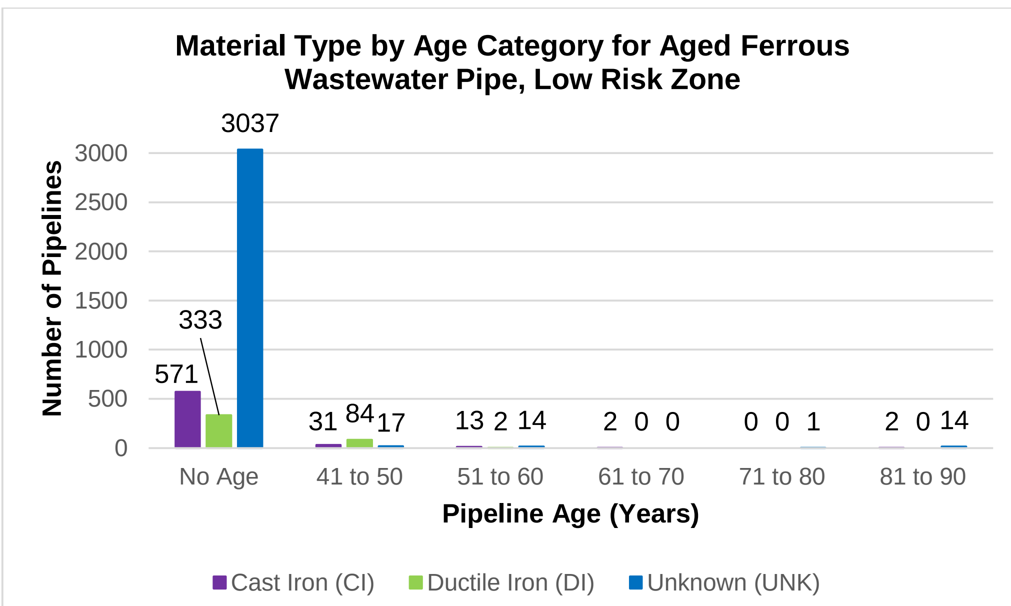

Figure 68: Material type by age category for aged ferrous wastewater pipe in the Low Risk flood zone

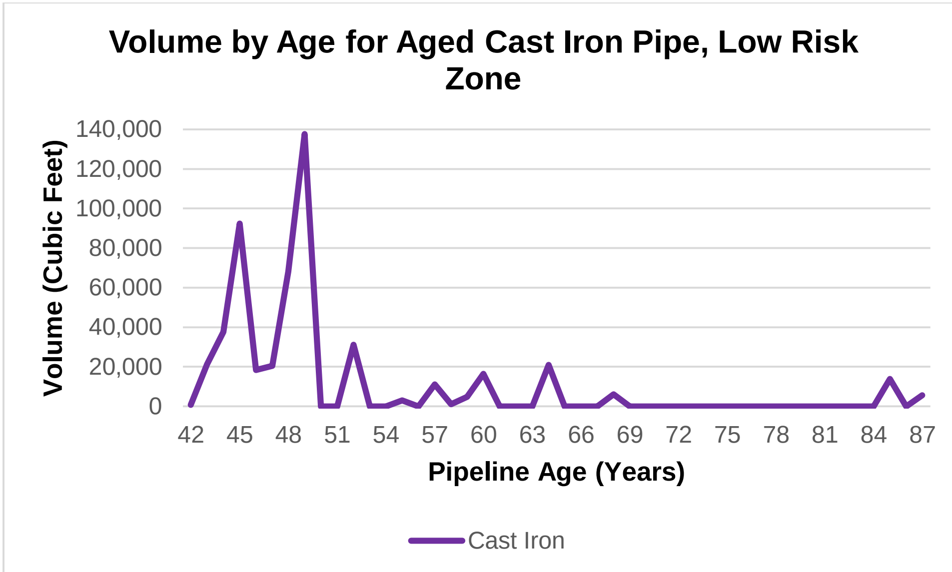

Figure 69: Volume by age for aged cast iron pipe in the Low Risk flood zone, excluding no-age pipe

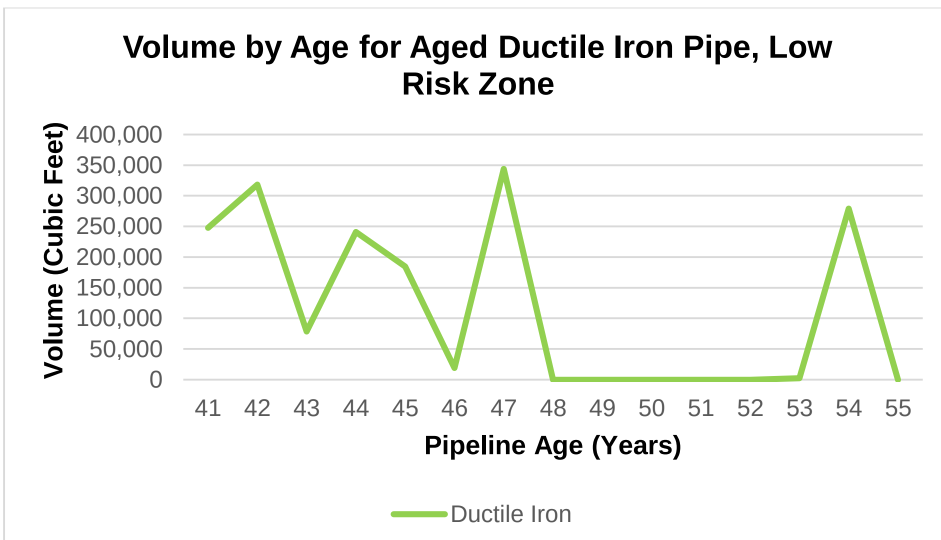

Figure 70: Volume by age for aged ductile iron pipe in the Low Risk flood zone, excluding no-age pipe

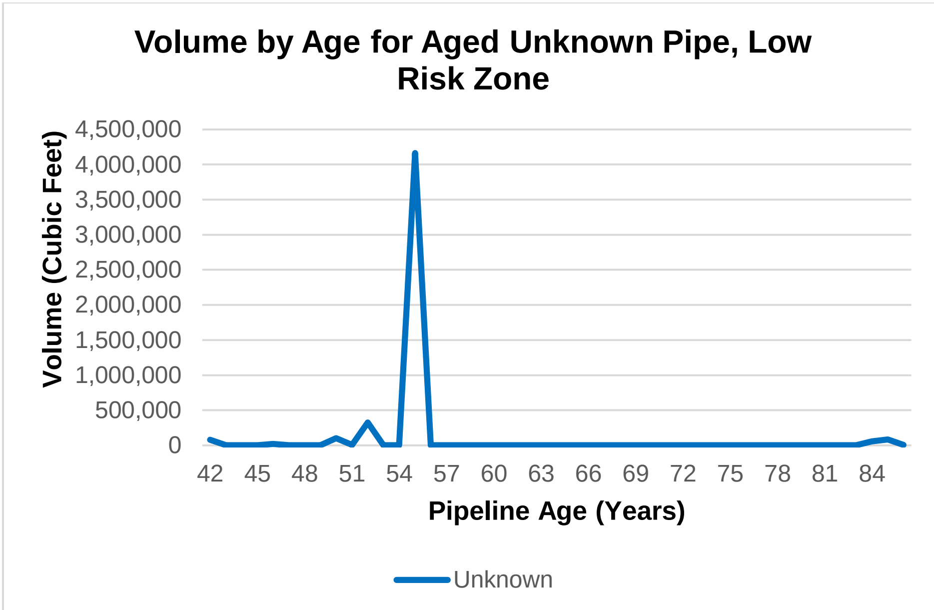

Figure 71: Volume by age for aged unknown pipe in the Low Risk flood zone, excluding no-age pipe

There are several observations to be made for these aged ferrous wastewater pipes in the Low Risk flood zone:

- **Limited Number of Ferrous Pipe Installation from 1936 to 1960.** There appear to have been very few ferrous pipe installed from the period 1936 to 1960 in the Low Risk flood zone. This may be consistent with population trends in the Austin area.
- **Increase in Relatively Young Ductile Iron Pipe Coincident With Cast Iron.** Interestingly, there were 11 cast iron pipelines proposed in 1971, together with 14 ductile iron pipes, to be installed in the Low Risk flood zone. This trend is remarkable given industry literature which suggests that ductile iron was replacing cast iron; here, it is observed that a number of cast iron and ductile iron pipes were proposed concurrently.
- **Very Aged Unknown Pipe, but Small Load.** Remarkably, there are 14 unknown pipes greater than 80 years old; however, these pipe appear to be carrying relatively small volumes of wastewater.

4. **At-Risk Aged Ferrous Wastewater Pipeline**

This section will provide the final layer of analysis: the aged ferrous wastewater pipelines in corrosive soils, by flood zone, that are at risk for corrosion through flooding. This section will answer the following research question and objective:

- **Research Question 3:** For the flood zone under evaluation, are there aged ferrous pipelines located in a potentially corrosive soil?
    - ***Objective:*** Overlay the USGS soil map for Travis County on the selected aged ferrous pipelines for the flood zone under evaluation and isolate any clays and silty clays.

Figure 72 below shows the clays and silty clays, the potentially corrosive soils to ferrous pipelines, which were isolated from the USGS soil data for purposes of this analysis:

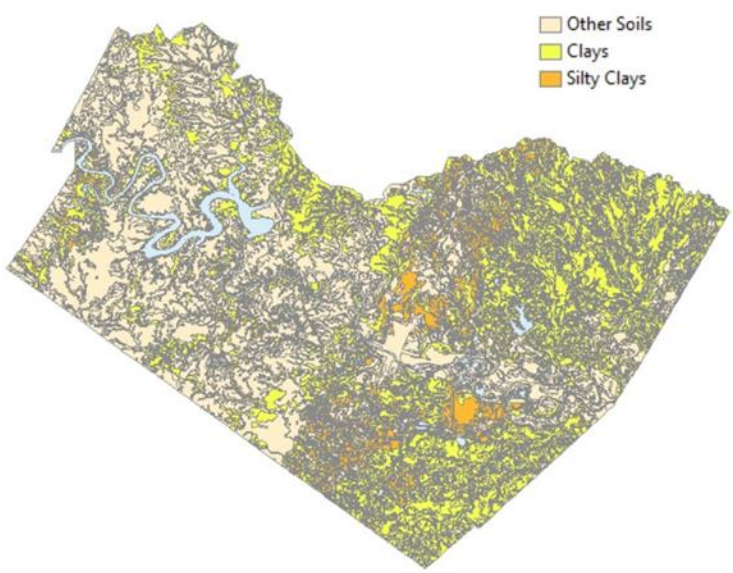

Figure 72: Clays and silty clays in Travis County, isolated from USGS soil data (source: USGS)

A. At-risk Pipe in the High Risk Zone

Figure 73 below shows the layer from the previous figure, the High Risk flood zone, and the aged ferrous pipelines that are both in the High Risk flood zone and located in the potentially corrosive soil:

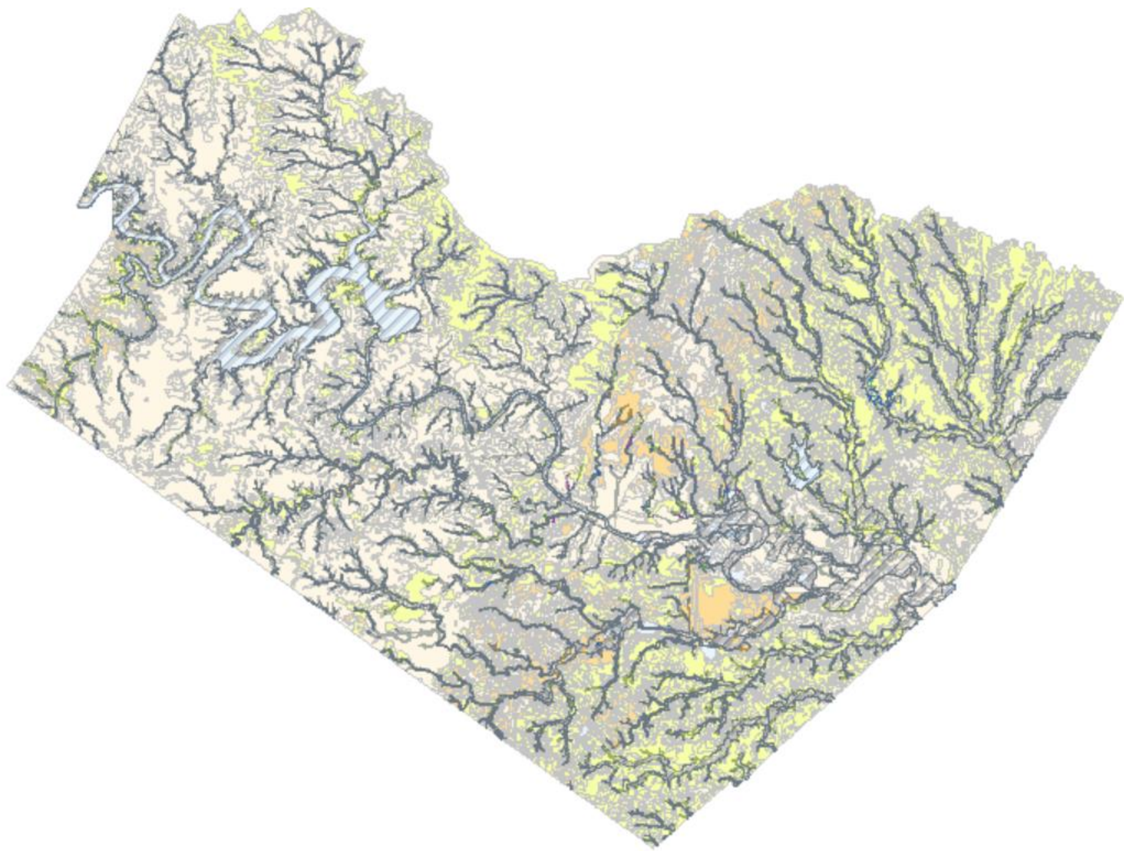

Figure 73: At-risk aged ferrous pipelines in the High Risk flood zone and in a corrosive soil (source: FEMA, USGS, Austin Water Utility)

The aged ferrous wastewater pipelines in a corrosive soil in the High Risk flood zone were isolated and an age profile created.

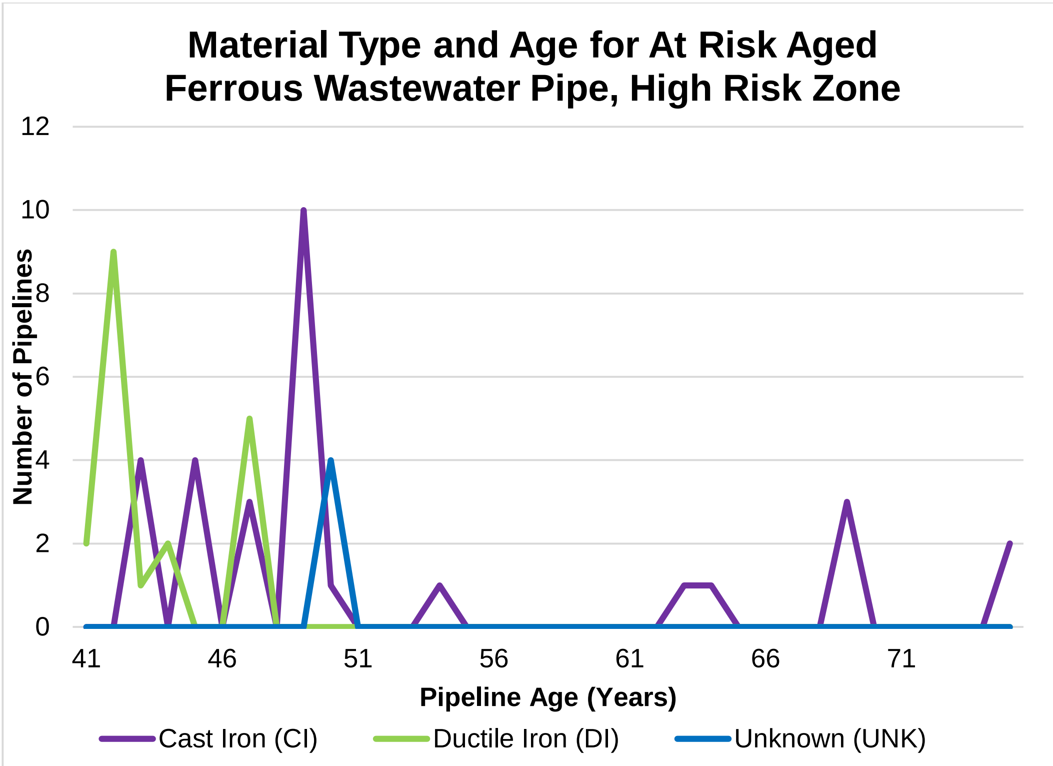

Figure 74: Material type and age for at-risk aged ferrous wastewater pipe in the High Risk flood zone, excluding no-age pipe

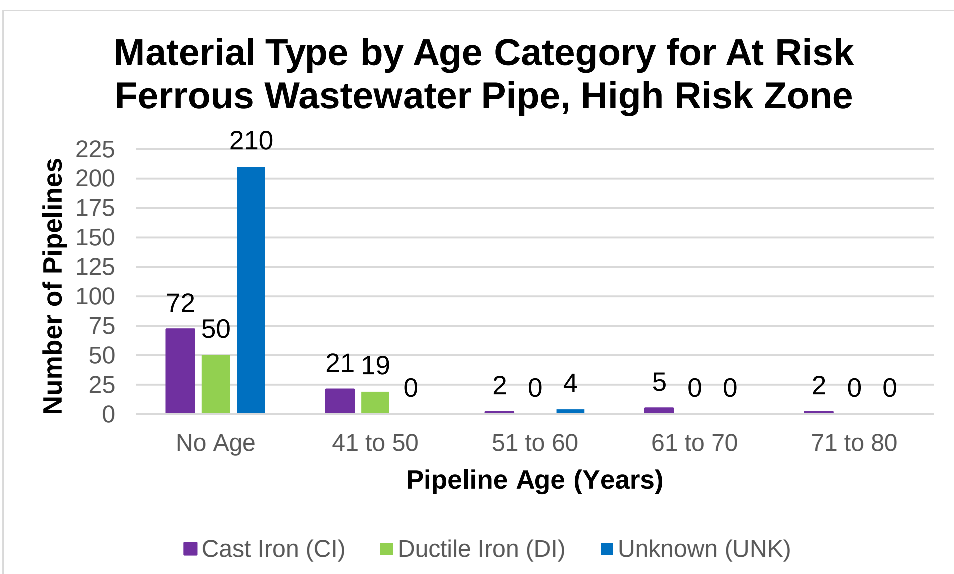

Figure 75: Material type by age category for at-risk ferrous wastewater pipe in the High Risk flood zone

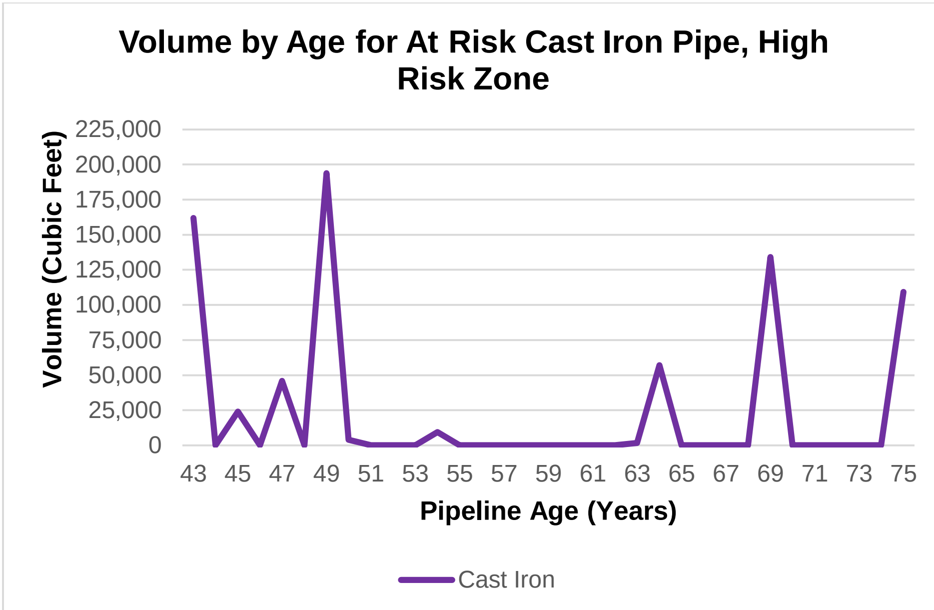

Figure 76: Volume by age for at-risk cast iron pipe in the High Risk flood zone, excluding no-age pipe

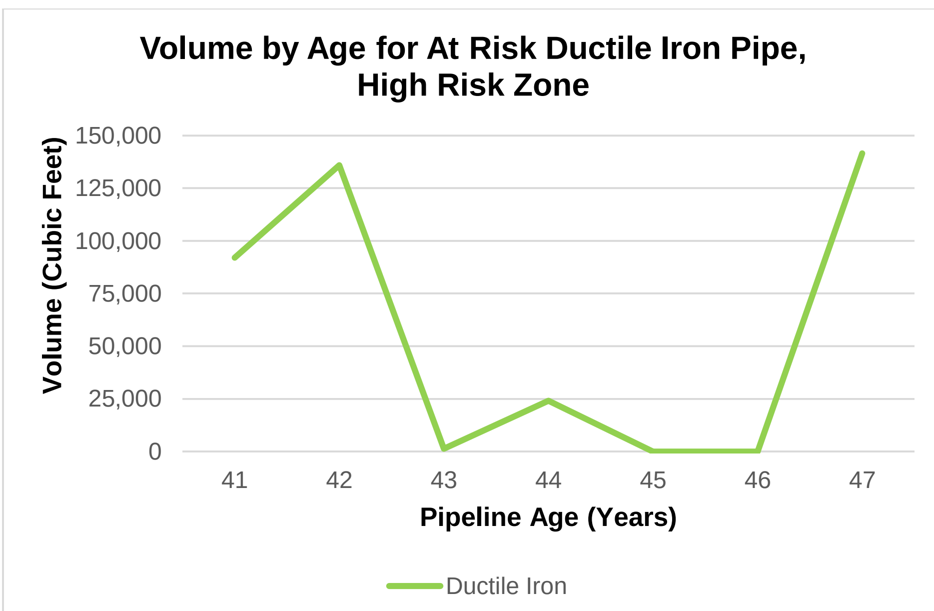

Figure 77: At-risk ductile iron pipe in the High Risk flood zone, excluding no-age pipe

As discussed earlier, there are only four "unknown" pipelines which had a year proposed date given in the GIS data, all of which were 50 years old; therefore, a volume was not created for the unknown pipelines. These pipelines carry a total volume of 900,000 cubic feet altogether.

There are several observations to be made for these at-risk pipes in the High Risk flood zone:

- **Relatively Young Ductile Iron.** There are a number of relatively young ductile iron pipes in the High Risk flood zone that are 41 to 50 years old. Ductile iron pipes aged 42 years are carrying over 135,000 cubic feet of wastewater.
- **Number of Cast Iron Pipes.** Eleven cast iron pipes are 49 years old, and together have a volume of approximately 200,000 cubic feet. Seven cast iron pipes in the High Risk flood zone are older than 61 years, and three 69 year old cast iron pipes are carrying over 130,000 cubic feet of wastewater.
- **Unknown Pipe, Unknown Age.** Only four unknown pipelines in the High Risk flood zone have a known age, 210 do not have a known age.

B. At-risk Pipe in the Moderate Risk Zone

The clays and silty clays previously isolated were overlaid on the Moderate Risk flood zone, and aged ferrous wastewater pipes that were determined to be in the Moderate Risk flood zone were then overlaid on the clays and silty clays to determine if there were any aged ferrous wastewater pipes in the Moderate Risk flood zone that were also in a potentially corrosive soil.

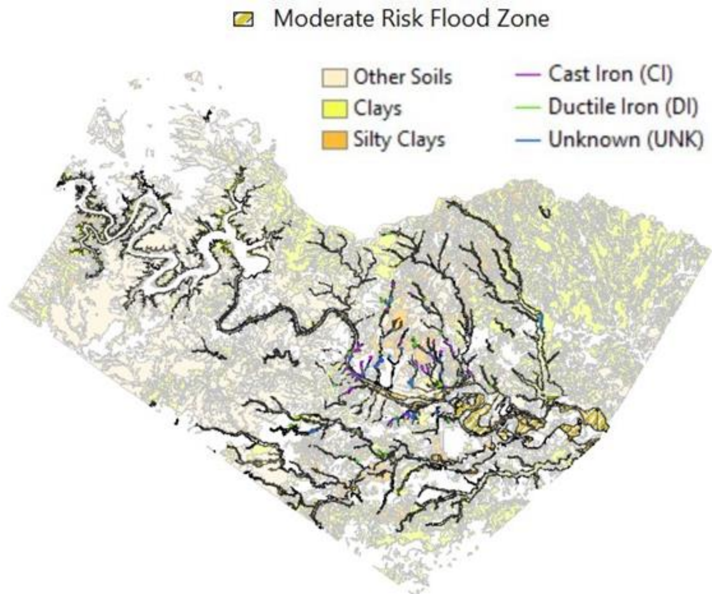

Figure 78: Clays and silty clays overlaid on the Moderate Risk flood zone and aged wastewater pipelines located in both (source: FEMA, USGS, Austin Water Utility)

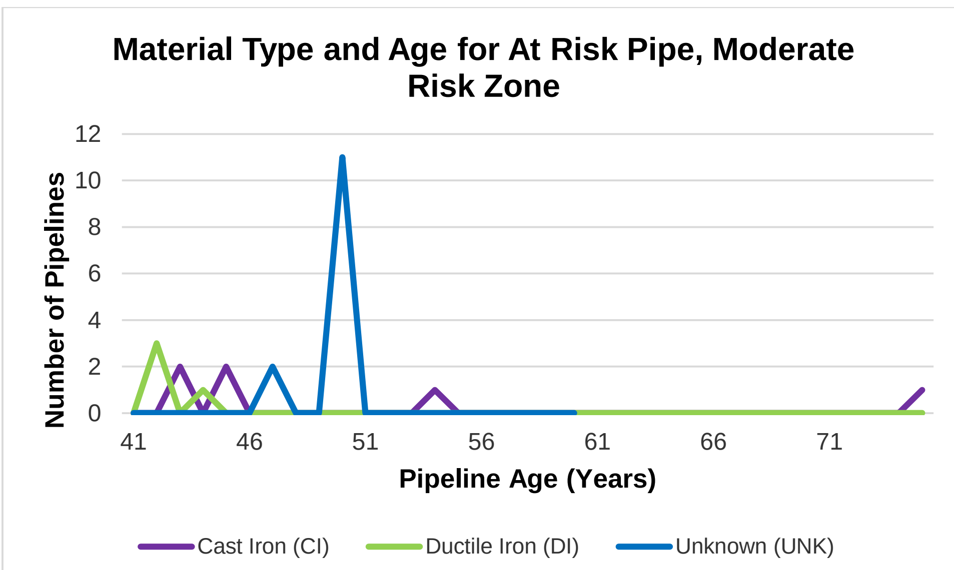

Figure 79: Material type and age for at-risk pipe in the Moderate Risk flood zone, excluding no-age pipe

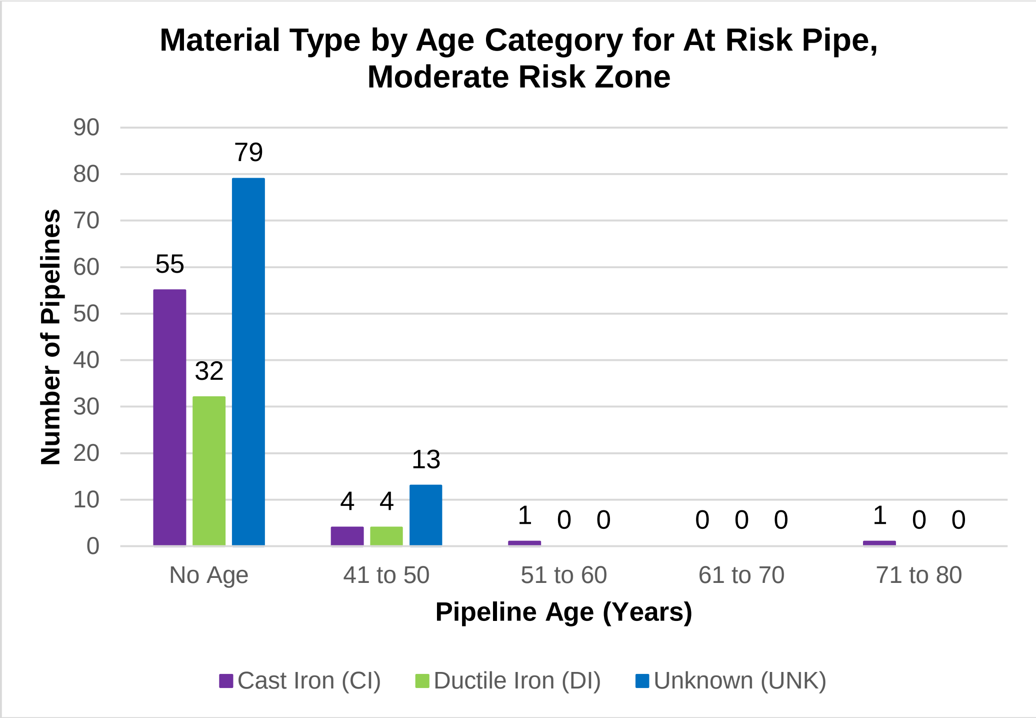

Figure 80: Material type by age category for at-risk pipe in the Moderate Risk flood zone

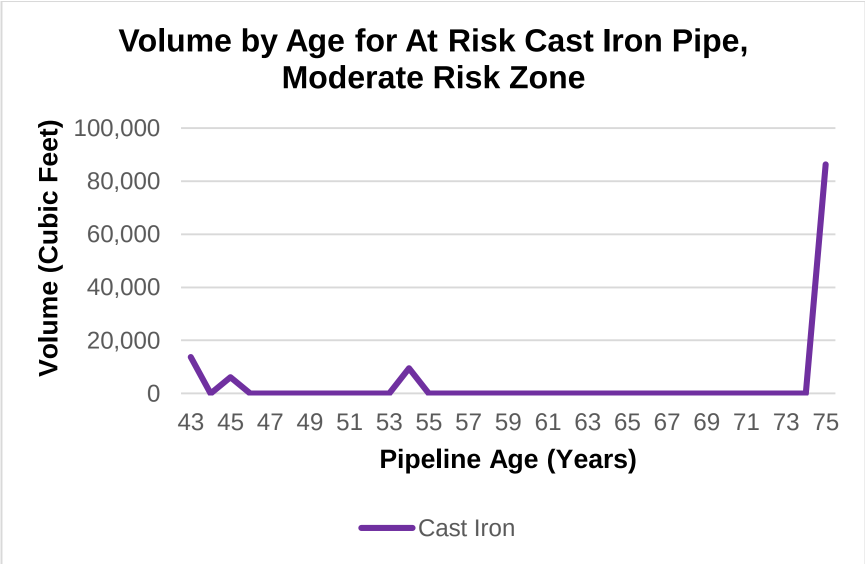

Figure 81: Volume by age for at-risk cast iron pipe in the Moderate Risk flood zone

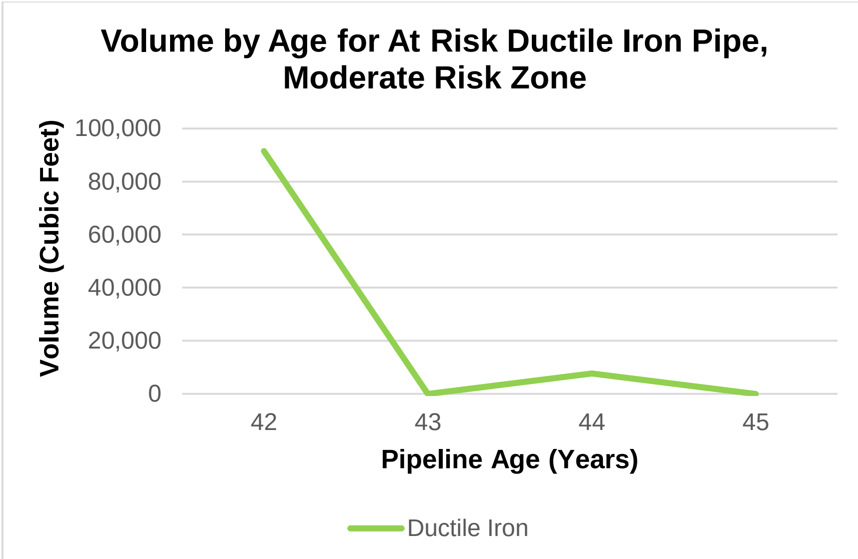

Figure 82: Volume by age for at-risk ductile iron pipe in the Moderate Risk flood zone

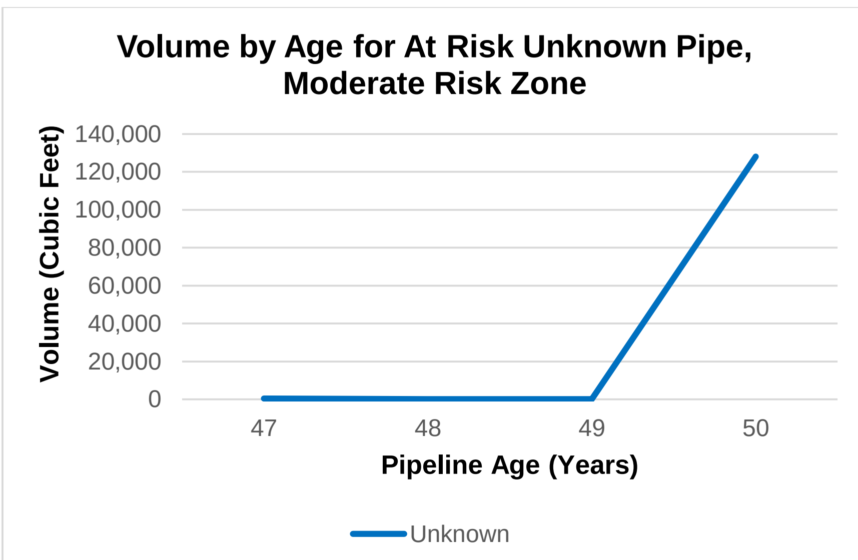

Figure 83: Volume by age for at-risk unknown pipe in the Moderate Risk flood zone

Several observations can be drawn for these at-risk pipes in the Moderate Risk flood zone:

- **Workhorse Unknown Pipes.** Eleven unknown pipes proposed 50 years ago in the Moderate Risk flood zone have a volume of approximately 125,000 cubic feet, more than any single age for cast iron pipes or ductile iron pipes.

- **Dark Period for Ferrous Pipes.** From 1942 to 1961, there appear to have been no ferrous pipes proposed in the Moderate Risk flood zone. This "dark period" may be partially the result of the United States' entry into World War II in December 1941, which would have likely made ferrous materials scarce for the construction of wastewater pipelines.
- **Small and Simultaneous Installation of Ductile Iron and Cast Iron.** Three ductile iron pipes and five cast iron pipes were proposed within three years of each other between 1974 and 1971.
- **Workhorse Aged Cast Iron Pipe.** A 75-year old cast iron pipe in the Moderate Risk flood zone has a volume of about 90,000 cubic feet. For comparison, a 42 year old ductile iron pipe in the Moderate Risk flood zone has a similar volume.

C. At-risk Pipe in the Low Risk Zone

Finally, the at-risk pipeline in a corrosive soil in the Low Risk flood zone were evaluated, and aged ferrous wastewater pipe that had been previously identified to be in the Low Risk flood zone were overlaid on the soil map containing the clays and silty clays, and evaluated to determine if there were any aged ferrous wastewater pipe in the Low Risk flood zone that were also in a potentially corrosive soil.

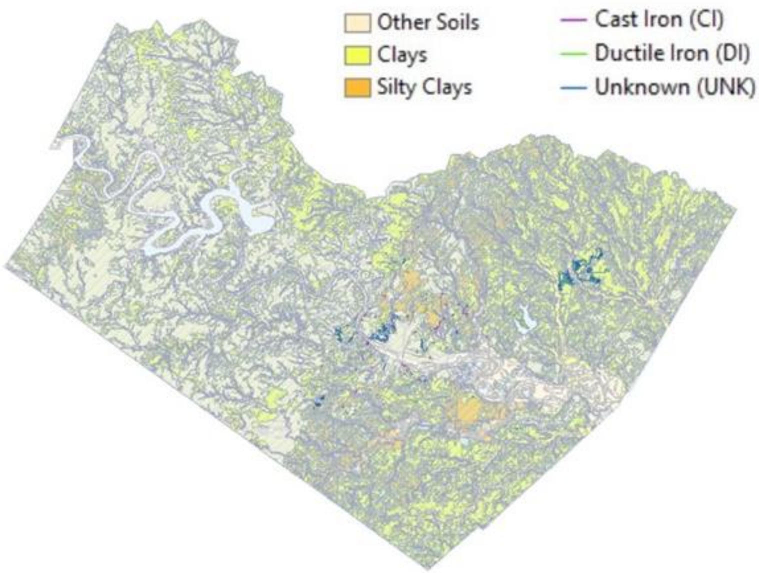

Figure 84: Aged ferrous wastewater pipelines in a clay soil, in the Low Risk flood zone (source: FEMA, Austin Water Utility, USGS)

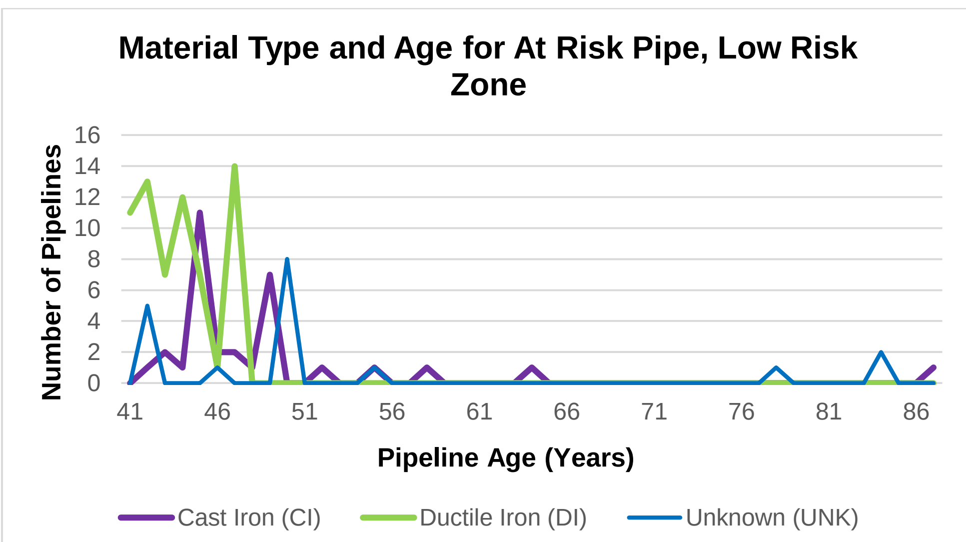

Figure 85: Material type and age for at-risk pipe in the Low Risk flood zone, excluding no-age pipe

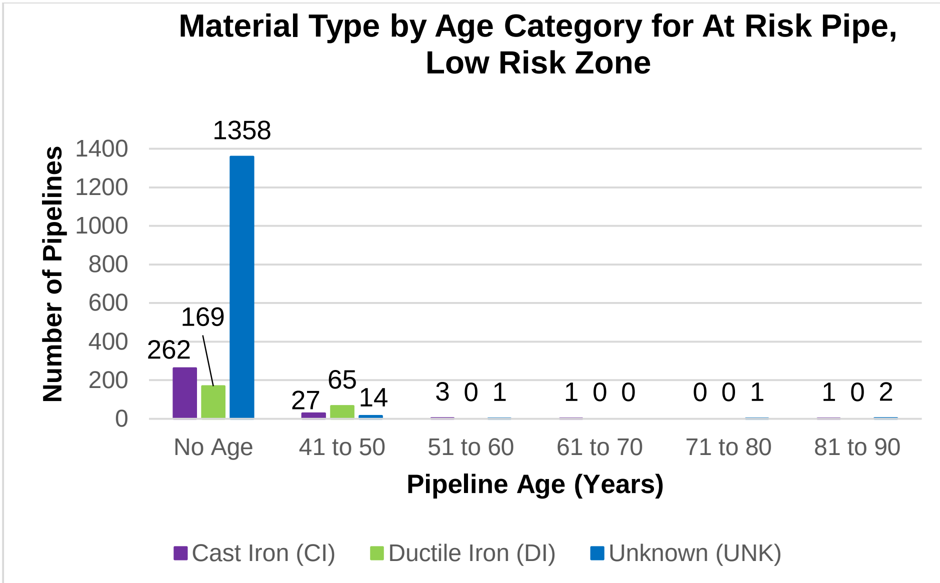

Figure 86: Material type by age category for at-risk pipe in the Low Risk flood zone

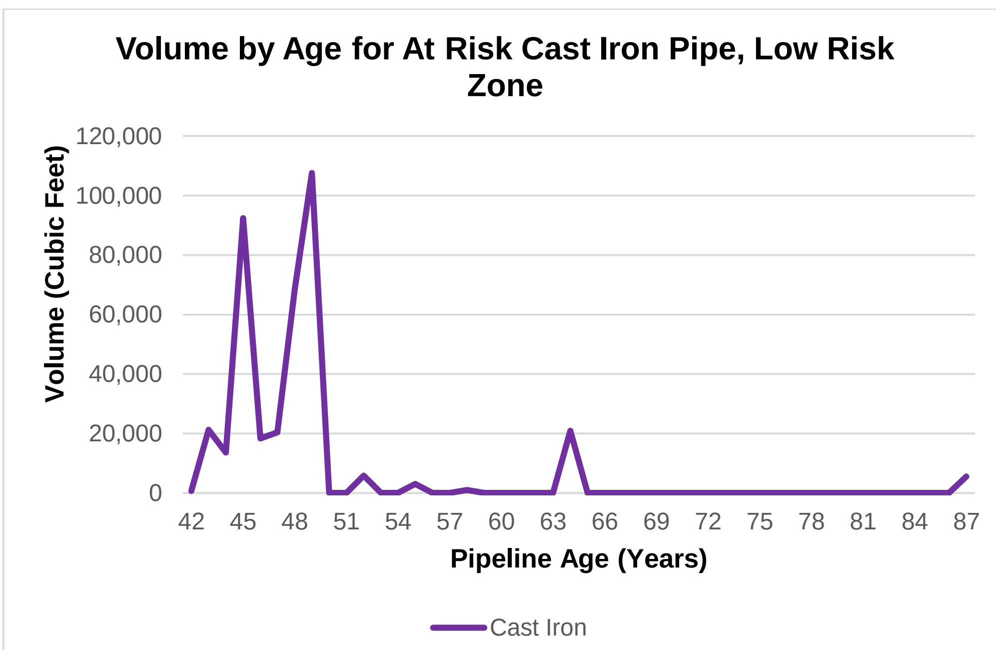

Figure 87: Volume by age for at-risk cast iron pipe in the Low Risk flood zone, excluding no-age pipe

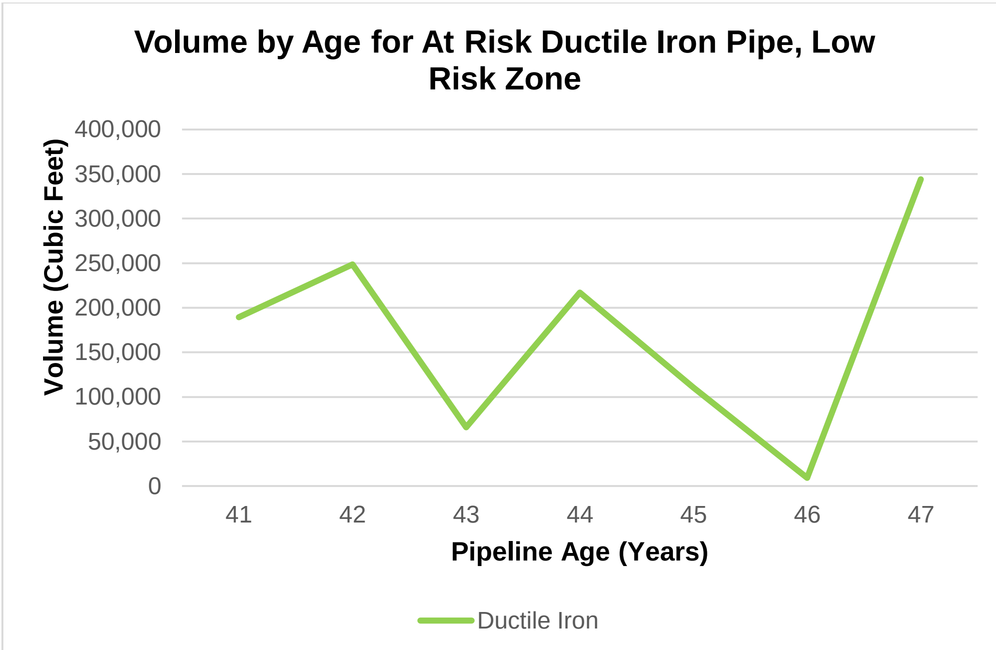

Figure 88: Volume by age for at-risk ductile iron pipe in the Low Risk flood zone, excluding no-age pipe

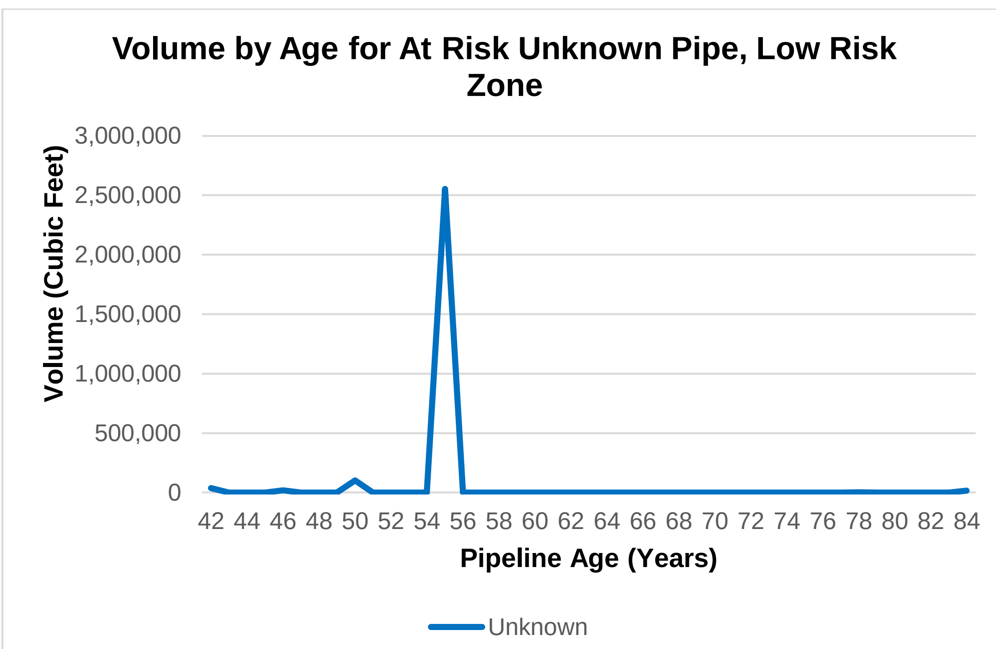

Figure 89: Volume by age for at-risk unknown pipe in the Moderate Risk flood zone, excluding no-age pipe

There are several observations regarding the at-risk pipes in the Low Risk flood zone:

- **Single, Workhorse Unknown Pipe.** A single, unknown 55-year old pipe in the Low Risk zone and in a corrosive soil has a volume of 2.5 million cubic feet. Given the installation age, if this pipe is ferrous, it is possible it is either a cast iron or ductile iron pipe.
- **Relatively Young, Steady Cast Iron Pipes.** Cast iron pipes proposed 47 to 49 years ago and located in a corrosive soil have a collective volume of over 200,000 cubic feet.
- **Large Number of No-age, Unknown Pipe.** Given that the Low Risk flood zone represents the broadest geographic area, it is expected to find a large number of no-age, unknown pipe at just over 1,300 pipes.

5. Evaluating the Edwards Aquifer Recharge Zone

Finally, for the High Risk zone, the at-risk aged ferrous wastewater pipeline in a cororsive soil was overlaid on the Edwards Aquifer recharge zone. There were 80 pipelines that were both at risk in the High Risk flood zone and also located in the Edwards recharge zone. Only the at-risk pipe in the High Risk flood zone was evaluated in comparison to the Edwards Aquifer recharge zone as it is the highest sensitivity of this analysis. Due to the complexity of groundwater recharge dynamics, this final layer of analysis is only intended to provide a high-level model as to how the wastewater manager can consider sensitive aquifers when evaluating the replacement of ferrous pipelines that could leak or break from corrosion through flooding.

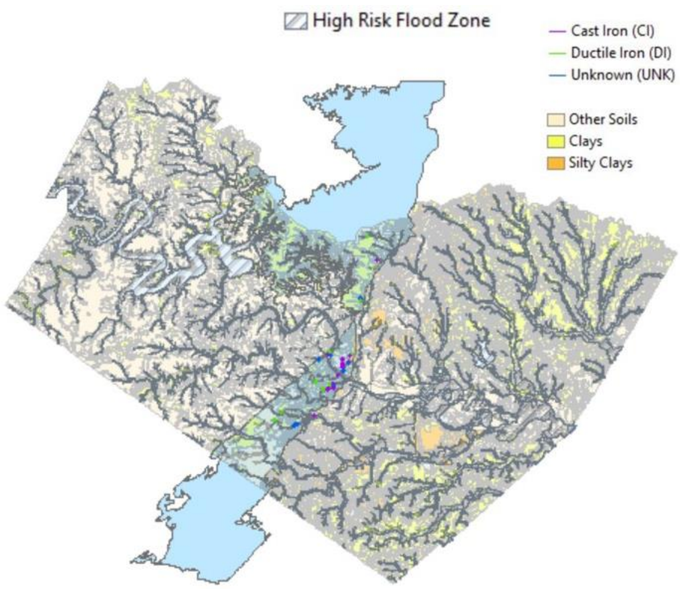

Figure 90: The at-risk pipe in the High Risk flood zone and in the Edwards Aquifer recharge zone

Table 4: Material type and length of at-risk pipe in the High Risk Zone and in the Edwards

Findings for Edwards Recharge Zone - High Risk				
	CI	DI	UNK	Total
Number	45	17	18	80
Total (Mi)	2.30	0.73	1.39	4.42
Avg (Ft)	270.11	226.87	409.41	-
Total Vol (ft^3)	606316.78	464063.8	332196.86	1402577.48
Avg Vol (ft^3)	13473.71	27297.87	18455.38	-
Avg Age (Years)	47.3	41.7	n/a	n/a
*Note: Average age excludes "no age" pipes for which an age of 0 is given.				

6. Summary of Findings

The tables below provide an overview of the findings for each layer of analysis, by material type and flood zone.

Table 5: Summary of findings for ferrous wastewater pipe, by material type and flood zone

	Summary of Findings for Ferrous Wastewater Pipe								
	High Risk Zone			Moderate Risk Zone			Low Risk Zone		
	CI	DI	UNK	CI	DI	UNK	CI	DI	UNK
Number	215	415	502	144	305	456	645	1611	3667
Total (Mi)	14.6	34.64	29.53	11.86	31.20	26.53	29.74	116.64	175.71
Avg (Ft)	358.47	44.91	310.58	442.98	486.42	307.20	243.42	382.27	253.00
Total Vol (ft^3)	5790920.41	35499698	25414916	4298740	31494180	38633669.73	8637403	73258911	63233097
Avg Vol (ft^3)	99843.46	633923.2	564775.9	29852.36	103259.61	508337.76	112174.1	1331980	743918.8
Avg Age (Years)	48.31	29	29	42.1	26.6	33.3	43.1	26.9	29
*Note: Average age excludes "no age" pipes for which an age of 0 is given.									

Table 6: Summary of findings for aged ferrous wastewater pipe, by material type and flood zone

	Summary of Findings for Aged Ferrous Wastewater Pipe								
	High Risk Zone			Moderate Risk Zone			Low Risk Zone		
	CI	DI	UNK	CI	DI	UNK	CI	DI	UNK
Number	207	138	454	139	87	392	619	419	3085
Total (Mi)	13.91	9.72	26.79	11.43	5.76	23.22	28.28	21.02	145.23
Avg (Ft)	354.73	371.99	311.62	434.31	341.64	312.71	241.22	263.63	248.56
Total Vol (ft^3)	5291125.11	12062916	23294532	3875743	11213683	36708595	7857821	15416966	54412524
Avg Vol (ft^3)	139240.13	753932.2	1552969	113992.4	700855.2	798012.93	167187.7	963560.4	1182881
Avg Age (Years)	52.4	44.4	49.4	51.1	43.4	53.5	50.8	44	60.4
*Note: Average age excludes "no age" pipes for which an age of 0 is given.									

Table 7: Summary of findings for at-risk pipe, by material type and flood zone

	Summary of Findings for At Risk Pipe								
	High Risk Zone			Moderate Risk Zone			Low Risk Zone		
	CI	DI	UNK	CI	DI	UNK	CI	DI	UNK
Number	102	70	214	61	36	92	249	234	1376
Total (Mi)	7.82	6.11	14.06	5.64	3.01	7.21	15.81	14.80	78.51
Avg (Ft)	404.83	467.34	346.99	487.95	429.08	413.92	283.96	331.04	300.83
Total Vol (ft^3)	2628751.43	2622609	10739641	1796999	1580414	2456162.4	4373194	5256701	26474425
Avg Vol (ft^3)	77316.218	327826	5369821	52852.92	316082.7	491232.49	93046.68	657087.7	601691.5
Avg Age (Years)	52.4	43.5	50	50.8	42.5	49.4	48.8	43.8	53.2
*Note: Average age excludes "no age" pipes for which an age of 0 is given.									

There are several observations to be noted:

- **Greater Number of Aged Ferrous in High Risk Zone.** There is a greater number of aged ferrous pipe in the High Risk flood zone in each category of material in the High Risk flood zone than in the Moderate Risk flood zone. This may be due to population dynamics in the Austin area; the central part of Austin, closer to water and therefore low-lying areas more susceptible to flood, may have been originally built out for wastewater when ferrous materials were more dominant in the industry.

- **Aged Cast Iron Relative to Ductile Iron.** Cast iron appears to be, on the whole, six to eight years older than ductile iron, which would be consistent with industry trends of ductile iron functioning as a replacement for cast iron.
- **More Ferrous in the High Risk Zone**. Interestingly, there is an increased length of ferrous pipe in the High Risk flood zone versus the Moderate Risk flood zone, in each ferrous category, and the ferrous pipes in the High Risk flood zone appear to be older for the cast iron and ductile iron categories, and only slightly younger for the unknown pipes.
- **Workhorse Ductile Iron Pipe**. In the High Risk flood zone, ductile iron pipes are workhorses, with a volume of 3.5 million cubic feet, and an average volume of approximately 634,000 cubic feet; the average volume of cast iron is relatively modest at nearly 1000,000 cubic feet, by comparison. In addition, ductile iron also covers the most ground in the High Risk flood zone, at a total of nearly 35 miles.

CHAPTER 5: DISCUSSION

1. Suggestions

A. Replacement of At-Risk Ferrous Pipelines

The wastewater manager should prioritize replacement of at-risk ferrous pipelines identified in the High Risk flood zone. Those pipelines that are of a known ferrous material (either cast iron or ductile iron) and a known age greater than 40 years, especially those that are particularly aged and carrying a certain threshold of volume, should be first prioritized. Particularly of note is that the three cast iron pipes that are 69 years old and located in a corrosive soil in the High Risk flood zone are carrying a total volume of approximately 135,000 cubic feet. In addition, there is a 75 year old cast iron pipe that is carrying a volume of 85,000 cubic feet that is also at risk for corrosion through flooding, which the wastewater manager may wish to consider replacing with a non-ferrous pipeline. In the Moderate Risk flood zone and in a corrosive soil, there are 19 ductile iron pipes that are together carrying 141,000 cubic feet of wastewater. The wastewater manager should consider investigating if any one of those pipe is carrying the brunt of that volume, and, if so, prioritize it for replacement.

Where there is a pipeline of an “unknown” material that is particularly aged, such as 85 years old, this pipeline should be assumed to be cast iron given construction trends, and should also be prioritized for replacement. In addition, the at-risk pipeline that is also in a recharge zone should be even more so prioritized for replacement.

B. “Unknown” Pipeline Materials

The municipal wastewater manager should make an effort to identify materials of wastewater pipelines that are currently listed as “unknown” in the GIS data and appropriately categorize such materials, as the location of the pipelines are available in GIS data, and could make such identifications as resources allow, or on other visits to the pipelines. Identifying and categorizing these materials will assist the wastewater manager in decision-making with respect to replacing pipelines, especially if the pipelines currently listed as "unknown" are ferrous pipelines located in a corrosive soil.

C. Age Data

In addition, the municipal wastewater manager should assess the pipeline network and also prioritize identification of missing age data, which may assist the manager in his or her approach to pipeline replacement. Where such age data cannot be found, estimates based on site visits would be an appropriate substitute, or levels of corrosion assessed, as such site visits are made.

2. Conclusion

This study could provide a foundation for a methodological approach for Austin Water Utility to consider flood risk based on the location of wastewater pipelines by considering the age and material of pipelines relative to flood zones and soil location when considering which pipelines to replace.

3. Limitations

A. Corrosion Potential

As discussed previously, it is certain soil properties that contribute to a soil's corrosion potential. This thesis did not consider all these soil properties as a whole, but rather selected two of the properties: soil resistivity, using soil type as a proxy, and high soil moisture, using flood zones as a proxy. Future work in this area could conduct site visits and test the soils in high risk flood zones in which there are ferrous pipelines for all of the soil properties that contribute to a soil's corrosion potential: soil resistivity, pH, chlorides, moisture, sulfates, redox, and stray current. Such a framework would be a more precise and comprehensive approach to measuring soil corrosion potential.

In addition, there may be more precise mathematical or computational models that can be formulated to better understand the rate of corrosion of a ferrous pipeline in a particular soil environment, perhaps with inputs of age and soil characteristics.

B. Unknown Pipelines

As discussed earlier, due to the categorization of pipelines whose materials were "unknown", this study may not have a complete and correct picture of the ferrous wastewater pipelines at risk for corrosion through flooding, as 68% of the aged ferrous pipelines evaluated in this thesis are categorized as "unknown", amounting to approximately 232 miles of the pipeline evaluated. The case may be that none of the pipelines categorized as "unknown" materials are ferrous, or that only some portion of those are ferrous. If Austin Water Utility were to update its GIS data for its wastewater network with all the materials of pipelines currently categorized as "unknown", future research could complete the analysis laid out in this study with a more accurate picture of the ferrous wastewater pipelines at risk for corrosion through flooding.

C. Internal versus External Corrosion

This thesis only considered external corrosion to a wastewater pipeline from surrounding soil. Internal corrosion of a wastewater pipeline is also a concern for the wastewater manager. Further work in this area could use a framework like the one laid out in this thesis for determining external corrosion to ferrous pipeline, and could also combine such work with internal corrosion for a wastewater network. Such work would provide a more holistic approach for determining the total effects of corrosion on a wastewater network.

D. Ferrous Pipelines

Only ferrous pipelines were considered in this work. There may be some other wastewater pipeline materials that are at risk for corrosion, whether it be internal or external. In addition to the analysis of ferrous pipelines presented in this thesis, some research indicates that asbestos cement or concrete pipelines may merit further study by those wishing to do more work in this area. Such an analysis, especially combined with a more holistic picture of internal and external corrosion, may provide a very useful decision-making framework for the wastewater manager.

E. Trade-Offs and Other Considerations

While this thesis provides for the municipal wastewater manager a framework for prioritizing replacement of aged ferrous wastewater pipelines, it does not make specific recommendations for non-ferrous materials with which to replace the ferrous pipelines. As discussed above, there may be trade-offs with other pipeline materials, such as internal corrosion, cost, or other environmental concerns. A table from the United States Environmental Protection Agency provides an overview of the trade-offs of various wastewater pipeline materials as an example of the possible considerations the wastewater managers may face when making decisions about his or her network:

Table 8: Advantages and disadvantages of materials (source: U.S. EPA, Wastewater Technology Fact Sheet)

Advantages	Disadvantages
Ductile Iron	
• Good corrosion resistance when coated	• Heavy
• High strength	
Concrete	
• Good corrosion resistance	• Requires careful installation to avoid cracking
• Widespread availability	• Heavy
• High strength	• Susceptible to attack by H_2S and acids when pipes are not coated
• Good load supporting capacity	
Vitrified Clay	
• Very resistant to acids and most chemicals	• Joints are susceptible to chemical attack
• Strong	• Brittle (may crack); requires careful installation
	• Short length and numerous joints make it prone to infiltration and more costly to install
Thermoplastics (PVC, PE, HDPE, ABS)	
• Very lightweight	• Susceptible to chemical attack, particularly by solvents
• Easy to install	• Strength affected by sunlight unless UV protected
• Economical	• Requires special bedding
• Good corrosion resistance	
• Smooth surface reduces friction losses	
• Long pipe sections reduce infiltration potential	
• Flexible	
Thermosets(FRP)	
• High strength	• High material cost
• Lightweight	• Brittle (may crack); requires careful installation
• Corrosion resistant	• High installation cost

In addition, the US EPA also provides an example of the cost per linear foot by pipe diameter, another consideration the wastewater manager faces:

Table 9: Average cost per linear foot by pipe diameter (source: U.S. EPA, Wastewater Technology Fact Sheet)

Pipe Material	2"	4"	6"	8"	12"	15"	18"	24"
VCP	-	-	$25	$30	$38	$50	$65	$110
DIP	-	-	-	$38	$50	N/A	$75	$110
RCP	-	-	-	-	$11	$17	$23	$31
PVC	$15	$19	$23	$25	$30	$38	$50	$75
PE	-	$7	$12	$14	$9*	-	$16*	-
FRP	$21	$30	$42	$60	-	-	-	-
ABS	$11	-	-	-	-	-	-	-

In addition, when evaluating the diversity of pipeline materials of a municipal network, it is important to consider, as Romer and Passaro (2007) discuss, the political forces that may be a factor in a wastewater pipeline manager's consideration of purchase of pipeline materials: faced with a budget given to the municipally owned utility by the city, the wastewater manager may choose to buy pipelines in bulk from a seller – all made of one material. Future research in this area could consider the matrix of decisions facing the wastewater manager in pipeline material selection, and the risk to each material.

F. Risk Calculation

This thesis did not consider an economic calculation of the risk exposure that the wastewater manager faces from corrosion of his or her network's ferrous wastewater pipelines to corrosion through flooding. Future research could assess a range of economic costs of potential damage, and compare the economic costs with a matrix of costs and savings to replacing the pipeline with non-ferrous materials. Such research would be especially complete and useful to the wastewater manager when paired with a decision-making matrix as discussed in the prior section.

G. Data to Calculate Age

To calculate the age of a pipeline, this thesis utilized the data available, the year in which the pipeline was proposed. Where there was no year proposed given, it was assumed that such pipes were aged. As there is some time that passes between when a pipeline is proposed to the time of its installation, such an approach, together with the approach of including ferrous pipelines in which no age was given, biases the results to over-estimate the amount of at-risk pipeline. Future research with a more complete data set could re-evaluate the data with the years in which the pipelines were installed.

4. Potential Contribution

This work could provide a methodological approach to evaluating the replacement of pipeline for a network with respect to a disaster avoidant perspective of preventing corrosion by identifying ferrous wastewater pipelines that are most at risk for corrosion through flooding, especially those located in an environmentally sensitive area, and replacing those with non-ferrous pipelines.

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