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Leaking Underground Storage Tank Impact Model

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Abstract

Leaking underground storage tanks (UST) pose a threat to the surrounding environment and population. The Montana Department of Environmental Quality (MT DEQ) has completed two phases of a risk analysis with the purpose of identifying the USTs at the greatest risk of leaking in order to reallocate department resources. This analysis builds upon prior analyses in three ways: (1) identifying how UST upgrades can reduce the risk of UST leaking, (2) how UST characteristics and upgrades relate to the cost of remediation, and (3) estimating the environmental and community impact of a release. The creation of linear regression models provided insight into how upgrades affect the risk coefficient and characteristics affect the cost of remediation. Further, the depreciation of nearby property values and an increase in cancer risk in community members due to a release provided a quantified estimation of environmental and community impacts.

Acknowledgements

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1 Introduction

According to the United States Environmental Protection Agency's (EPA) 2018 Semi-annual Report of UST Performance Measures, there are 550,379 EPA regulated Underground Storage Tanks at approximately 199,00 different sites across the United States [7]. But, the EPA estimates only 70.3% of the regulated underground storage tanks (USTs) were in compliance from October 2017 to September 2018 [7]. The EPA and the individual states' Department of Environmental Qualities (DEQ) maintain regulations and perform inspections to prevent environmental harm as a result of USTs. The highest level goal of the regulations and inspections is to prevent USTs from leaking. However, despite the laws and efforts of government agencies, USTs continue to spring leaks.

The same EPA report indicates in 2018 that 5,654 new releases were confirmed, 8,128 releases were remediated, but remediation is incomplete or not started in a whopping 65,446 releases [7]. The severity of leaking underground storage tanks (LUSTs) greatly vary, as the term releases includes small overflows above ground to leaks underground that contaminate surrounding ground water. Thus, the communal effects of a release can range from practically no effect to the contamination of an entire community's primary drinking water source. In addition to the economic impacts, the remediation cost of releases greatly vary. Most states have a designated state fund, supported by gas taxes or fees from UST owners, with the sole purpose to pay for remediation costs of a UST leak. Yet, even the most effective remediation method cannot always return the release site to the exact prior condition.

Leaking USTs have the capability to cause significant environmental harm; however, the large number of USTs reduces the frequency of inspections.

1.1 Statement of Purpose

While the prior risk analysis provides insight into which USTs are of greatest risk, the analysis fails to model the detriments associated with an increased risk or how to reduce the risk. Thus, this analysis seeks to provide insight into the financial and environmental effects of a UST release and how to most effectively reduce an UST's risk of leaking.

1.2 Scope

This analysis seeks to answer the following questions:

- Do upgrades relate to the UST's risk value? If so, how?
- What is the financial cost to the community due to the increased health risk due to a UST leak?
- Can upgrades change the potential financial cost of a leak for the owner? If so, by how much?
- Are upgrades a feasible and effective way for UST owners to reduce potential costs and risks? If so, what upgrades have the greatest possibility of reducing the potential costs and risks?

1.3 Affected Parties

The parties benefiting from the decision support of this analysis include:

- All Montana Department of Environmental Quality programs associated with the regulation of USTs and remediation of UST spills.
- Owners and operators of USTs.

Further, the public and other government agencies benefit from the analysis, as the analysis provides an understanding of possible effects communities may encounter in the case of a leak.

1.4 The Importance of This Analysis

A deeper understanding of the risk, cost, and health risk of a UST leak can lead to:

- An adoption of policies to reduce risks and costs
- Increased information for future financial planning
- Statistically founded predictors of future leaks for regulators and inspectors
- Improved understanding of how preventative maintenance and replacements can reduce risk and cost in the event of a leak

2 Background

2.1 MT DEQ Prior Risk Analysis

In 2018, the Montana Department of Environmental Quality (MT DEQ) began a risk assessment of the state's USTs aimed at identifying USTs with the greatest risk of leaking. At the request of the MT DEQ, and to remain consistent with the techniques used in a similar risk analysis by the Utah DEQ, the risk analysis was performed using Analytical Hierarchy Process (AHP). The risk assessment was split into two phases. The first phase sought to identify the highest risk USTs based on tank characteristics. The second phase identified the highest risk USTs using tank, environmental, and facility characteristics. Appendix A lists all the variables used for phase one and two, and provides descriptions of how each was numerically classified for the AHP analysis. MT DEQ UST experts ranked the characteristics in order of the likelihood of increasing the severity of a release. Further, each characteristic was classified on a scale of zero to four by MT DEQ UST regulators, where zero is the best case and four is the worst scenario.

2.2 Montana UST Regulations

According to Montana regulations all MT DEQ regulated UST facilities must be inspected at least every three years, or at least 90 days prior to the expiration of the facility's operating permit, by licensed private inspectors [8]. Once the inspector completes the department mandated forms regarding the facility's adherence to policies, the MT DEQ reviews the report to determine if a violation has occurred. Moreover, the renewal and issuance of UST operating permits requires an inspection that indicates the facility's compliance with state and national regulations [8].

Moreover, Montana state and federal regulations require owners and operators of USTs to have the proper equipment to prevent and detect spills, as well as appropriate financial responsibility. The EPA defines financial responsibility as a set monetary amount of coverage to finance the costs of remediation and compensate affected third parties [1]. The Montana state regulations include standards for UST equipment, design, and installation [9].

2.3 Montana Petroleum Fund

Federal regulations set forth by the EPA require UST owners to have a minimum "amount of financial responsibility", usually backed by state Petroleum Funds or insurance companies [1]. The required amount of financial responsibility varies depending upon the type and size of the UST. In addition to the per occurrence coverage seen in Table 1, the owners must have aggregate coverage of $1 million and $2 million for ownership of fewer than 100 USTs and more than 100 USTs, respectively [1].

Further requirements, such as copays and fees are set forth by the financial re-

Use of USTs	**Per Occurrence Coverage**	**Required Copay**
Producers, refiners, marketers	$1 million	$17,500
Non-marketers	$500,000 if throughput is <10,000 gal/mo or $1 million if throughput >10,000 gal/mo	$5,000

Table 1: *The required per occurrence coverage required for UST owners by the EPA, referenced from [1]. Montana Petroleum Fund required copays referenced from [2].*

sponsibility insurers. In the instance of a release, the Montana (MT) Petroleum Fund requires a copay for all owners prior to the fund paying for all necessary and eligible expenses, whose values are seen in Table 1. In the MT Petroleum Fund, the copay is taken out of the first $35,000 submitted eligible costs, or costs that are within the scope of actual, reasonable, and necessary. Furthermore, the source of funding for Petroleum Funds vary, but the MT Petroleum Fund finds its funding through a UST clean up fee charged to distributers [10]. In title 75 chapter 11 part 314, the Montana Code states the clean up fee is a per gallon fee paid by the distributor where the fee was not paid by any other distributor [10]. For substances such as gasoline and heating oil, the fee is $0.75 per gallon [10].

2.4 Environmental Impact

The environmental impact of leaking USTs did not gain national attention until the early 1980s when a leaking UST in Rhode Island contaminated the drinking water of surrounding communities [11]. As a result, the federal and state regulatory departments increased regulation and now provide funding for remediation costs.

The damaged caused by a UST leak varies, as releases can contaminate soil, ground water, surface water, and vaporize to emit toxins into soil and air [11]. The contamination of ground water most directly impacts primary water sources such as private wells and public water systems, exposing the community to contaminated drinking water. Once in soil, the contaminants can also travel to surface water endangering wildlife and local ecosystems. When UST contaminants vaporize, it is formally known as vapor intrusion. Contaminant vapor can travel through numerous mediums including: soil, sewer lines, and storm drains [11], exposing nearby residents and community members to toxic air. The contaminated vapor can enter buildings, endangering near by residents and businesses in their homes and at work. The Utah DEQ estimates 1% of LUSTs released vapors into surrounding homes and businesses. Moreover, the presence of flammable liquid or gas contaminants add the additional risk of fire to near by homes and businesses, though in Utah less than 1% of LUSTs caused explosions or fires [3].

2.5 Community Impact

The EPA issues maximum concentration levels for each contaminant contained in USTs at which inhalation and consumption of contaminated air and substances are likely to result in negative health effects after long term exposure. The Utah Department of Environmental Quality recognizes the potential risks of inhaling gasoline fumes and ingesting gasoline in Table 2. While some situations are unlikely, such as death, the health effects in Table 2 emphasize the importance of preventing, detecting, and properly remediating a release. The Utah DEQ recognizes the health risks of diesel fuel when inhaled and ingested include [3]:

- Skin, eye, nose, lung, and throat irritant
- Headache
- Increased blood pressure
- Chemical pneumonia
- Lower blood's ability to clot

Concentration	Health Effect
0.001 PPM	1 in 1,000,000 risk of cancer if ingested 2 liters of contaminated water per day for 70 years
0.009PPM	1 in 1,000,000 risk of cancer if inhaled 70 years, 24 hours a day
0.01 PPM	1 in 1,000,000 risk of cancer if ingested 2 liters of contaminated water per day for 7 years
0.09 PPM	1 in 1,000,000 risk of cancer if exposed 7 years, 24 hours a day
0.005-10 PPM	Detectable by taste and smell
12 oz	Death if ingested
140-300 PPM	Eye irritation and gastrointestinal discomfort after 8 hours for fumes
1000 PPM	Numbness after 15 minutes from inhaling fumes
2000 PPM	Mild anesthesia in 30 minutes from inhaling fumes
10000 PPM	Death in 5 to 10 minutes from inhaling fumes
13000 PPM	Lower explosive limit for fumes

Table 2: *Health effects at various exposure levels, if inhaled and ingested, as recognized by the Utah Department of Environmental Quality [3]. The Utah Department of Environmental Quality refers to cancer as all types of cancer.*

- Kidney damage

However, the Utah DEQ suggests the lack of data of diesel fuel exposure impedes the ability to accurately associate health effects with exposure levels [3]. As a result, the goal of the UST regulation is to reduce the risk of a release and effectively clean up releases in order to reduce human exposure to UST contaminants.

Furthermore, the EPA suggests the lingering liability of a property with a LUST results in a lower future property value and a deteriorated desire to purchase the property [11]. Research by Zabel et al. suggests LUSTs only impact property prices when the release and possible affects were highly publicized [12]. Little or non-publicized releases did not result in a statistically significant change in property prices.

Highly publicized releases are likely those that had a direct impact on the safety and health of individuals.

Moreover, Guignet et al. conducted an hedonic analysis of the change in surrounding property values of seventeen high-profile LUSTs between 1985 and 2013 and discovered with all seventeen sites the average property values depreciated by 3% to 6% during a five year period after the release discovery [5]. Within five years after the completion of remediation, the property prices appreciated by 4% to 9%, but remediation has an inconsistent effect on property values, as the appreciation of property values ranges from negligible to counter-intuitive [5]. Further, the research of Guignet et al. suggests the affect on property values diminishes with distance from the release and affects properties within a two to three kilometer radius of the release [5].

3 Data Sets

In addition to the data sets used for the two prior risk analyses, the MT DEQ provided three additional data sets for this analysis. Until 2018, information regarding UST releases and remediation was maintained through paper files in the MT DEQ. This information includes the estimated volume and spread of a release, as well as the unique tank ID of the LUST. A facility can have many USTs on site, but the release and Petroleum Fund information references the unique facility ID.

3.1 Risk Analysis Data Sets

For the first two phases of the MT DEQ risk analysis, the department provided two data sets, one with UST characteristics and the other with environmental characteristics. The variables contained in the data sets are shown in Appendix A. As described above, MT DEQ regulators categorized each variable in order of severity. However,

Variable	Description
Release ID	Unique release identifier
Event Facility ID	Unique UST facility identifier
City	City of the facility
County	County of the facility
Confirmed Date	Date the release was confirmed by DEQ officials or contracted inspectors
Resolved Date	Date of remediation completion
Petroleum Fund Eligible	If the facility is eligible to receive financial assistance from the MT Petroleum Fund
Federally Regulated	If the UST is federally regulated
Site Name	Name of the facility
Active	If the UST site is currently active
Substance	Substance released by the UST
How Found	How the release was discovered
Source	Where the release originated
Cause	Cause of the release

Table 3: *A list and description of the variables contained in the release information data set.*

for this project the MT DEQ also provided the non-categorized version of each data set. Combining the two data sets yields 3,407 complete entries of unique USTs that correlate to 1,019 unique facilities.

3.2 Release Information Data Set

The release information data set contained information regarding documented Montana LUSTs. The variables contained in the data set are shown in Table 3.

The data set has 5,339 records, but only 2,897 records are complete. Complete entries in this data set are allowed to have empty RESOLVED DATES, as the lack of a resolved date indicates an ongoing cleanup. Approximately 69.7% of the complete entries do not have a resolved date. Of the complete records, 2,563 entries are unique release IDs and 286 release IDs occur more than once. Similarly, of the unique records, 2,151 records correlate to unique facility IDs and 487 facility IDs occur more than once. All future data analysis and visualization is done using only the complete records.

Figure 1 shows the number of release instances that are eligible for funding from the Montana State Petroleum Fund and whether the facilities are federally regulated. Approximately 29.3% of the facilities with releases are not federally regulated, meaning approximately 70.7% of the facilities are federally regulated.

Figure 1: *Histogram of the Montana state Petroleum Fund eligibility and Federal Regulation status of the LUSTs.*

Notice from Figure 2, Montana LUSTs most often contain diesel, gasoline, and heating oil. USTs containing gasoline and diesel fuels make up 45.6% and 30.6% of all LUSTs, respectively.

Given the strict regulations and inspections conducted by the state, it may be intuitive to believe the primary discovery method of releases are inspections. However,

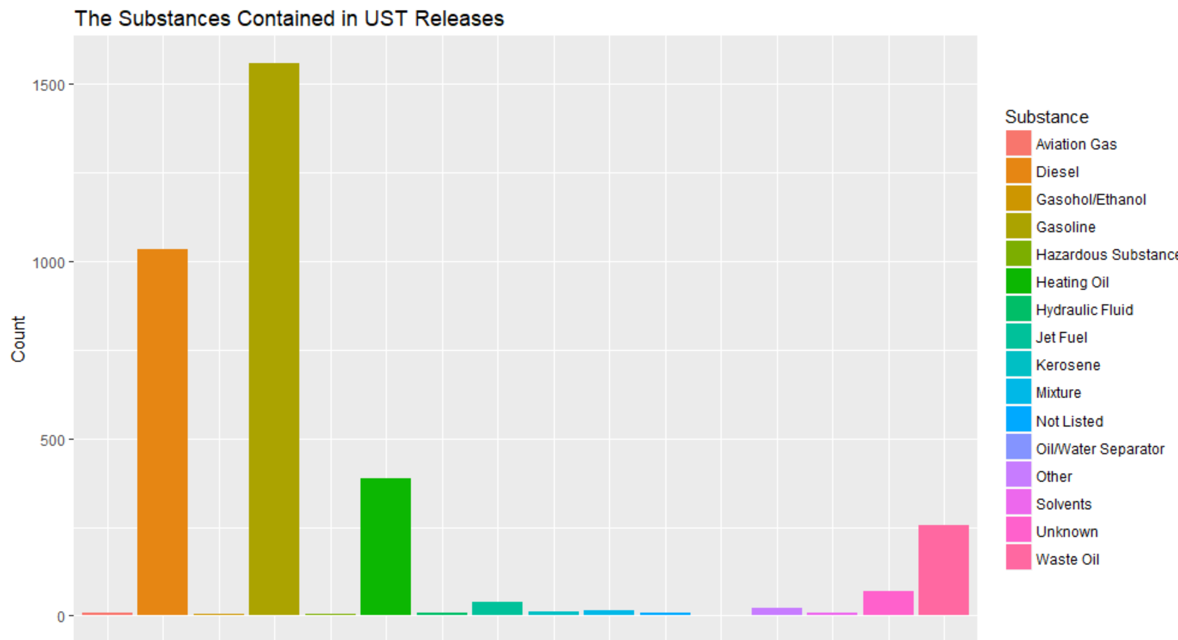

Figure 2: *Histogram of the substances stored in Montana LUSTs.*

as seen in Figure 3 the majority of releases are not discovered until the closure process. In fact, 53.9% of releases were discovered at the time of closure, compared to the 0.45% of releases discovered by compliance inspections.

Figure 4 shows the underlying cause of Montana LUSTs broken down according to the source of the release. There are almost an equal number of releases with an original cause resulting from corrosion/deterioration, historical contamination, spill, or an unknown cause. While 30.5% of the releases originate from the tank itself, an alarming number of releases are a result of historical contamination and unknown causes. Yet, the 22.6% of releases with a source of historical contamination makes sense given the number of releases discovered at closure in Figure 3.

3.3 Financing Remediation

The Petroleum Fund data set contained information regarding the financial cost of remediation. The variables contained in the data set are shown in Table 4. Of the total 2,261 records, 1,231 records are complete, each referencing a unique release ID.

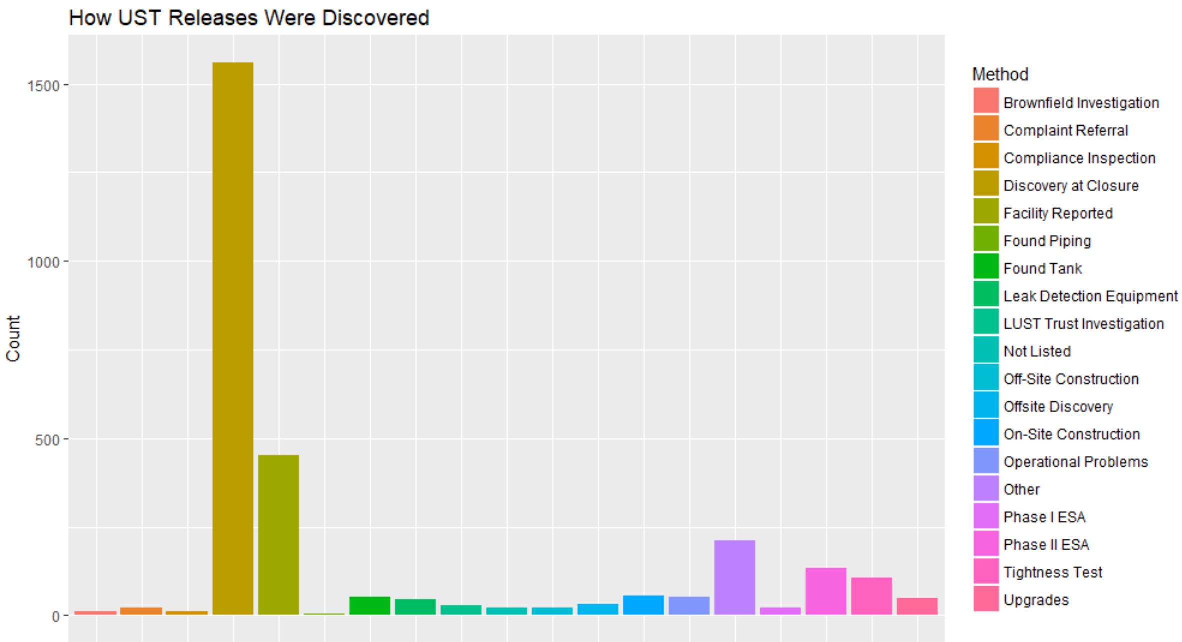

Figure 3: *Histogram of the methods by which Montana LUST releases were discovered.*

Variable	Description
Release ID	Unique release identifier
Tank Category	Tank type identifier
Tank Type	Description of the size of the tank
Copay Required	Required copay amount, as seen in Table 1
Copay So Far	Current amount paid toward the copay
Copay Met	Boolean if the required copay was met
Copay Remaining	COPAY REQUIRED - COPAY SO FAR
Total of Adjustment	The total expenses deemed by the Petroleum Fund as outside the scope of actual, reasonable, and necessary [2]
Credit	The amount paid by the MT Petroleum Fund

Table 4: *A list and description of the variables in the financial remediation data set.*

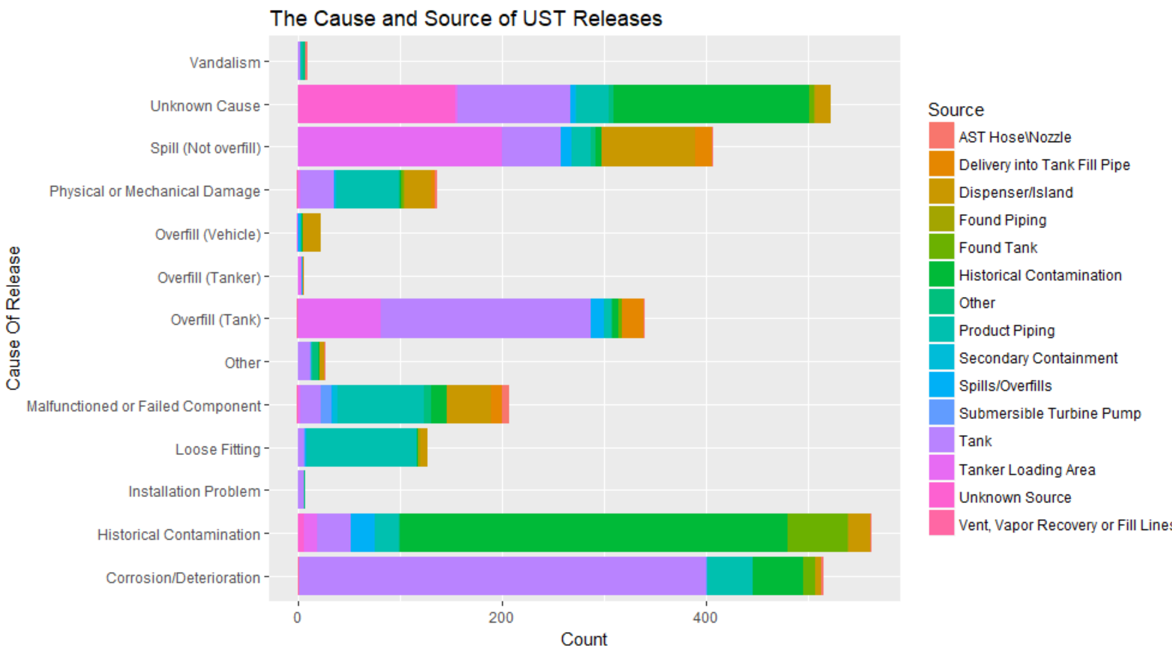

Figure 4: *Histogram of LUSTs causes broken down by the LUST source.*

While the total cost of remediation was not provided, given the information from Table 4 the total cost, or the amount paid by both the owner and the MT Petroleum Fund, can be calculated by the equation:

$$T = (P - P_R) + A - C \tag{1}$$

where T is the total remediation cost, P is the required copay, P_R is the copay remaining, A is the total adjustment amount, and C is the credit. The credit is subtracted, as it is standard accounting practice to record credit values as negative. However, the date of payments were not provided, so it is unknown whether the dollar values are inflated to current dollars.

As seen in Figure 5, the costs of remediation greatly vary, though most remain between the minimum and third quartile of $57 and $35,624, respectively. Yet, the largest total cost was $1,009,639.

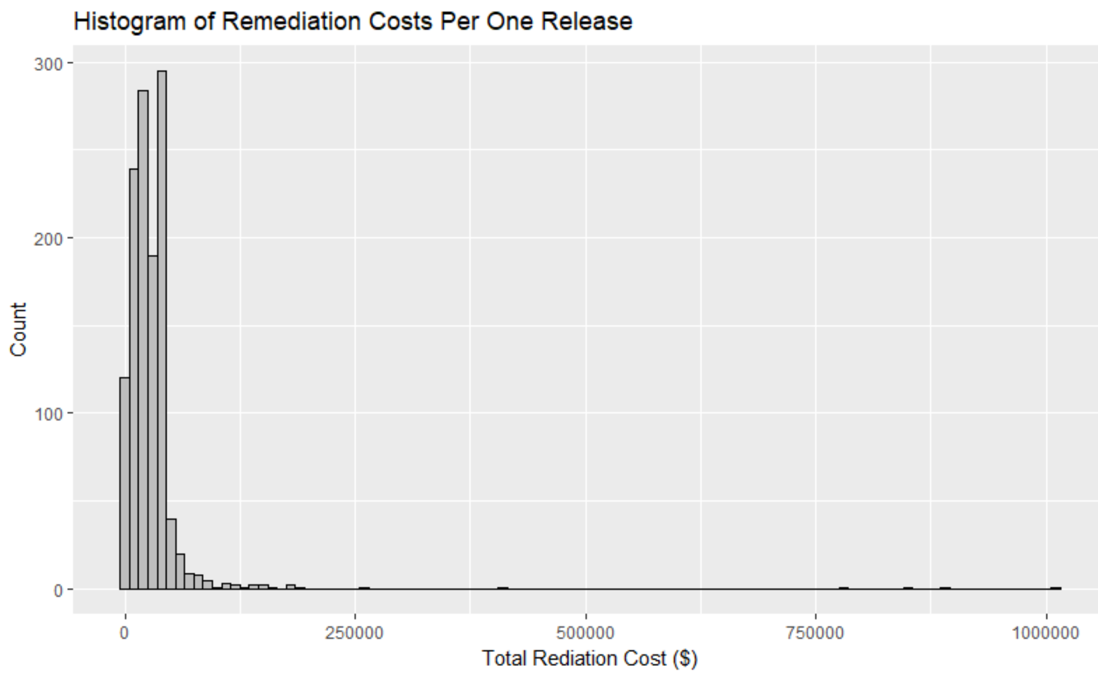

Figure 5: *Histogram of the current total remediation cost for UST releases calculated according to Equation 1.*

Variable	**Description**
WPID	Unique work plan identifier
ReleaseID	Unique release identifier
WPName	Combination of work plan codes

Table 5: *A list and description of the variables in the remediation work plan data set.*

3.4 Remediation Work Plan

The remediation work plan data set contains information regarding the investigative and clean up steps that form the work plan for each release. The data set contains the variables seen in Table 5, where WPNAME contains a combination of work plan codes seen in Appendix B. Appendix B provides a description of each work plan code and shows wether the step is an investigative or restorative work plan step.

4 Financial Analysis

4.1 Exploratory Data Analysis

One might suspect the number of releases per facility would relate to the number of USTs at the facility. Figure 6 shows the linear regression line

$$R = 8.313T - 4.617$$

where R is the number of releases and T is the number of tanks of a facility. The p-value of the number of USTs per facility is less than $2e-16$, which suggests that null hypothesis that the number of USTs has a negligible effect on the number of releases in false. Yet, the linear regression model has a residual standard error of 32.71 and a R-squared value of 0.2299, meaning only 22.99% of the variation in the number of releases is explained by the number of USTs per facility where the standard deviation of the residual values, (the difference between the predicted and observed number of releases), is 32.71. Thus, number of USTs alone is not enough to accurately predict the total number of releases at a facility. Therefore, contrary to a natural assumption, the greater number of tanks at a facility does not imply a greater number of releases.

Similarly, it seems reasonable to hypothesize the total remediation cost correlates to the number of releases at the facility. The linear regression line in Figure 7 appears to fit the data fairly well with the exception of the one outlier. Like the prior hypothesis, the number of releases has a significant p-value of $3.03e-12$, but the regression line has a residual standard error of 2,234,000 and an R-squared value of 0.3286. Therefore, the linear line does not fit the data as well as it appears in Figure 7, and the total cost cannot be accurately explained by number of releases.

As a result, it is apparent there are more factors that influence the costs of remediation. Determining the best predictors of remediation costs prompted a deeper

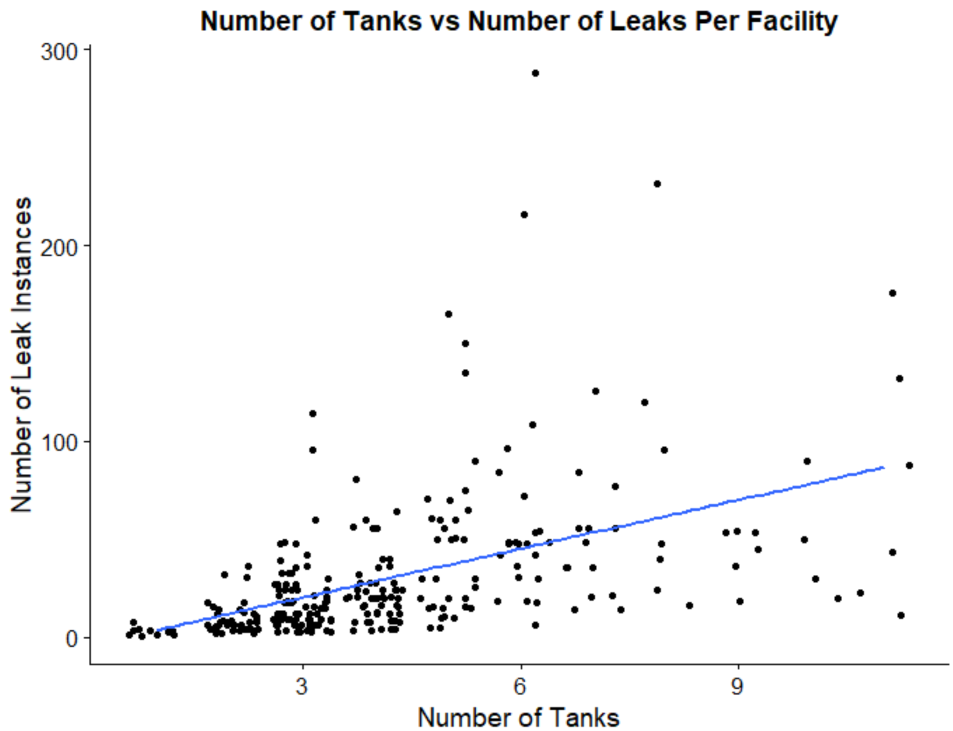

Figure 6: *The number of USTs per facility versus the number of leaks per facility with the linear regression line seen in Equation 4.1.*

exploration and analysis of the data.

4.2 Measure UST Similarity

The release records are only associated with a facility, and thus do not indicate what UST was the source of the release. This posed a severe problem, as the 23 tank and environmental characteristics categorized from zero to four leaves a possible 5^{23} or approximately $1.192093e + 16$ different characteristic combinations. In fact, 83.6% of facilities have more than one UST and 84.2% of facilities have multiple release records, which leads to the natural question, "How different are the USTs at a facility?". Large differences between USTs at the same facility would result in uncertainty of what characteristics to associate with a release's financial cost.

By measuring of the difference between USTs at a facility, the data set could be subsetted to only include the facilities with little variance between USTs, thus al-

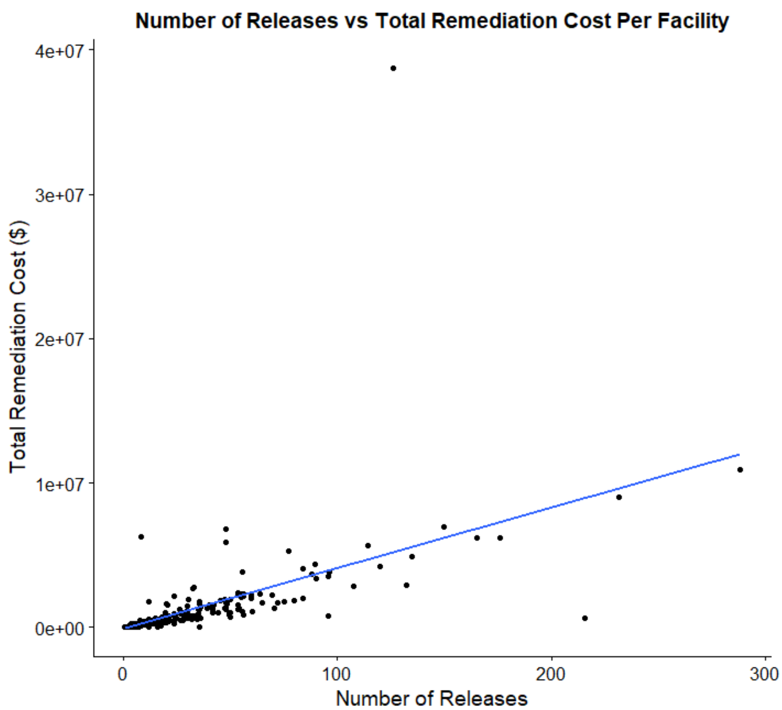

Figure 7: *The number of releases per facility versus the total remediation cost per facility.*

lowing a better understanding of which tank and environmental characteristics are associated with a release. This was addressed by calculating the pairwise Euclidean distances between USTs from the same facility using the categorized tank and environmental characteristic data.

For example, this facility has two USTs (3519 and 3520) with the categorized characteristics shown in Table 6. The tanks vary in one characteristic, so calculating the Euclidean distance between the tanks yields $\sqrt{(1)}$ or 1. Since there are only two USTs at this facility, the measure of similarity is 1. However, if there were multiple tanks at a facility, the measure of similarity between tanks at a facility is the maximum Euclidean distance between any two tanks of the facility.

The summary statistics of the similarity measure are seen in Table 6. There are 167 facilities with only one UST, but there are an additional 477 facilities with multiple USTs which have a maximum distance of zero. Furthermore, there is a total

Tank Characteristics			
Characteristic	3519	3520	Squared Difference
Spill Prevention	0	0	0
Under Dispenser Containment	4	4	0
Overfill Prevention	2	2	0
Piping Configuration	3	3	0
Piping Material	2	2	0
Tank Configuration	4	4	0
Tank Material	3	3	0
Age	4	3	1
Pipe Leak Detection	0	0	0
Tank Leak Detection	1	1	0
Sum of Tank Squared Differences			1
Environmental Characteristics			
Source Water Protection	1	1	0
Closest Well	2	2	0
Status of Closest Well	4	4	0
Surface Water Distance	4	4	0
Water Quality	0	0	0
Soil Texture	2	2	0
Soil Permeability	2	2	0
Population Density	1	1	0
Land Use	2	2	0
Tank Material	3	3	0
GWIC Wells Distance	3	3	0
Sum of Environmental Squared Differences			0
Square Root of Sum Squared Differences			1

Table 6: *To find the Euclidean distance between two USTs of a facility, first find the difference between each tank and environmental categorized variable, square the differences, find the sum of the squares, then take the square root of the sum.*

Min	1st Q	Median	Mean	3rd Q	Max
0	0	0	1.462	2.499	9.220

Table 7: *Summary statistics of the measure of similarity for facilities.*

of 606 facilities with multiple USTs with a maximum distance less than the mean, 1.462. However, the results also signal that many facilities maintain USTs of very similar tank and environmental characteristics.

Further exploration revealed that there is no apparent correlation or pattern between the number of USTs at a facility and the maximum Euclidean distance between the USTs of the facility, as seen in Figure 8. However, Figure 8 displays the large cluster of facilities with less than five USTs and a maximum Euclidean distance less than 1.25, as represented by the data point size.

Understandably, one would believe the environmental factors of USTs at the same facility would be very similar or identical. But rather than assuming this, the same Euclidean distance method was applied to the tank and environmental characteristics separately, as seen in Figure 9. As anticipated, the results when using only the tank characteristics is very similar to those seen in Figure 8, but the results from using only the environmental characteristics opposed the prior inclination. Though the distance between USTs using only environmental factors is less than that when using all UST characteristics, Figure 9 clearly shows the environment characteristics are not the same for all USTs of the same facility. However, like Figure 8, the similarity measures using only environmental characteristics shows a large cluster of facilities with fewer than five USTs and a similarity measure of zero.

All further financial analyses were conducted with data for facilities with one UST or a maximum euclidean distance of zero. However, notice in Figure 8 the number of USTs facilities with a zero distance greatly varies. But contrary to intuition, the facility with a zero maximum distance and eleven USTs does not have an associated

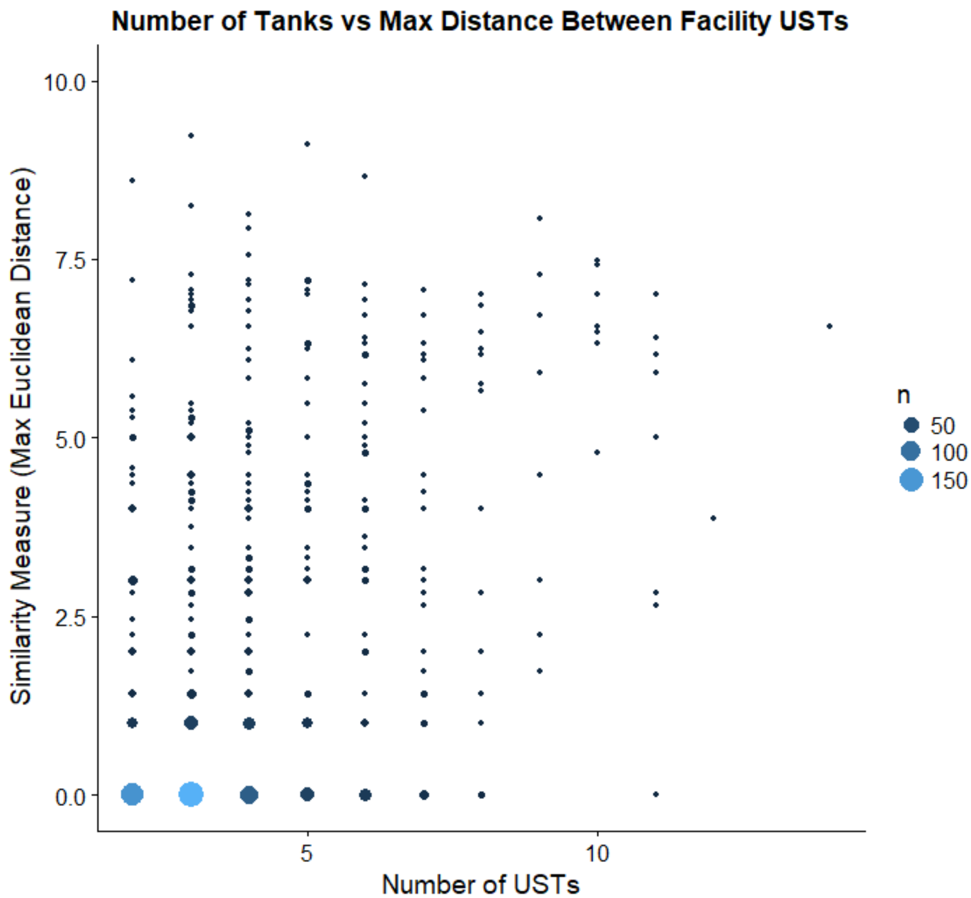

Figure 8: *The number of USTs per facility versus the measure of similarity between a facility's USTs, or the maximum euclidean distance between the USTs of the facility. The size of the data point describes the number of facilities at each discrete point.*

release record.

4.3 Financial Model

Merging the complete entries of facilities with only one UST or similarity measure of zero from the tank and environmental characteristic data set, release information data set, and Petroleum Fund financial data set yielded a data set composed of 33 variables and 3458 records.

Next, intuition would suggest that the duration of the release would likely affect the total cost of remediation. The duration is the number of years between the

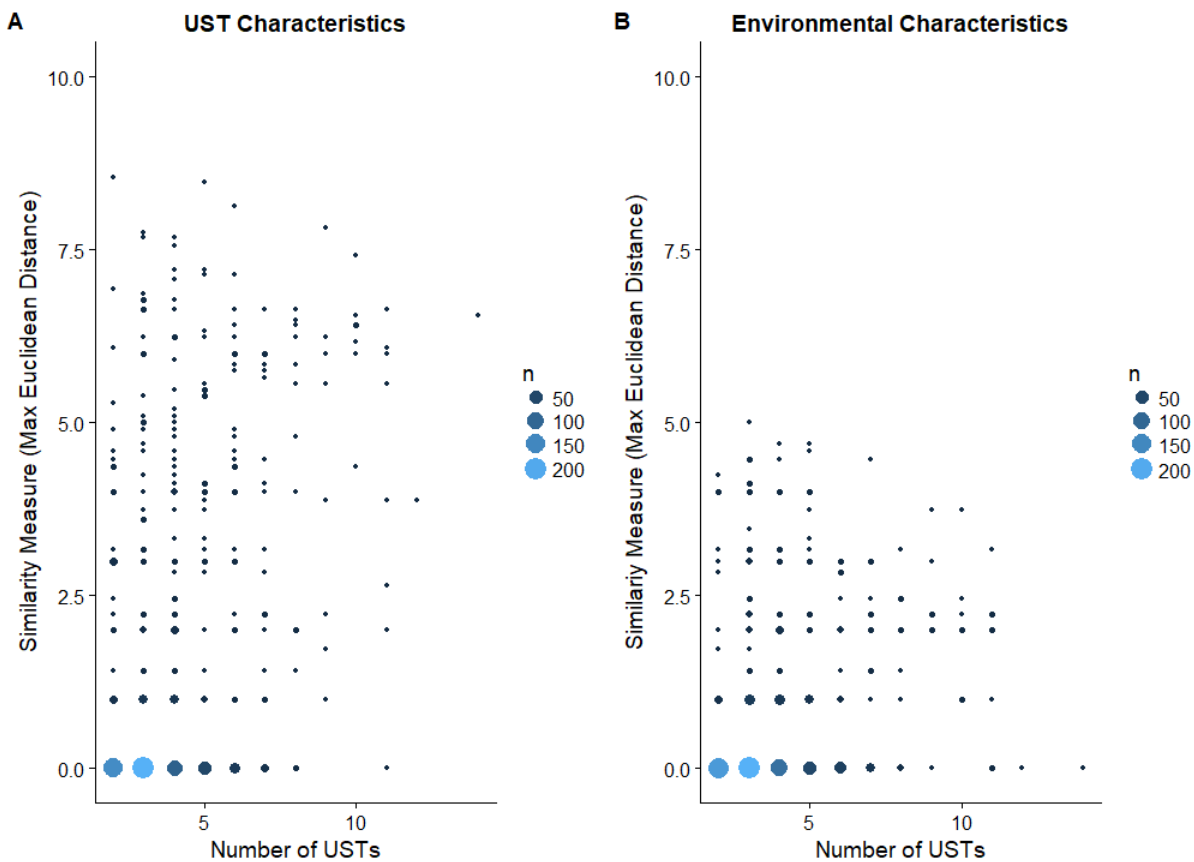

Figure 9: *The number of USTs per facility versus the facility measure of similarity, or the maximum euclidean distance between the USTs of the facility. The size of the data point describes the number of facilities at each discrete point. Plot A uses only the UST characteristic variables and plot B uses only the environmental characteristic variables.*

Confirmed Date and the Resolved Date. It was assumed that release records without a completed date are on-going; therefore, the duration was calculated using the date of analysis: February 11, 2019. This field was added to the data set to create a 34^{th} variable. The 35^{th} variable, Year Release Confirmed, is the year of the Confirmed Date. This variable is meant to provide an additional context to the time component of the releases.

Using all variables, a linear regression model was created to predict the total remediation cost. Then, a mixed variable selection technique determined the most accurate linear regression model had a R-squared value of 0.248 with a root mean

First Linear Regression Model Predictors	
Source Water Protection Zone	Active
Tank Age	Tank Leak Detection
Pipe Leak Detection	GWIC Wells Distance
Soil Texture	Water Quality
Land Use	Type of Closed Wells
Federally Regulated	Tank Configuration
How Found	Petroleum Fund Eligible
Pipe Configuration	Under Dispenser Containment
Substance	Surface Water Distance
Soil Permeability	Overfill Protection
Tank Material	Population Density
Status of Closest Well	WPName

Table 8: *The best predictors as determined by mixed variable selection that result in the greatest R-squared in a linear regression model, and the coefficients of the predictors in the model.*

squared error of 15,535.88. The model uses the predictors, as determined by the mixed variable selection, seen in Table 8. However, the low R-squared value indicates the cost of remediation cannot be accurately predicted using a linear model and the data provided.

In an attempt to improve the model, the model was altered in the following ways:

1. Inflating the dollar values to 2019 dollars

2. Sub-setting the data set to only include records with RESOLVED DATES

The data provided did not indicate the date of remediation payments and the CONFIRMED DATES of the release records span from 1982 to 2018, creating a concern of whether the affect of inflation was a cause of poor correlations in the prior model. However, without payment dates, it was assumed the payments occurred in the same year as the release discovery. This assumption could easily be false in many release records, as payments for ongoing release clean ups can extend to 2018. Thus, the total remediation cost was inflated from the year of the CONFIRMED DATE to current dollars. The inflated remediation cost was calculated using the Consumer Price Index

(CPI) indices from the Federal Reserve Bank of Minneapolis [13] according to the equation:

$$T_i = T\frac{250.5}{y}$$

where T_i is the inflated total remediation cost, 250.5 is the estimated CPI for 2018, T is the total remediation cost (calculated using Equation 1) for a release, and y is the CPI index for the year of the CONFIRMED DATE for release associated with cost T.

Creating another linear regression model to predict the inflated total remediation cost resulted in a similar R-squared value of 0.238 and mixed variable selection suggested the same predictors seen in Table 8. This result is not enough to indicate the lack of inflation did not influence the low accuracy of the model, as over-inflating due to the prior assumption could also negatively influence the accuracy of the model. Using the dates of payment to determine the inflation values would help determine if the possible lack of inflation has a significant impact on model accuracy.

Inflating the total remediation cost failed to improve the model, yet all time descriptive variables depended upon the accuracy of the CONFIRMED and RESOLVED DATES. Removing all release records that did not have a RESOLVED DATE reduced the data from 3458 records to a mere 952 records, but the 952 records correlate to only 56 of the 644 unique facility IDs with only one UST or a zero similarity difference between USTs.

However, re-running the model and mixed variable selection yielded the more accurate linear model,

$$
\begin{aligned}
T = &-2286.85(Source) + 1140.01(Overfill\ Protection) - 12698.38(Age)+\\
&4599.49(Tank\ Material) + 7092.81(Under\ Dispenser\ Containment)+\\
&1638.03(Cause) + 508.21(How\ Found) + 24190.84(Petroleum\ Fund\ Eligible)+\\
&1.35(Duration) + 1551.31(Tank\ Configuration) + 2025.14(Water\ Quality)+\\
&1521.20(Source\ Water\ Protection\ Zone) - 1579.77(Soil\ Texture)+\\
&5885.75(Tank\ Category) - 2006.58(Pipe\ Leak\ Detection)+\\
&1565.53(Surface\ Water) + 60.83(WPName) + 505.55(Substance) - 41350.36
\end{aligned}
\tag{2}
$$

where T is the total remediation cost and -41350.36 is the intercept term. If the coefficient is positive, the predictor is directly related to the total remediation cost. Likewise, if the coefficient is negative, the predictor is indirectly related to the total remediation cost.

Notice how many of the predictors are the same as the first model (Table 8), but a few predictors are different. This second linear regression model has a R-squared value of 0.6948 and a root mean square error of 7674.00. Therefore, the model explains 69.48% of the variation in the total remediation cost, making the model useful in estimating an approximate remediation cost in the instance of a release.

4.4 How Upgrades Affect The Total Cost of Remediation

The coefficients in Equation 2 help identify how upgrades affect the total cost of remediation, as the coefficients represent the amount added to the total remediation cost for each predictor per incremental increase in classification. For example, if a UST has underground dispenser containment classification of zero, meaning the UST has underground dispenser containment, then the term,

$$7092.81(Under\ Dispenser\ Containment)$$

in Equation 2 becomes zero. But if the UST has a classification of four then the term becomes $28,371$, meaning the potential total cost of remediation increases by \$28,371. Therefore, financially speaking, it is important for USTs to have under dispenser containment.

Substituting the categorized values for each variable into Equation 2 provides an approximated remediation cost. Using the coefficients for the linear model in Table 9, rather than those in Equation 2, to calculate the remediation cost provides a 95% confidence interval for the remediation cost.

4.5 Results and Discussion

While predictors such as Duration may be statistically significant in predicting the total remediation cost, the coefficients in Equation 2 show they are not necessarily financially significant. In other words, for each additional year the release remediation continues, the total cost increases by a mere \$1.35, yet the predictor Duration has a p-value less than $2e-16$. On the other hand, an adjustment in whether a UST is Petroleum Fund eligible results in an increase of \$24,190.84 in the total remediation cost.

Table 9 shows a 95% confidence interval for the model coefficients in Equation 2, meaning the average financial impact as a result of a UST's Petroleum Fund eligibility exist between \$18,254.84 and \$30,126.84 with a 95% confidence rate.

The greatest increase in the total remediation cost results from Petroleum Fund Eligible and Underground Dispenser Containment, as signaled by the largest positive coefficients in Equation 2. Since 99.3% of the financial informa-

Predictors	**2.5%**	**97.5%**
Intercept	−54546.173069	−28154.548450
Source	−2563.110873	−2010.585303
Overfill Protection	771.819418	1508.200598
Age	−13689.991062	−11706.773072
Tank Material	4017.701143	5181.271064
Under Dispenser Containment	6138.465489	8047.158800
Cause	1356.412477	1919.657454
How Found	371.286364	645.128851
Petroleum Fund Eligible	18254.837202	30126.837556
Duration	1.064486	1.627235
Tank Configuration	1072.379287	2030.245065
Water Quality	1524.344672	2525.939990
Source Water Protection Zone	1091.276762	1951.114221
Soil Texture	−2445.168678	−714.370241
Tank Category	3632.896849	8138.595737
Piping Leak Detection	−2891.632620	−1121.529309
Surface Water	748.432441	2382.622480
Work Plan Name	20.219933	101.444311
Substance	86.009170	925.085954

Table 9: *A 95% confidence interval of the coefficients in Equation 2, the linear model used to predict the non-inflated total cost of remediation when only using release records with* RESOLVED DATES.

tion is from Petroleum Fund Eligible USTs, the exact cause of why being Petroleum Fund eligible results in a $24,190.84 increase in the total remediation cost could be a base cost for releases, but affirming or rejecting this as the true cause would require further research. Secondly, Under Dispenser Containment is likely very important to the financial cost of remediation, as the containment system is a primary release prevention system. Under Dispenser Containment is an important predictor, despite only approximately 4.6% of the releases to train the model originated from a dispenser.

Conversely, the greatest decrease in the total remediation cost results from Tank Age. It seems counter-intuitive for the total remediation cost to be inversely related, as the UST increases in age and moves from one age classification to another. Figure 10 shows how the average total remediation cost for USTs with an age classification of four is much lower than the average of the other age categories. Further, Tank Age and the total remediation cost have a correlation coefficient of -0.305. Therefore, it makes sense for the Tank Age coefficient to be negative.

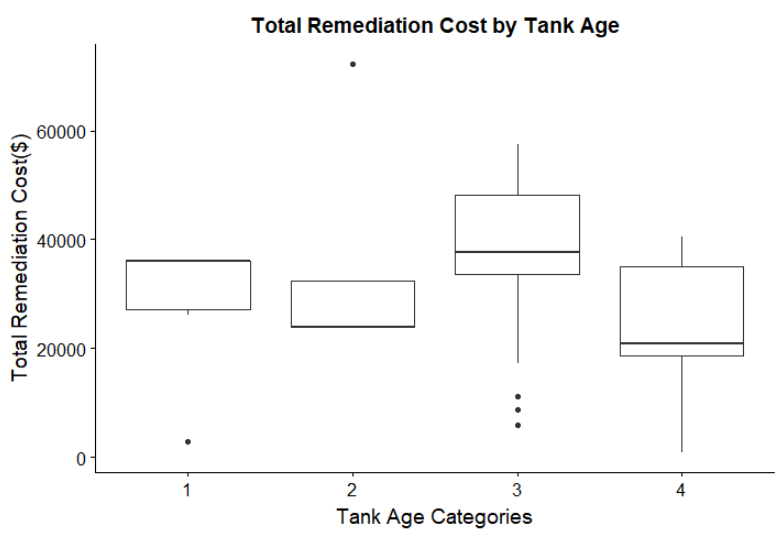

Figure 10: *The average total remediation cost of USTs with an age classification of four is smaller than the average costs for all other categories. See Appendix A for description of risk classification categorization.*

However, the intensity of the value for AGE remains unexplained. The classifications of the older tanks in the categories with positive coefficients, the older tanks have a predominantly higher risk classifications than younger tanks. For example, notice in Figure 11, that the classifications of the older tanks in UNDER DISPENSER CONTAINMENT and TANK MATERIAL are one average higher than the younger tanks.

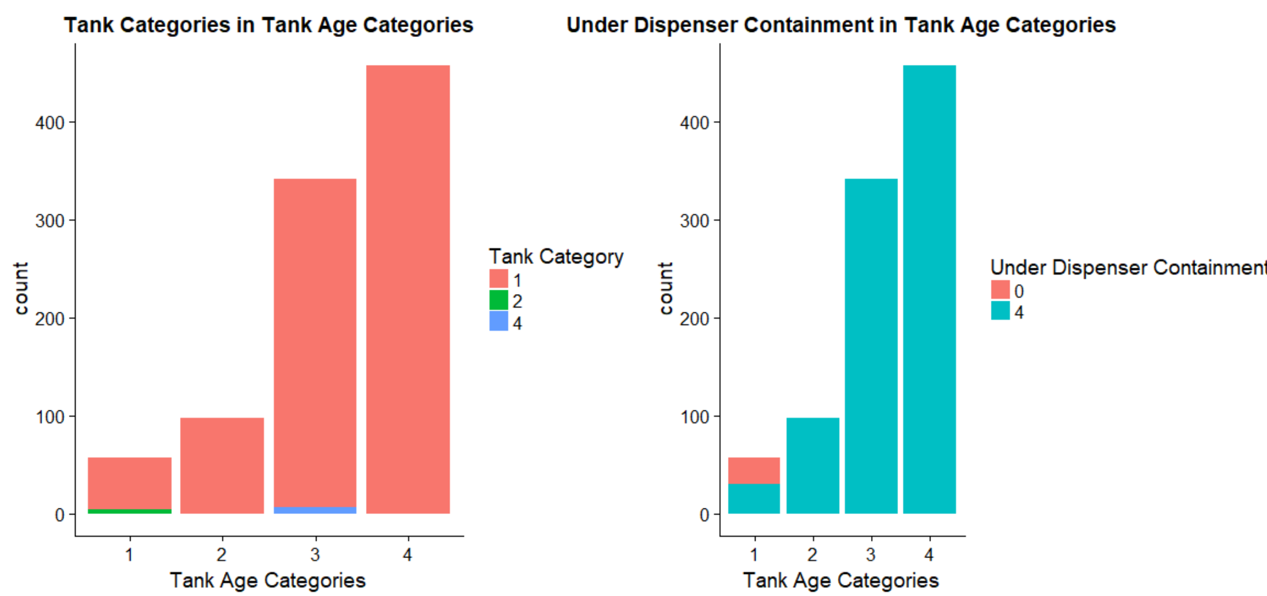

Figure 11: *USTs with a higher age classification also tend to have higher risk classifications in other categories such as* TANK CATEGORY *and* UNDER DISPENSER CONTAINMENT. *See Appendix A for description of risk classification categorization.*

The coefficient of AGE could be negative to offset the higher positive values generated by the larger average risk values, as seen in Figure 11. But the negative value could further signal currently unknown relationships. Identifying the exact cause of the large negative coefficient would require futher investigation into the correlations between TANK AGE and the other predictors.

5 How Upgrades Affect Risk Coefficients

Like many other states, MT DEQ's prior risk assessments used AHP to assign risk coefficients from zero to one based on how each UST compares to all the other USTs. While this method provided the risk values sought by the MT DEQ, this method relies on human expertise to determine which factors are the most and least important, as well as how to categorize each variable.

AHP requires pairwise comparisons and calculating or approximating the dominant eigen vector for large matrices. The risk coefficients are the values in the dominant eigen vector, and thus the AHP method is computationally expensive when working with thousands of USTs. However, keeping the AHP risk coefficients as the comparable standard, the MT DEQ was interested to know how an upgrade to a UST system would affect the AHP risk coefficient. Since the computation time of a linear model is much smaller than that of AHP, a linear model was used to analyze how an upgrade would affect the risk coefficient. Further, a linear model is easier to understand and use by people of all fields.

5.1 Linear Regression Model

A ten fold cross validated linear regression model that used the same variables as the prior analyses in Appendix A was created to predict a UST's new AHP risk coefficient after a system upgrade. The cross validation method determined the most accurate model for predicting the risk coefficients is,

$$
\begin{aligned}
r = {} & 0.019211(Source\,Water\;Protection\;Zone) + 0.013831(Distance\,To\,Closest\,Well) + \\
& 0.017834(Type\;of\;Closest\,Well) + 0.012589(Status\;of\;Closest\,Well) + \\
& 0.014882(Surface\,Water) + 0.028252(Water\;Quality) + 0.016965(Soil\,Texture) + \\
& 0.011879(Soil\;Permeability) + 0.020722(Population\;Density) + 0.002212(Land\,Use) + \\
& 0.018896(Spill\;Prevention) + 0.016654(Under\;Dispenser\;Containment) + \\
& 0.019582(Overfill\;Prevention) + 0.030484(Piping\,Configuration) + \\
& 0.027122(Piping\;Material) + 0.12521(Tank\,Configuration) + 0.022662(Tank\;Material) + \\
& 0.010689(Tank\;Age) + 0.004261(Pipe\;Leak\;Detection) + \\
& 0.003044(Tank\;Leak\;Detection) + 0.022718
\end{aligned}
\tag{3}
$$

where r is the approximated risk coefficient. The model resulted in an R-squared value of 0.99549 with a root mean squared error of $7.17e-3$, and all predictors have p-values less than $2e-16$. While the risk value takes into account the environmental variables, it is assumed upgrades occur only to tank characteristics.

Like the financial model, the coefficients of the predictors indicate the impact and importance of the predictor to the risk coefficient and describes the proportional change to classifications in each category. For example, of a risk coefficient, r, a classification four in Piping Configuration would constitute 0.0121936 of r. However, if the owner upgraded the UST to a classification three, the UST's risk coefficient would decrease by 0.030484. Equation 3 indicates Piping Configuration and Water Quality have the greatest impact on the risk coefficient, where Land Use and Tank Leak Detection have the least impact on the risk coefficient.

However, keep in mind a UST's AHP risk coefficient is dependent upon all other USTs in the data set, but the linear model approximates the UST's risk coefficient independent of all other USTs. Therefore, the linear model will work well to approximate the new risk coefficient if only a few UST systems upgraded. If too many owners upgrade UST systems then the results provided by AHP and the linear model will greatly vary.

5.2 Results and Discussion

Since AHP requires the ranking of variables from least important to most important, one might expected the most important factors will have the greatest impact on risk values, and to an extent this is true. Table 10 provides a 95% confidence interval for the coefficients in Equation 3, and lists the predictors in order of impact. Like the financial model confidence interval, 95% of the impacts on the risk coefficients as a result of and upgrade in each category exist within the confidence interval.

Substituting all new classifications into Equation 3 provides an approximation of the new risk coefficient, as a result of upgrades. Using the coefficient values from the confidence interval in Table 10 further provides a confidence interval for the new risk coefficient. An alternative approach to calculate the risk coefficient after upgrades, r_{new}, follows the equation,

$$r_{old} - \sum_{n=1}^{m} u_n(c_{old} - c_{new}) \leq r_{new} \leq r_{old} - \sum_{n=1}^{m} l_n(c_{old} - c_{new}) \tag{4}$$

where r_{old} is the old risk coefficient, m is the number of upgrades, u_n is the 97.5% approximated coefficient for predictor n, l_n is the 2.5% approximated coefficient from predictor n, c_{old} is the old classification value for predictor n, and c_{new} is the new classification value for predictor n as a result of upgrading. For example, if an owner upgrades the Piping Configuration and Piping Material from category four to category two for a UST with a current risk coefficient of 0.5, then the calculation

Impact	Upgrade	2.5%	97.5%
1	Piping Configuration	0.030191753	0.030775555
2	Water Quality	0.027885401	0.028618624
3	Piping Material	0.026766524	0.027477117
4	Intercept	0.020219404	0.025216726
5	Tank Material	0.022397723	0.022926916
6	Population Density	0.020439585	0.021003786
7	Overfill Prevention	0.019427715	0.019737131
8	Source Water Protection Zone	0.019035685	0.019385582
9	Spill Prevention	0.018317019	0.019474204
10	Type of Closest Well	0.017599375	0.018069260
11	Soil Texture	0.016482158	0.017447949
12	Under Dispenser Containment	0.016335396	0.016971895
13	Surface Water	0.014589512	0.015175451
14	Distance to Closest Well	0.013408758	0.014254063
15	Status of Closest Well	0.012379900	0.012797864
16	Tank Configuration	0.012326844	0.012715262
17	Soil Permeability	0.011470761	0.012287019
18	Tank Age	0.010263389	0.011113948
19	Pipe Leak Detection	0.004019548	0.004501934
20	Tank Leak Detection	0.002763873	0.003324115
21	Land Use	0.001946049	0.002477290

Table 10: *Confidence interval for the coefficients in Equation 3, the linear regression model used to approximate risk coefficients. The variables are listed in order of greatest impact on risk coefficients.*

of the new risk coefficient, r_{new}, using Equation 4 is as follows,

$$0.5-(0.0307755(4-2)+0.0274771(4-2)) \leq r_{new} \leq 0.5-(0.0301917(4-2)+0.0267665(4-2))$$

$$0.3834947 \leq r_{new} \leq 0.3860834$$

Thus, there is a 95% chance the new risk coefficient will be between 0.3834947 and 0.3860834. However, if many owners choose to upgrade their systems, then, like the model, the confidence interval may vary greatly from AHP results.

The affect of upgrades on the risk coefficients is the absolute value of the difference between the original risk value and the value predicted by the linear regression model when one tank characteristic from Appendix A was upgraded.

While owners and operators have the option to upgrade all tank characteristics, some characteristics such as Tank Material, Age, and Tank Configuration require the purchase and installation of a new UST. Under Dispenser Containment requires digging up the UST system to install the protection equipment below the UST. On the other hand, options such as Piping Configuration and Piping Material require the replacement of most or all piping material, which can be expensive but not as expensive as replacing the UST. Replacing all system equipment with the newest and safest options will obviously reduce the risk, it is also the most expensive upgrade. Therefore, if other upgrades can reduce the risk value, then it is assumed the owner/operators will choose the other upgrades rather than those that require UST replacement.

While some variables such as Spill Prevention have higher AHP rankings than all other variables, it does not necessarily result in the greatest decrease in risk. This can be attributed to the AHP risk coefficients' dependency on all USTs, as only 42 of the 3407 USTs in the data set do not have spill prevention, as seen in Figure 12. Therefore, installing spill prevention, though important, does not make a tank have a lower risk of leaking than all others since most USTs already have spill prevention.

The average decrease in the risk value from completing any upgrade is 0.012. However, the average decrease in the risk coefficient as a result from upgrading from the greatest risk (category four) to any other category is 0.015, and the average is slightly higher at 0.016 when upgrading to the lowest risk category. Upgrading from categories two and three decrease the risk values by an average of 0.0097 and 0.0084, respectively. Surprisingly, on average, upgrading from category one decreases the risk value by 0.0127. At first this may seem surprising, but only six of the ten factors allow for upgrades to a less risky classification from classification level one.

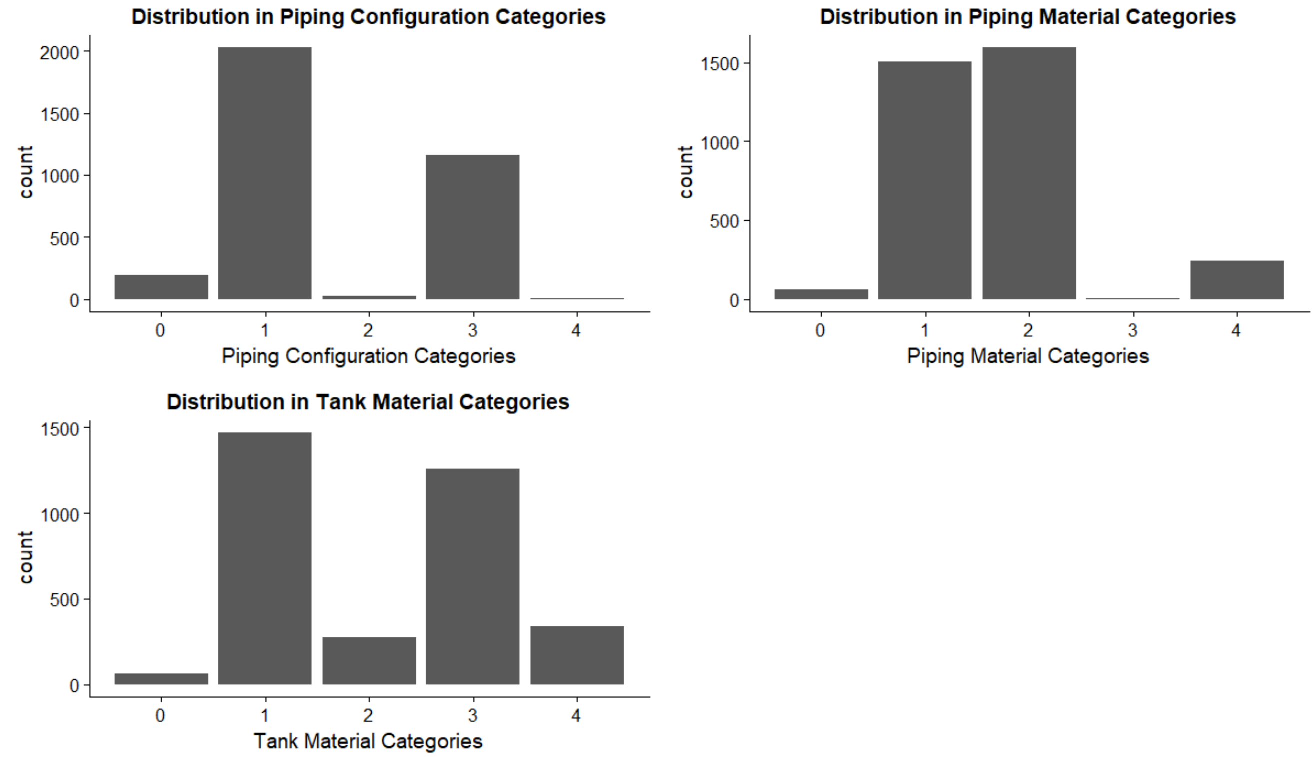

Figure 12: *The three predictors that result in the greatest change, increase and decrease, of the risk coefficients. The plots show how the most impactful factors are those with dominant classifications other than zero and four. See Appendix A for description of risk classification categorization.*

As seen in Equation 3, the factors that result in the greatest change, increase or decrease, in the risk value are Piping Configuration, Piping Material, and Tank Material. These high impacts occur due to the distribution of classifications in these factors, as seen in Figure 12. Figure 12 shows two dominant classifciations other than zero and four.

On the other hand, the least impactful upgrades on the risk value are Age, Pipe Leak Detection, and Tank Leak Detection, as seen in Equation 3. Figure 13 shows the distribution of these three predictors. Notice how the distributions have strong positive or negative skew, meaning the distributions extremely favor classifications zero and four. Age, Pipe Leak Detection, and Tank Leak Detection

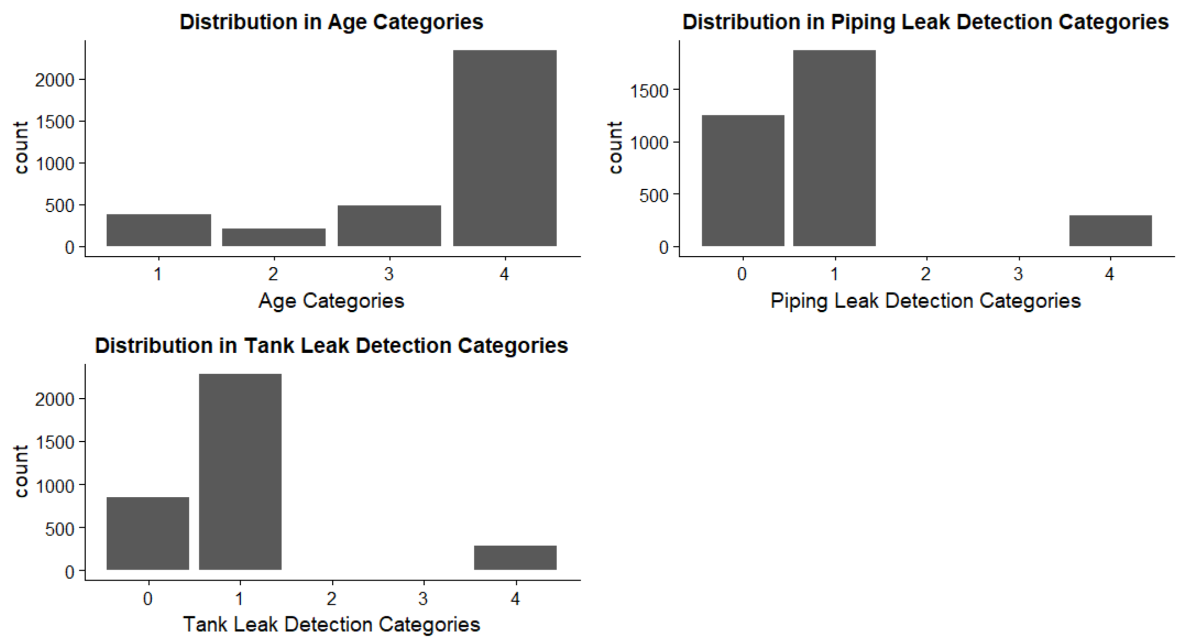

Figure 13: *The three predtictors that have the least impact, increase or decrease, on the risk coefficients. The graphs show how the factors with the least impact have a strong skew. See Appendix A for description of risk classification categorization.*

have a linear skewness values of -1.5167, 1.9542, and 2.0109, respectively.

6 Modeling Release Spread

Information such as the volume of contaminant in a release, area of soil contaminated, estimated rate of substance release, and estimated duration of the release is not readily available. A diffusion driven differential equation was used to roughly approximate these factors. The model makes the following assumptions:

- the leak occurs at the bottom of the UST
- the soil permeability and texture are the same throughout the modeling area
- the soil is completely dry prior to the release

While the model is only two-dimensional, the model assumes the spread in the x and y directions are the same. Further, the models represents the soil area as a matrix, storing the concentration of contaminant for each discrete block of soil.

6.1 Model Boundary Condition

Torricelli's Law relates the rate at which a liquid flows out of a hole due to gravity to the height of the liquid in the container for vented container that does not lose pressure, as described by

$$v = \sqrt{2gh} \tag{5}$$

where v is the velocity of the contaminant exiting the UST (m/s), g is the gravitational acceleration $9.81 m/s^2$, and h is the height of the fluid (m) [14].

Bernoulli's equation is the same as Torricelli's law, but includes a discharge coefficient to account for the change in pressure [15]. The discharge coefficient is simply a ratio between the actual discharge and the theoretical discharge described in Torricelli's law [15]. Bilton suggests the standard discharge coefficient for circular orifices with fluid height over 45 inches and an orifice diameter of 0.75 inches (or approximately 1.9 cm) is 0.613 [16]. Therefore, the change in volume leaving the tank through a circular hole can be modeled by

$$B(r_h, h) = C_d(264.172)(\pi r_h^2)\sqrt{2gh}dt \tag{6}$$

where $B(r_h, h)$ is in gallons, $C_d = 0.613$ is the discharge coefficient, 264.172 converts m^3 to gallons, r_h is the radius of the hole (m), and dt is the change in time. Assuming the UST is full at the start of the release, h is the diameter of the UST.

The use of initial boundary conditions allow the model to advance the concentration through time using numerical methods. The combination of Bernoulli's equation and a Gaussian curve with a mean of $\mu = 0$ and standard deviation of $\sigma = \frac{1}{4}$ provide the volume of contaminant exiting the UST through the orifice, as seen in Equation

7.

$$V(r_h, h) = B(r_h, h) \left(\frac{4}{\sqrt{2\pi}} \right) e^{-8x_0^2} \tag{7}$$

where x_0 describes the position. Then, the boundary condition can be described in terms of concentration (gal/m^2) according to Equation 8,

$$C_0(r_h, h) = \frac{V(r_h, h)}{V_s} \tag{8}$$

where V_s is the area of the discrete soil block (m^2). For example, Figure 14 shows the top boundary condition if $r_h = 0.001m$ and $h = 1.8288m$. For all further boundary conditions it is assumed the radius of the whole is $r_h - 0.001m$. Appendix C provides the dimensions of the National Board Standard USTs used to calculate the boundary conditions.

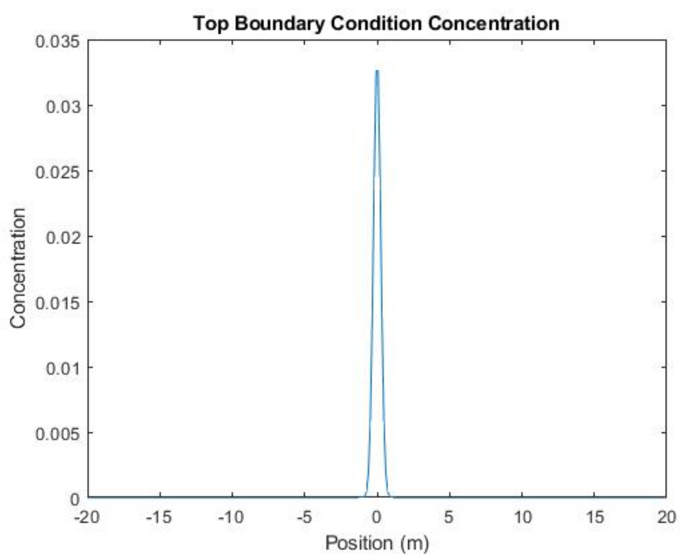

Figure 14: *Concentration boundary condition for a UST with a diameter of* $h = 1.8228m$ *and a hole with radius of* $0.001m$*, as determined by Equation 8.*

Soil Type	**Effective Diffusion Coefficient** D_e ($\frac{m^2}{s}$)
Compacted Silty Sand	$(3.0 \pm 1.3)10^{-6}$
Compacted Clay Sands	$(3.2 \pm 1.5)10^{-6}$
Clay	$(2.7)10^{-6}$

Table 11: *The effective diffusion coefficients ($D(\theta)$) for specific soil referenced from [4].*

6.2 Diffusion Driven Model

Fick's second law describes the accumulation or depletion of concentration in a volume that is proportional to the divergence of the concentration gradient,

$$\frac{dC}{dt} = D\nabla^2 C \tag{9}$$

where C is the concentration of the contaminant (gal/m^3) and D is the effective diffusion coefficient for the type of soil (m^2/s) [17]. Then, using Euler's method, the Equation 9 can be transformed into the arithmetic sequence:

$$\theta^{n+1}_{x,z} = \theta^{n}_{x,z} + D(\theta)(\Delta t)\left(\left(\frac{\theta^{n}_{x+1,z} + \theta^{n}_{x-1,z} - 2\theta^{n}_{x,z}}{\Delta x}\right) + \left(\frac{\theta^{n}_{x,z+1} + \theta^{n}_{x,z-1} - 2\theta^{n}_{x,z}}{\Delta z}\right)\right)$$

Equation 6.2 models the diffusion of the contaminant through the soil without accounting for the effective bearing stress and gravity. The model further assumes the soil is homogeneous throughout. Therefore, the diffusion will be symmetrical, as seen in Figure 15.

Like many numerical solutions to differential equations, Equation 6.2 is not always stable. To make the model stable each time step must be less than or equal to 0.01 seconds. Therefore, to model a year or even a full day is a lengthy process. However, notice the volume of contaminant in the soil appear to increase almost linearly in

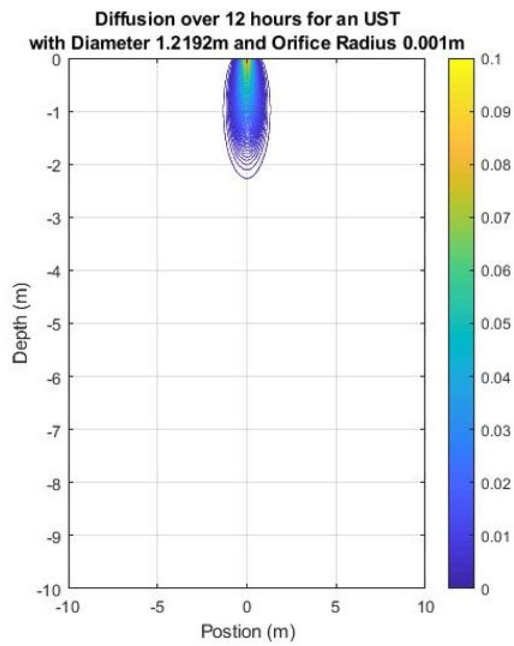

Figure 15: *Contaminant concentration in soil after first 12 hours of release from a UST with a 1.2192m diameter and a 0.001m hole radius.*

Figure 16 after only 12 hours. Therefore, the creation of a line to fit the modeled volume of contaminant in the soil provides a quick approximation of the contaminant volume farther in the future, as seen in Figure 17.

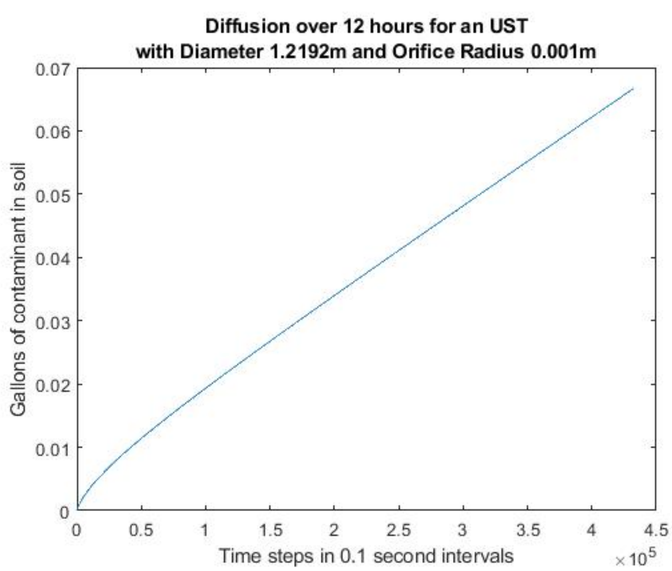

Figure 16: *The volume (gallons) of contaminant in the soil during the first twelve hours of release. These values were simulated using Equation 6.2.*

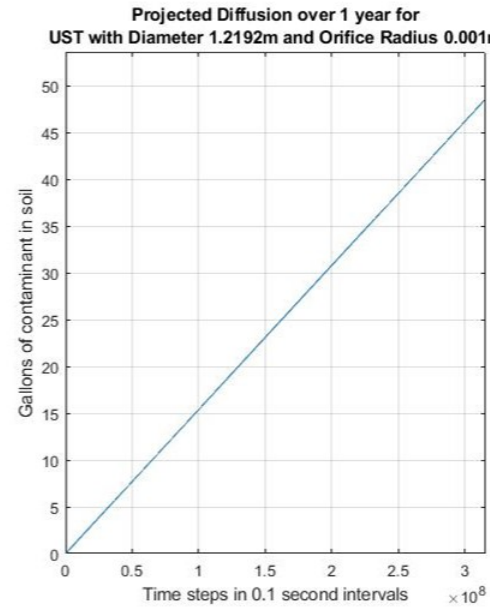

Figure 17: *A linear model fitted to the simulated volumes in Figure 16, which approximates the volume (gallons) of contaminant in the soil during the first year of release for a UST with a 1.2192 diameter and a 0.001m hole radius.*

6.3 Results and Discussion of Models

Table 12 shows how long the LUST will leak at the constant rate until empty, as determined by Equation 8. This assumes the UST starts full and is not refilled. Due to the time inefficiency of the diffusion models, the values in Table 12 are based on the linear models fitted to the volume of contaminant in the soil.

Notice the difference in duration due to soil type, as seen by the effective diffusion coefficient. Notice the direct relationships between the diffusion time, effective diffusion coefficient, and the volume of the tank. Yet, notice there is a slight inverse relationship between the diameter and the diffusion time for tanks of the same volume but different diameter. This is due to the constant boundary condition, as the UST with a smaller diameter will have a slower constant leaking rate.

UST Characteristics		**Duration Leaking Until Empty (yrs) with D_e**				
Capacity (gal)	Diameter (m)	$4.7e-6$	$3.2e-6$	$3.0e-6$	$2.7e-6$	$1.7e-6$
550	1.2192	10.74	11.24	11.31	11.42	11.81
1000	1.2192	19.53	20.43	20.56	20.76	21.46
1100	1.2192	21.49	22.47	22.62	22.83	23.61
1500	1.2192	29.30	30.64	30.84	31.14	32.20
1500	1.651	25.18	26.33	26.20	26.76	27.67
2000	1.651	33.57	35.11	35.34	35.68	36.89
2500	1.651	41.97	43.89	44.17	44.60	46.12
3000	1.651	50.36	52.67	53.00	53.52	55.34
4000	1.651	67.15	70.23	70.67	71.36	73.78
5000	1.8288	79.75	83.41	83.94	84.75	87.63
5000	2.1336	73.84	77.22	77.71	78.46	81.14
7500	2.1336	110.76	115.83	116.57	117.70	117.70
7500	2.4384	103.60	108.35	109.04	110.10	113.84
10000	2.4384	138.14	144.47	145.39	146.80	151.79
10000	3.048	123.56	129.22	130.04	131.30	135.77
12000	2.4384	165.77	173.37	174.47	176.16	182.15
12000	3.048	148.27	155.07	156.05	157.56	162.93
15000	2.7432	195.36	204.32	205.61	207.61	214.67
15000	3.048	185.34	193.84	195.07	196.95	203.66
20000	3.048	247.12	258.45	260.09	262.61	271.55
25000	3.048	308.90	323.06	325.11	328.26	339.43
30000	3.048	370.68	387.67	390.13	393.91	407.32

Table 12: *Duration of release when leaking at a constant rate when the UST starts full. These values are based on the linear lines fitted to the volume of contaminant in the soil.*

Both models are very simple, and fail to take into account many factors which affect the accuracy of the results. Not accounting for the direct affect of gravity likely causes the model to overestimate the time required to empty the UST and underestimates the vertical flow distance. Further, the model does not account for the change in flow rate due to a decreasing pressure in the UST, which will cause the model to underestimate the time for the UST to empty. However, due to the effective stress of the surrounding soil, the leak rate of the UST is slower than the rate suggested by Bernoulli's equation, once again causing the model to underestimate the time for the UST to empty.

Despite the simplicity of the model, the model provides valuable insight into the affect of diffusion on a LUST. Since the contaminant diffuses very slow through the soils the plume size as a result of diffusion is relatively small. Therefore, large plumes of contaminant can be attributed to other factors such as gravity, water flux, and other factors not modeled.

7 Environmental Impact Analysis

7.1 Impacts on Property Values

Regardless of how far the contaminant spreads, LUSTs have the potential to impact adjacent properties through contaminating drinking water and depreciating property values. A LUST impacts adjacent properties by depreciating property values between 3% and 6%, which has diminishing effect out to three kilometers 741 acres [5]. So, all properties within the $9\pi km^2$ area, or approximately 6987 acres, formed by a circle with a radius of 3 kilometers where the LUST is the origin experience a depreciation in property values. The decreasing affect on housing prices as distance increases is modeled by the bivariate Gaussian distribution [18],

$$f(x,y) = \frac{1}{2\pi\sigma_x\sigma_y} exp\left(-\frac{1}{2}\left(\frac{(x-\mu_x)^2}{\sigma_x^2} + \frac{(y-\mu_y)^2}{\sigma_y^2}\right)\right) \tag{10}$$

where x, y form a grid of one acre blocks, $\mu = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$ and $\sigma = \begin{bmatrix} 3493.5 \\ 3493.5 \end{bmatrix}$. Therefore, Equation 10 simplifies to

$$f(x,y) = \frac{1}{13974\pi} exp(-\frac{1}{2}\frac{x^2+y^2}{1220452.25}) \tag{11}$$

In order to determine the depreciation rate, $f(x,y)$ can be transformed by

$$g(x,y,d) = d * f(x,y)/max(f(x,y)) \tag{12}$$

where d is the maximum depreciation rate experience by adjacent properties. Figure 18 shows the contour of $g(x, y, 0.045)$ when $d = 0.045$, the average between 3% and 6%, when the LUST facility exists at $(0, 0)$.

In addition, Montana private property values range from below \$59,329 to above \$1,187,212 with an average of \$245,262 [19]. Calculating the total change in property values due to depreciation is as simple as

$$PD = p * \sum_{y=0}^{741}\sum_{x=0}^{741} g(x,y,d) \tag{13}$$

where p is the property value. This model assumes all properties within the three kilometers are private residential properties with the same initial value. Table 13 shows the total loss in property value due to depreciated property costs. Using 3% and 6%, and \$59,329 and \$1,187,212 as lower and upper bounds for depreciation and

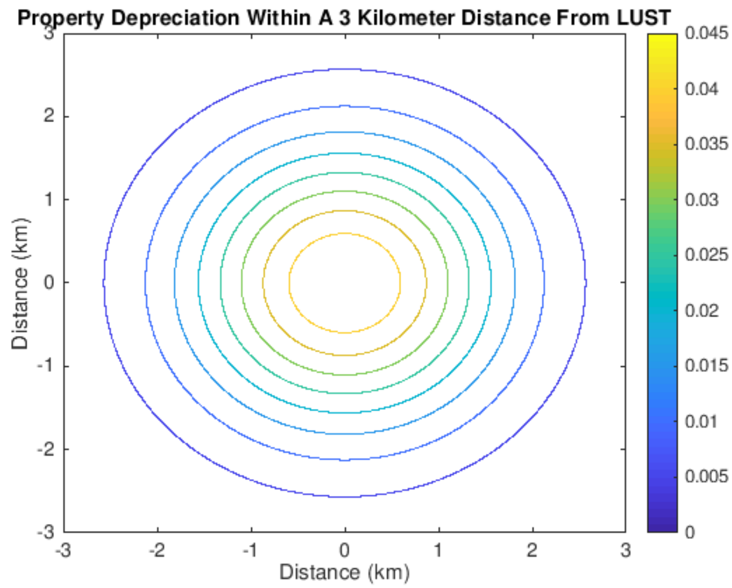

Figure 18: *Contour plot of Equation 12. The contour values are the depreciation values for surrounding properties, assuming the LUST facility exists at* $(0, 0)$.

Housing Price	**3%**	**4.5%**	**6%**
$59,329	$1.02	$1.52	$2.04
$245,262	$4.21	$6.32	$8.42
$1,182,212	$20.30	$30.45	$40.60

Table 13: *Total property value loss of private properties within three kilometer radius of a LUST due to three different depreciation rates [5].*

property values, respectively, yields a best case scenario of $0.384 billion and a worse case of $15.357 billion, as seen in Table 13 [19] [5].

However, it is important to remember that though Guignet et al. concluded property prices depreciate as a result of LUSTs, Guignet et al. also observed an appreciation after the completion of remediation [5]. However, since only 27.5% of the complete release records have remediation dates, it is possible the observed appreciation may not occur until decades later. Zabel et al. indicates depreciation of property values only occurs when the release is highly publicized, meaning many small releases could have little to no impact on property values [12].

7.2 Inhalation and Consumption of Contaminants

As discussed prior, releases can have adverse health affects and USTs commonly contain materials toxic to humans when ingested and inhaled. Adverse side affects include an increased risk of cancer, amnesia, and death in extreme instances. Though the type of cancer impacts cost and probability of survival, but for this project the term cancer refers to all types of cancers. Ekweume et al. estimates the annual financial impact of surviving cancer as $16,213 for individuals 18 to 64 years of age and $16,441 for individuals 65 and older, who did not have a history of cancer [20]. Therefore, after inflating to current dollars, the model uses $18,752.47 as the approximate annual financial burden of surviving cancer. These annual values include direct medical costs and indirect costs such as, missed works days, employment disability, and loss of productivity [20]. Siegel et al. observed an average 68% and 61% survival rate of all cancers for individuals of Caucasians and African Americans, respectively [21]. Then financial cost of an increased risk of cancer can be modeled by:

$$m_1(Y, CR) = 18752.47Y(0.645)(CR) \tag{14}$$

where m_1 is the approximated total cancer survivor cost over Y years with a cancer risk of CR.

Similarly, the cost of mortality due to cancer can be modeled by:

$$m_2(CR) = (SVL)(1 - 0.645)(CR) \tag{15}$$

where m_2 is the approximated cost of mortality for a increased cancer risk of CR and VSL is the value of statisical life. The EPA recommends the use of $7.4 million (2006 dollars), so after inflation the statistical value of life is $9.19 million ($2018) [22].

As seen in Table 2, ingesting or inhaling gasoline at very low levels for 70 years increases the risk of cancer. However, of all Montana LUSTs records, the duration of a release and remediation did not exceed 70 years, yet 40.48% of LUSTs have a duration of release and cleanup that exceeds seven years. From historical data, the Utah DEQ estimates 33% of LUSTs affect ground water, resulting in contaminant concentrations between 0.0003ppm to 517ppm with a mean of 0.42ppm [3]. However, the Utah DEQ estimates only 1% of LUSTs impact the air quality. Since the individuals had not prior history of cancer, their risk of cancer is described by the probabilities provided by the Utah DEQ. So, the total cost per person due to an increase risk of cancer from inhaling or ingesting contaminants for seven years can be approximated by

$$\begin{aligned} M(Y) &= 0.33\left(m_1\left(Y, \frac{1}{1,000,000}\right) + m_2\left(\frac{1}{1,000,000}\right)\right) \\ &+ 0.01\left(m_1\left(Y, \frac{1}{1,000,000}\right) + m_2\left(\frac{1}{1,000,000}\right)\right) \end{aligned} \tag{16}$$

Then, for four adjacent households with four family members who had no prior risk of cancer, the cost for 1, 10, 25, 50, and 75 years is $16 * M(1) = \$17.80$, $16 * M(10) = \$18.40$, $16 * M(25) = \$19.40$, $16 * M(50) = \$21.04$, and $16 * M(75) = \$22.68$, respectively. The model does not take into account the increased risk of cancer over the course of 70 years, the risk of mortality due to high concentration levels in the air and water since these events are less likely to occur due to the high concentration levels and time requirement. As a result, these events would result in a lower yearly cost than that produced by Equation 16.

8 Future Development

8.1 Financial Model

The financial model used to predict the remediation cost for releases with Resolved Dates, but the model would be most useful to predict the total cost of remediation upon release discovery or prior to a release. The financial model is most accurate using records with Resolved Dates, and includes the variable Duration to account for the end date. However, the coefficient of Duration indicates that it is not an extremely important factor, and thus completion of remediation may not be as crucial to predicting the cost as the R-squared values lead on. Therefore additional research into the relationships between predictors and remediation cost and the introduction of new predictors could increase the prediction accuracy for releases with and without Resolved Dates.

Though unknown, the increase in accuracy could be a result of a smaller training data set or fewer unique facilities, both of which result in a smaller total variance in the data set. Including facilities with a UST similarity value greater than zero would increase the number of unique facilities in the data set, and thus improving the model's accuracy predicting remediation costs for USTs at all facilities. Moreover, the subset of release records with Resolved Dates could be a more linear subset of the data, thus resulting in a higher accuracy model.

8.2 Risk Values

The use of Analytical Hierarchy Process (AHP) to create risk values for each UST works well when comparing USTs. However, the complexity and extensive computation makes AHP hard to replicate in an efficient manner. The use of other ranking methods or classification methods, would allow for more frequent and efficient risk coefficient updates. Developing a method that uses characteristics from prior LUSTs to help inform what USTs are of greater risk may help increase the accuracy of the risk coefficients.

8.3 Modeling Contaminant Spread

Future development would also include specifically three elements to make the diffusion model more realistic for modeling the contaminant flow through soil. First, the model would include accounting for gravitational pull, which could easily be modeled by an additional term added to the current numerical model in Equation 6.2.

Second, the model would account for the changing pressure in the UST as a result of losing contaminant. However, modeling the change in volume of contaminate released will not be completely correct without modeling the effective bearing stress. However, recalculating the volume of contaminant in the UST at each time step, then using Bernoulli's equation and the new volume in the tank to calculate the new rate of release will provide more accurate boundary conditions, as the rate at which the contaminant exits the UST will decrease rather than remaining constant.

Lastly, future work includes altering the model to model for extended periods of time. The ability to model farther in the future in a shorter period of time benefits this analysis in two major ways: more accurate estimations of when the LUSTs will empty and probabilities of whether the release impacts adjacent properties and ground water based off of plume dimensions and concentrations. This ability would especially help to understand what conditions such as hole size, soil type, volume, and proximity to facility property boundaries, affect the likelihood of a release to impact a neighboring property and the surrounding community

8.4 Environmental and Community Impact

Further developments to the environmental and community impact section include:

- Accounting for varying property sizes, property values, and property types when modeling property depreciation.
- Using probabilities determined by the contaminant spread model to determine

potential impacts.

- Modeling impacts according to the LUST's proximity to the facility's property boundaries.
- Determining how UST system upgrades affect the environmental and community impact.

9 Conclusion

A primary goal of the MT DEQ is to educate individuals of the consequences of a release and to prevent releases when possible through proper inspections, equipment, and identification of high risk USTs. The MT DEQ unarguably has the correct goals in mind, but the achievement of these goals depends on a wide range information, some of which is unattainable. While this analysis provides insight into the relationship between UST characteristics, environmental characteristics, release characteristics, total financial cost of remediation, and risk coefficients, the analysis exposes the necessity for more information to fully understand these relationships. Both the lack of information and the possibility for incorrectly entered information can greatly hinder the ability to answer the most desired questions. Answering these questions must begin with documenting the necessary information and checking its accuracy.

This analysis provides key pieces of information to aid the MT DEQ in addition to the use of the models. First, while a more efficient routine of performing compliance inspections based on risk is very important, the majority of releases are discovered through historical contamination and facility reports. Thus, preventing releases and the severity of the releases should also start with enhancing methods and policies to detect releases prior to closure and methods of encouraging owners and operators to be extra attentive and immediately report all possible releases. Policy adaptions could include incentives, additional classes in release impacts, and the adherence to minimum risk classifications in specific UST characteristic categories. Second, since the USTs of most facilities are very similar, repeated releases at a facility could have many causes including the specific type of UST the facility uses most. Third, understanding how UST and environmental characteristics impact risk coefficients should serve as resource when making decisions regarding the installation of new USTs. In some instances it may be in the best interest of an owner to opt for one lot over another for a new facility due to environmental characteristics of each plot, and it may be in the best interest of regulators to require specific UST characteristics for new USTs. Lastly, community awareness of the community and health risks posed by LUSTs should serve as an encouragement for community members and operators to report all releases and possible forms of water and air contamination.

Appendices

A Characteristic Classifications

The tank and environmental characteristics used in prior MT DEQ risk analyses, as well as this analysis. The characteristics was classified on a scale of zero to four my MT DEQ UST regulators, where zero is the best case and four is the worst case characteristics. The worst case characteristics are those most likely to be a result of a release.

Classification	0	1	2	3	4
Tank Characteristics					
Spill Prevention	Yes				No
Under Dispenser Containment	Yes				No
Overfill Prevention	Flapper Valve, Auto Limiter, Positive Shutoff		High Level Alarm		None or Ball Float Valve
Piping Configuration	None	Double-Walled, Steel-Terminal piping,	Secondary Containment Chase, PVC	Single-Walled	Cathodically Protected Steel
Piping Material	None	High Density Polyethylene, Flexible Plastic	Fiberglass, Fiberglass Reinforced Plastic	Copper	Steel, Unknown
Tank Configuration	Above Ground	Double-Walled		Excavation Liner	Single-Walled
Tank Material	Concrete	Fiberglass, Reinforced Plastic	Steel Clad	Cathodically Protected Steel	Bare Steel, Unknown
Age of Tank		< 10	11-15	16-19	20+
Pipe Leak Detection Methods Used	2 Methods	1 Method			MTG, GW, Vapor Selected
Tank Leak Detection Methods Used	2 Methods	1 Method			MTG, GW, Vapor Selected

Classification	0	1	2	3	4
Environmental Characteristics					
Source Water Protection Zones		Outside of Protection Zones			Within Protection Zones
Distance To Closest Well		> 5000	1000-5000	500-1000	< 500
Type of Well Closest		Irrigation	Industrial	Commercial	Private, Municipal, Domestic
Status of Well Closest	Abandoned, Plugged	Inactive			Active
Surface Water		> 5000	1000-5000	500-1000	< 500
Water Quality	No Assessed Stream With 0.25	Class 5, Class 4	Class 3	Class 2	Class 1
Soil Texture	Other, Null	Clay	Loam	Sand	Gravel
Soil Permeability	Very Slow	Moderately Slow, Slow	Moderate	Rapid, Moderately Rapid	Very Rapid
Population Density	(ppl/sq mile)	$< 5,000$			$> 5,000$
LUST	None		Past		Present
Land Use		Other	Industrial, Commercial	Residential, Exempt	School

B Work Plan Codes

Code	Code Name	Cleanup Technology	Investigative
ABS	Unknown - 1 record		x
ART	Sparging	x	
AS	Air sparging	x	
BS	BioSparging	x	
BV	Bioventing	x	
CF	Carbon filtration	x	
COX	Chemical addition	x	
DP	Dual phase		x
EB	Enhanced bioremediation	x	
ECO	Electro-catalytic oxygenation	x	
FPR	Free product recovery	x	
FPRF	fixed for FPR	x	
FS	Feasibility Study		x
G	Result of WP Name being too long		x
GW	fixed for GWM		x
GWM	Groundwater Monitoring		x
HC	Hydraulic conductivity assessment		x
IBI	Intrinsic Biological Indicators		x
LF	Landfarming		x
LFI	Landfarming		x
LIF	Laser Induced Fluorescence		x
M	Result of WP Name being too long		x
MNA	Monitored natural attenuation		x
MPE	Multiphase Extraction Pilot Study		x
OI	Other investigation		x
ORC	ORC additive		x
OT	Other?		x
OX	Oxygen addition	x	
PC	Could not replicate code when running query		x
PR	Phytoremediation	x	
PT	Pump & Treat (water)	x	
PT	Pilot Test		x
PT	Pump & Treat (water); Pilot Test	x	x
R	Result of WP Name being too long		x
RC	Receptor survey		x
RS	Remediation system?	x	
RSD	Remediation system design		x
RSI	Remediation system install		x
RSO	Remediaiton system O&M	x	

Code	**Code Name**	**Cleanup Technology**	**Investigative**
RSR	Remediation system removal		x
RT	Reagent treatment	x	
S	Study		x
SB	Soil borings		x
SD	Remediation system shut down		x
SF	Soil flushing	x	
SGS	Soil gas survey		x
SR	Soil removal	x	
ST	Slug Test		x
SUB	Subcontract		x
SVE	Soil vapor extraction	x	
TD	Thermal desorption	x	
TP	Test pits		x
TW	Temporary well		x
UCI	Utility Corridor Investigation		x
UI	Utility investigation		x
VI	Vapor intrustion		x
WA	Well abandonment		x
WD	Well Development		x
WI	Well Installation		x
WN	Well Notch		x
WP	Work plan		x
WR	Well repair		x

Table 14: *The names of the work plan codes used in the remediation work plan data set.*

C Common UST Sizes

Capacity (gal)	**Diameter (m)**	**Length (m)**
550	1.2192	1.8288
1000	1.2192	3.302
1100	1.2192	3.6322
1500	1.2192	4.7752
1500	1.651	2.7432
2000	1.651	3.6068
2500	1.651	4.5212
3000	1.651	5.3848
4000	1.651	7.2136
5000	1.8288	7.2136
5000	2.1336	5.3848
7500	2.1336	8.0772
7500	2.4384	5.9944
10000	2.4384	8.0772
10000	3.048	5.1816
12000	2.4384	9.6012
12000	3.048	6.2992
15000	2.7432	9.6012
15000	3.048	7.7724
20000	3.048	10.5156
25000	3.048	12.954
30000	3.048	15.621

Table 15: *The National Board Standard sizes for cylindrical underground fuel tanks [6]*

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