EVALUATING THE COST OF SEWER DISPOSAL TO OTHER ALTERNATIVES
FOR THE MANAGEMENT OF TRUCK WASH WATER GENERATED DURING
WINTER MAINTENANCE ACTIVITIES

A Thesis
Presented to
The Graduate Faculty of The University of Akron

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

Joshua J. Slaga
May, 2014
EVALUATING THE COST OF SEWER DISPOSAL TO OTHER ALTERNATIVES
FOR THE MANAGEMENT OF TRUCK WASH WATER GENERATED DURING
WINTER MAINTENANCE ACTIVITIES

Joshua J. Slaga

Thesis

Approved: 

Advisor
Dr. Christopher Miller

Dean of the College
Dr. George K. Haritos

Faculty Reader
Dr. William Schneider IV

Dean of the Graduate School
Dr. George R. Newkome

Faculty Reader
Dr. Stephen Duirk

Date

Department Chair
Dr. Wieslaw Binienda
ABSTRACT

The trucks performing snow and ice removal for the Ohio Department of Transportation are frequently washed to prevent corrosion associated with the salt the trucks spread on the roadways. Strategies for the management of wash water generated during routine washing of salt trucks have been previously studied and collecting and hauling off-site for disposal or connecting to a sanitary sewer system have generally been determined to be the most feasible options. The purpose of this research is to compare the annualized cost of both strategies to determine the most cost effective option by using a probabilistic based approach. The cost equation input variables were based on two datasets; statewide data for all ODOT maintenance facilities and data for ODOT maintenance facilities without access to the sanitary sewer, as well as labor rate, cost of fuel, and discount rate. The variables were defined by probability distribution and cost calculations were performed using Monte Carlo Simulation. The calculations determined that the annualized cost of the management strategies were most sensitive to the number of trucks, number of winter events, roundtrip hauling distance, capital cost of the sanitary sewer and discount rate. The change in the probability that the collection and off-site hauling of wash water for disposal is the most cost effective strategy was less than 30% when the capital cost of the sanitary sewer connection was $300,000 or greater. The probabilities were much more sensitive to the changes in the key input variables when the sanitary sewer capital cost was set to $100,000. The overall probability based on all input
distributions was calculated based on the capital cost of the sanitary sewer. For all facilities, the collection and off-site disposal strategy has a 90% or greater probability to be the most cost effective strategy when the capital cost exceeds $280,000; however, the capital cost decreases to $172,000 for the same probabilities when considering only facilities without existing sanitary sewer access. This result revealed that collection and off-site disposal is the generally the most cost effective management strategy for ODOT maintenance facilities currently lacking sanitary sewer access when the capital cost of connecting to the sanitary sewer exceeds $100,000.
ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Christopher M. Miller, for his guidance and assistance throughout this project. I would like to thank all of the people who provided input and performed the previous research that this research built upon. Most importantly, I would like to thank my wife for all her assistance and patience.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>LIST OF TABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Tables</td>
</tr>
<tr>
<td>vii</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LIST OF FIGURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Figures</td>
</tr>
<tr>
<td>ix</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. INTRODUCTION</td>
</tr>
<tr>
<td>I.1 Background</td>
</tr>
<tr>
<td>I.2 Objectives</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>II. LITERATURE REVIEW</th>
</tr>
</thead>
<tbody>
<tr>
<td>II.1 Wash Water Management Strategies</td>
</tr>
<tr>
<td>II.2 Estimating Cost with Uncertainty and Variability Inputs</td>
</tr>
<tr>
<td>II.3 @Risk Simulations</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>III. APPROACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>III.1 Cost Equation</td>
</tr>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IV. RESULTS AND ANALYSIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV.1 Advanced Sensitivity Analysis</td>
</tr>
<tr>
<td>IV.1.1 Collect and Dispose Option</td>
</tr>
<tr>
<td>IV.1.2 Sanitary Sewer Option</td>
</tr>
<tr>
<td>30</td>
</tr>
</tbody>
</table>

| vi               |
LIST OF TABLES

Table                          Page

3.1  Summary of cost factors used in the calculation of the annualized wash water management costs.........................................................12

3.2  Summary of cost factors defined by distributions in the Collect and Dispose or Sanitary Sewer annualized cost calculations. The values are based on all ODOT county and outpost garages. ........................................13

3.3  Costs of operating a truck used to haul wash water to disposal at an off-site ODOT facility.................................................................20

4.1  The range of values calculated for the annualized cost of collecting and disposing of wash water at a nearby ODOT maintenance facility based on an advanced sensitivity analysis calculated using @Risk. The cost factors were varied between 5% and 95% of their defined distributions. The annualized cost is most sensitive to the number of trucks, number of winter events, and the roundtrip hauling distance........33

4.2  The range of values for the annualized cost of the connection to an existing sanitary sewer system based on the capital cost of the sewer construction. The minimum and maximum values were calculated by an advanced sensitivity analysis in @Risk, where the discount rate was varied between 5% and 95% of its defined distribution.................36

4.3  Comparison of the probability that Collect and Dispose is least costly management strategy for all ODOT maintenance facilities and facilities lacking access to a sanitary sewer system. ........................................49

4.4  Summary of the site characteristics of the two facilities that tied into existing sanitary sewer systems...............................................................51
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>ODOT Districts and maintenance facility locations</td>
<td>3</td>
</tr>
<tr>
<td>1.2</td>
<td>ODOT maintenance facilities lacking access to sanitary sewer</td>
<td>4</td>
</tr>
<tr>
<td>3.1</td>
<td>The distribution defined for the discount rate. The distribution is a discrete histogram based nominal treasury interest rates of 30-year maturity from 1979 to 2013 (Office of Management and Budget 2013). The mean discount rate is 0.0740.</td>
<td>16</td>
</tr>
<tr>
<td>3.2</td>
<td>The distribution defined for number of trucks used in the Collect and Dispose annualized cost calculations. The distribution is a discrete histogram based on all ODOT county and outpost garages. The data was provided by ODOT.</td>
<td>21</td>
</tr>
<tr>
<td>3.3</td>
<td>The distribution defined for the number of winter events used in the Collect and Dispose annualized cost calculation. The distribution is a discrete histogram based on the number of winter events recorded at all ODOT county garages from 2008 to 2011. The data was provided by ODOT.</td>
<td>22</td>
</tr>
<tr>
<td>3.4</td>
<td>The distribution defined for the roundtrip distance of hauling the stored wash water used in the Collect and Dispose annualized cost calculation. The distribution is based on the distances of outpost garages to country garages and county garages to district garages based on addresses supplied by ODOT. The average roundtrip hauling distance is 49.2 miles.</td>
<td>34</td>
</tr>
<tr>
<td>3.5</td>
<td>The distribution defined for labor rate used in the Collect and Dispose annualized cost calculation. The distribution is a lognormal distribution with ( \alpha = 5.7701, \beta = 6.9332, ) and shift = 16.3638. The distribution was fit by @RISK based on the hourly wage supplied by ODOT ($17.50/hour), multiplied by a factor of 1.55 to account for salary and benefits (Bureau of Labor Statistics, 2012), and multiplied by ((1+i)^n), where ( i ) is a distribution of yearly wage increase based on the Average Wage Increase from 1951 to 2013 (Social Security Administration, 2014), and ( n ) is 12 years based on the planning period used in the Collect and Dispose annualized cost calculation.</td>
<td></td>
</tr>
</tbody>
</table>
Dispose annualized cost calculations. The mean labor rate is $56.37/hour.

3.6 The distribution defined for the cost of fuel per gallon used in the Collect and Dispose annualized cost calculation. The distribution is a normal distribution with a mean of 4.315 standard deviation of 0.395. The distribution was fit based on low, likely, and high predictions for the cost of a gallon of diesel fuel in the year 2020 (U.S. Energy Information Administration, 2013).

3.7 The distribution defined for the cost of disposal per gallon of wash water via sanitary sewer in the Collect and Dispose and Sanitary Sewer annualized cost calculation. The distribution is a Lognormal distribution with $\mu=0.016936$, $\sigma=0.0043147$, and shift = -0.0048511. The distribution was fit by @Risk based on a histogram of sanitary sewer rates for the entire state of Ohio multiplied by $(1+i)n$, where i is a histogram distribution of rate increases based on historical data (Ohio EPA, 2013), and n is 15 years based on the midpoint of planning period used in the Collect and Dispose annualized cost calculations. The average disposal rate is $0.012/gallon.

3.8 The distribution defined for number of trucks at ODOT facilities currently without sanitary sewer access. The distribution is a discrete histogram based data provided by ODOT. The average garage without sanitary sewer access has five (5) trucks.

3.9 The distribution defined for the roundtrip distance of hauling the stored wash water for facilities currently without sanitary sewer access. The distribution is based on the distances of outpost garages without sanitary sewer access to country garages and county garages without sanitary sewer access to district garages based on street addresses supplied by ODOT. The average roundtrip hauling distance is 39.9 miles.

4.1 The range of values calculated for the mean of $C_D$ based on an advanced sensitivity analysis in which the model input values were varied between 5% and 95% of the model distribution.

4.2 The probability that the annualized cost of collecting and disposing wash water at a nearby ODOT facility is the least costly strategy based on the number of trucks at the facility. The probability that at average number of eight (8) trucks collecting and disposing is less costly than a sanitary sewer capital cost of $100,000, $300,000, and $500,000 is 37.0%, 95.9%, and 99.5% respectively.
4.3 Snowfall gradient for the State of Ohio based on data from 2009. ..................41

4.4 The probability that the annualized cost collecting and disposing of wash water at a nearby ODOT facility is the least costly strategy based on the number of winter events at the facility. The probability at the average number of winter events, twenty-eight (28), that Collect and Dispose is less costly based on a sanitary sewer capital cost of $100,000, $300,000, and $500,000 is 34.7%, 93.2%, and 99.2% respectively.................................................................42

4.5 The probability that the annualized cost collecting and disposing of wash water at a nearby ODOT facility is the least costly strategy based on the roundtrip distance of hauling the wash water for disposal. The probability that the average roundtrip distance, 49.2 miles, that Collect and Dispose is less costly based on a sanitary sewer capital cost of $100,000, $300,000, and $500,000 is 18.7%, 83.0%, and 96.0% respectively.................................................................44

4.6 The probability that the annualized cost collecting and disposing of wash water at a nearby ODOT facility is the least costly strategy based on the discount rate. The probability at a discount rate of 7% that Collect and Dispose is less costly based on a sanitary sewer capital cost of $100,000, $300,000, and $500,000 is 41.4%, 93.8%, and 98.7% respectively.................................................................46

4.7 The cumulative distribution function for collect and dispose as best management strategy based on the capital cost of the sanitary sewer connection.................................................................48

4.8 The cumulative distribution function for collect and dispose as best management strategy based on the capital cost of the sanitary sewer connection for ODOT facilities without current sanitary sewer access. ............50
CHAPTER I
INTRODUCTION

1.1 Background

Snow and ice removal is essential to minimize the impact of winter events on the transportation network within the State of Ohio. The Ohio Department of Transportation (ODOT) has a fleet of 1,583 trucks equipped with material spreaders located at 88 county and 136 outpost garages to address the needs for snow and ice removal. The material spreaders utilize salt for winter maintenance of roadways. ODOT has an average salt usage of 600,000 tons throughout the 43,000 lane miles of highways (Ohio Department of Transportation, 2011). In an attempt to minimize corrosion, trucks are washed after every outing.

The waste water generated from washing the trucks after winter events has been identified to contain elevated concentrations of suspended solids, dissolved solids, oil and grease, and heavy metals (Alleman et al., 2004; Fitch et al., 2004; Miller et al., 2014). Where available, the wash water is treated with an oil/water separator and discharged directly to the sanitary sewer. However, sanitary sewer access is not always present at ODOT maintenance facilities. Previous research has identified and evaluated additional strategies to manage this waste water (Alleman et al., 2004; Fitch et al., 2004, 2006, 2008; Miller et al., 2014) when sanitary sewer access is absent.
The research by Miller, et al. (2014) identified six feasible management strategies for use within the state of Ohio. A cost assessments for the six viable management strategies were performed for a typical ODOT county and outpost garage. The collection and off-site disposal of truck wash water, using ODOT personnel at a nearby ODOT facility was calculated to have the lowest annual cost. The research determined that any values deviating from the statistical mode may impact what management strategy is the most cost effective.

The preferred management strategy of many state Departments of Transportation (DOT) is to tie the facilities to the sanitary sewer system for disposal of the truck wash water. Connecting the facility to the sanitary sewer has many benefits, including minimized annual operating costs, maintenance, and labor. This strategy also eliminates the need for collection, storage and disposal of truck wash water. Despite minimal annual costs, the capital costs to connect to an existing sanitary sewer system can be high. Any evaluation of management strategies should include connection to the sanitary sewer due to its benefits.

ODOT divides the state into twelve (12) districts. Each district is composed of a district office, county garages, and outpost garages. The fleet of ODOT trucks involved with snow and ice removal are located throughout the state of Ohio at the 88 county and 136 outpost garages. Fleet sizes range from one (1) to twenty-four (24) trucks. The number of trucks at each facility varies based on the site specific conditions. Per the statistical mode, a typical county garage will consist of twelve (12) trucks and a typical outpost garage will have three (3) trucks. The number of trucks directly affects the volume of wash water generated.
Figure 1.1   ODOT Districts and maintenance facility locations.

Over 40% of the facilities involved in routine truck washing do not have access to a sanitary sewer system. Subsequently, current management strategies are often substandard due to increasing regulations. These facilities will require the selection of an alternative management strategy. The selected strategy must be cost effective and meet all disposal regulations. These factors, as well as other site specific characteristics, should also be considered when the management strategy of a facility completes its lifecycle, or a new facility is established.
Objectives

The overall objective of this project was to evaluate wash water management strategies to determine most cost effective option by using a probabilistic based approach. The evaluation was performed by calculating the probabilities that select management strategies will be less costly than the others. The following four (4) specific objectives were achieved in order to complete the overall objective of the project.

Objective 1: Define probability distributions in the cost equations for the input variables that have uncertainty or variability;
Objective 2: Determine each strategy’s cost sensitivity for each variable;

Objective 3: Calculate the probabilities that select strategies will be less costly than the others based on specific site conditions. Assess the influence of those site conditions on the calculated probabilities;

Objective 4: Use data from the results to assess recent construction at an ODOT facilities.
CHAPTER II
LITERATURE REVIEW

Previous research has identified feasible truck wash water management strategies. In evaluating those feasible strategies, cost assessments were performed utilizing typical, or average, values when calculating the cost of different strategies. Evaluations in prior research utilizes point estimates which do not accurately predict, nor provide probabilities of each strategy’s annual cost. Incorporating the variability and uncertainty of input parameters requires techniques developed for risk assessments. Risk assessment is common approach when variability and uncertainty is present. The objective of this project is to incorporate the variability and uncertainty of the cost of the management strategies.

2.1 Wash Water Management Strategies

The management of truck wash water has been previously studied and numerous management strategies were identified (Alleman et al., 2004; Fitch et al., 2004, 2006, 2008; Miller et al., 2014). In particular interest to this project, the research by Miller, et al. (2014) determined six feasible management strategies for implementation by the Ohio Department of Transportation; (1) connection to an existing sanitary sewer system, (2) the use of a contractor to pump and haul stored wash water for off-site disposal, (3) disposal of wash water at a waste water treatment plan using ODOT equipment (i.e., trucks) and personnel for hauling, (4) collection and off-site disposal at a nearby ODOT
maintenance facility, (5) media filtration and disposal at a nearby ODOT maintenance facility, and (6) media filtration and reuse for brine.

Cost assessments for the six viable management strategies were performed for a typical ODOT county and outpost garage (Miller, et al., 2014). The cost assessments demonstrated that, for a typical ODOT garage, collecting and disposing of wash water at a nearby ODOT maintenance facility is a more cost effective management strategy than commercial disposal or disposal at a waste water treatment plant. Filtration, and either disposal or reuse, are predictably more costly than collecting and disposing due to the additional step of filtration.

Due to the higher costs, commercial disposal, disposal at a WWTP, filtration and disposal, and filtration and reuse were not further analyzed in this project. Based on the results of the literature review, the calculations performed in this project compared of the costs of collection and off-site disposal at a nearby ODOT maintenance facility to the costs of connecting to an existing sanitary sewer system. Currently, the preferred management strategy of many DOTs is connection to an existing sanitary sewer system.

2.2 Estimating Cost with Uncertainty and Variability Inputs

Cost estimates can utilize probabilistic or deterministic values. Previous research on wash water management used deterministic values, based on typical values. Deterministic values are best to be used when detailed or specific values are available. A probabilistic approach uses probability distributions for one or more variables in a risk equation to quantitatively characterize variability. Variability may occur due to a large deviation of values, uncertainty and a lack of available data (U.S. EPA, 2001). This method is often employed in risk assessments. Although this project is not a risk
assessment, the techniques used in risk assessments can be applied to the uncertainty and variability encompassing wash water management strategies.

Cost estimation using probabilistic ranges of values has been used in prior research to incorporate the uncertainty and risk (Arena, et al., 2006; Chou, et al., 2009; Khodakarami, et al., 2014). The results of the estimate are also in probabilistic form. Deterministic estimates utilizing single values were often found to be unreliable. The probabilistic ranges improve the cost estimate reliability (Chou, 2009).

Monte Carlo Simulation (MSC) is the most widely used probabilistic method (EPA, 2001), and was used in the cost estimating models for all literature reviewed for this project. The simulations of MSC define cost uncertainty with input distributions. The input distributions are often derived from technical experts or historical data. The ultimate goal of the MCS is to estimate a cumulative distribution function for the final cost, which includes all of the uncertainty (Khodakarami, et al., 2014).

The MCS process consists of the following steps: (1) identify the major and uncertain work components, (2) define statistical distributions of each uncertain item, (3) use the model to calculate the desired output parameters with a predetermined number of iterations for the desired confidence and simulation error. Cost estimates are composed of both fixed and variable parameters (Carr, 1989). Therefore, not every input must be defined by probabilistic distributions.

MCS is numerical technique that relies on repeated random sampling to obtain results. As previously stated, multiple iterations of the calculations must be performed for the desire confidence level. Often times, thousands of iterations must be performed.
Computer software has simplified the technique, which has led to the widespread use of the simulation technology (Cooper et al., 2005).

2.3 @Risk Simulations

Numerous computer software simulation packages are available to perform MCS. Palisade @Risk is the world's leading risk and decision analysis software (Palisade, 2010). The software is an add-in to Microsoft Excel to apply MCS to spreadsheet models. The software has been used on numerous projects ranging from engineering to finance (Herbold 2000; Ordonez, 2014; Smith, 2004; Yoe, 2000; Zhao 2010).

The research reviewed created models in Microsoft Excel. In a typical Excel model, the input variables are defined as a deterministic value which results in a single output. With the @Risk software, the models can be modified to provide probabilistic distributions for the input variables. The program then runs a simulation that performs the calculations for a predetermined number of iterations of the calculations. The resulting output value is also in probabilistic distribution form.
CHAPTER III

APPROACH

3.1 Cost Equation

This project will evaluate the costs of two wash water management strategies; (1) connection to an existing sanitary sewer system and (2) collection and off-site disposal at a nearby ODOT facility using ODOT personnel. Although six feasible management strategies for use by ODOT have been identified, a detailed cost evaluation was performed only for the above two options. As discussed in Chapter II, previous research concluded that disposal of truck wash water at an ODOT facility is less costly than commercial disposal, disposal at a waste water treatment plant (WWTP), filtration and disposal, and filtration and reuse. However, these five options all share similar cost factors. Any changes to the input variables will affect the feasibility of all five options and have the same relative effect on the cost. Therefore, disposal at an ODOT facility will almost always be the less costly option than commercial disposal, disposal at a WWTP, filtration and disposal, and filtration and reuse.

Annualized costs were calculated in order to evaluate both options at a common basis for comparison. Under further evaluation, cost equations were created two strategies: (1) connection to an existing sanitary sewer system and (2) collection and off-site disposal at a nearby ODOT facility using ODOT personnel. For future discussion purposes, the two strategies will be referred to as "Sanitary Sewer option" and "Collect
and Dispose option”. The annual cost of the strategies will be referred to as $C_{SAN}$ and $C_{DISPOSE}$. The annualized costs are composed of capital costs and operational costs, as shown in Equations 3.1 and 3.2.

\[
C_{SAN} = \text{Annualized Capital Cost} + \text{Operational Cost} \quad (3.1)
\]

\[
C_{DISPOSE} = \text{Annualized Capital Cost} + \text{Operational Cost} \quad (3.2)
\]

where $C_{SAN} =$ Annualized cost of the tying into an existing sanitary sewer

$C_{DISPOSE} =$ Annualized cost of collection and off-site disposal at a nearby ODOT facility using ODOT personnel.

The capital costs must be put in annual terms by calculating the annualized capital cost factor, as shown in Equation 3. The annualized capital cost is then the product of the capital cost and annualized capital cost factor, as shown in Equation 3.3.

\[
\text{Annualized Factor} = \frac{i}{(1+i)^n-1} + i \quad (3.3)
\]

where $i =$ discount rate and $n =$ planning horizon in years

\[
\text{Annualized Capital Cost} = \text{Capital Cost} \times \text{Annualized Factor} \quad (3.4)
\]

The number of years used in the annualized capital cost calculation differed between the two management strategies based on the planning horizon of each option.

The collection and off-site disposal at a nearby ODOT facility using ODOT personnel, utilized a thirty (30) year planning horizon. This length was selected based on the useful life of the storage tank used to hold the wash water until disposal. ODOT indicated storage is achieved through the use of an underground fiberglass storage tank (Kennedy, 2013). The life expectancy of this type of storage system is typically assumed to be 30 years (Yale Environmental Health & Safety 2011; Xerxes Corporation 2014).
The other management strategy of connecting to an existing sanitary sewer system used a fifty (50) year planning horizon. This strategy was assigned a fifty year horizon based on the useful life expected for a sanitary sewer (Bizier 2007).

The annualized cost equation is summarized in Table 3.1. The Sanitary Sewer option is composed of a capital cost for the construction of sanitary sewer to connect to the existing system and an annual operational cost for disposal. The Collect and Dispose option consists of a capital cost for storage and annual operational costs for water quality monitoring, hauling and disposal. A more detailed description of the costs will be provided in next sections.

Table 3.1. Summary of cost factors used in the calculation of the annualized wash water management costs.

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Capital Cost</th>
<th>Operating Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Sanitary Sewer</td>
<td>Construction</td>
<td>Disposal</td>
</tr>
<tr>
<td>(2) Collect and Dispose</td>
<td>Storage</td>
<td>Water Quality Monitoring</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Disposal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hauling</td>
</tr>
</tbody>
</table>

3.2 Definition of Input Variables

The variables that compose the annualized cost equation were defined as either point estimations or probability distributions. Probability distributions were used in the cost equation to quantitatively characterize the variability and uncertainty for multiple variables. The calculated annualized cost outputs from the cost equations are probability distributions that reflect the combination of multiple probability distributions and point estimations.
Variables were defined by probability distributions when its value was uncertain or demonstrates variability. This may occur due to a lack of available information or differences among the population of values. This approach accounts for the range of feasible values (minimum through maximum) for each variable that may occur at an ODOT maintenance facility. Subsequently, calculations utilizing the distributions will provide a range of annualized costs and associated probabilities for both strategies. The two management strategies can be compared in probabilistic terms. Statements can be made about the probability of each management strategy having a lesser annualized cost.

Table 3.2  Summary of cost factors defined by distributions in the Collect and Dispose or Sanitary Sewer annualized cost calculations. The values are based on all ODOT county and outpost garages.

<table>
<thead>
<tr>
<th>Cost factor</th>
<th>Distribution</th>
<th>5 Percentile Value</th>
<th>Average</th>
<th>95 Percentile Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount rate (decimal)</td>
<td>Histogram</td>
<td>0.0443</td>
<td>0.0740</td>
<td>0.1143</td>
<td>Office of Management and Budget 2009</td>
</tr>
<tr>
<td>Cost of disposal of wash water ($/gal)</td>
<td>Lognormal</td>
<td>$0.0060</td>
<td>$0.0121</td>
<td>$0.0199</td>
<td>Ohio EPA 2013</td>
</tr>
<tr>
<td>Number of trucks</td>
<td>Discrete Histogram</td>
<td>2</td>
<td>8</td>
<td>16</td>
<td>ODOT</td>
</tr>
<tr>
<td>Hose flow rate (gpm)</td>
<td>Uniform</td>
<td>4.1</td>
<td>5.0</td>
<td>5.9</td>
<td>ODOT</td>
</tr>
<tr>
<td>Wash time per event per truck (minutes)</td>
<td>Normal</td>
<td>40.3</td>
<td>60</td>
<td>79.7</td>
<td>ODOT</td>
</tr>
<tr>
<td>Number of winter events</td>
<td>Discrete Histogram</td>
<td>16</td>
<td>32</td>
<td>54</td>
<td>ODOT</td>
</tr>
<tr>
<td>Roundtrip distance of hauling (miles)</td>
<td>Histogram</td>
<td>16.3</td>
<td>49.2</td>
<td>109.7</td>
<td>ODOT</td>
</tr>
</tbody>
</table>
Monte Carlo Simulations can be used to calculate a distribution for a final cost when variables are defined as probability distributions. A Monte Carlo simulation performs calculations for a specified number of iterations. Each iteration randomly selects a value for each variable based on the defined probability distribution of the variable. The resulting output, annualized cost, will be in distribution form. The Monte Carlo Simulation can create a cumulative density function for the annualized cost of each management strategy.

Computer software enables simulations with numerous calculations to be performed. The Monte Carlo Simulations were performed using Palisade’s @Risk software. The software is a risk analysis and simulation add-in for Microsoft Excel. The current version, Version 5.7, was released in September 2010. The @Risk add-in enables input variables to be defined by probability distributions (Palisade 2010). Probability distributions were applied to the ten inputs defined in Table 3.2. Not all inputs had distributions associated to their value.

3.2.1. Discount Rate

The discount rate is an opportunity cost value, or the time value of money. The proper selection of a discount rate can be a difficult proposition for governmental agencies (Veneziano et al., 2010; Zerbe Jr. et al., 2002). A review of literature did not provide a census on the rate, but provides many potential methods to determine a suitable rate. For public projects, such as those undertaken by state transportation agencies, the discount rate is often based on the interest rate. The rate can reflect both the positive action of interest accumulation and the negative action of inflation. In private projects, the rate is typically based on alternative investments or the minimum attractive rates of
return (Heathcote, 2009). Since funds for winter maintenance are reserved exclusively for winter maintenance activities, no alternative investments or minimum rates of return exist. Therefore, the discount rate can be defined by the Office of Management and Budget's (OMB) "Discount Rates for Cost Effectiveness, Lease-Purchase, and Related Analyses" guidance (Veneziano et al., 2010). This document is an appendix in "Circular A-94: Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs" published by the OMB. This document sets the discount rates to be used in calculations by most Federal programs.

The discount rate is defined as a probabilistic distribution based on the nominal interest rates on treasury notes and bonds of a specified maturity. The specified maturity is based on the planning horizon of the project. Planning horizons for durations of 30 years or longer use the 30-year interest rate from Appendix C in the OMB Circular No. A-94 (Office of Management and Budget, 2013). The discount rates set by the OMB varies yearly. Using historic data from the OMB document, the distribution was defined as a histogram based on the discount rate of a 30-year maturity from 1979 to 2013.

The cost equations for both the Collect and Dispose and Sanitary Sewer strategies will utilize the same discount rate distribution. The distribution will be used in calculations of the annualized cost factor. Using this factor, capital costs will be put in terms of annual costs.
Figure 3.1 The distribution defined for the discount rate. The distribution is a discrete histogram based nominal treasury interest rates of 30-year maturity from 1979 to 2013 (Office of Management and Budget, 2013). The mean discount rate is 0.0740.

3.2.2. Collect and Dispose Option - Capital Costs

As previously discussed, the Collect and Dispose option will require a holding tank system to store the truck wash water until it can be hauled to and disposed at another ODOT facility. The storage tank system will be the only capital cost for this management option. The cost of the storage system will be approximately $30,000 based on systems recently purchased by ODOT (Kennedy, 2013). The system includes a 3,000 gallon underground fiberglass storage tank, 500 gallon oil/water separator, and associated electrical components. A 3,000 gallon tank was selected in order to provide more storage...
capacity than the available hauling capacity of the tanker trucks used to transport the wash water to a nearby ODOT facility with sanitary sewer access. Truck size is assumed to be 2,000 gallons based on the current fleet of ODOT vehicles.

3.2.3. Collect and Dispose Option - Operational Costs

Operational costs are a summation of the disposal, monitoring, and hauling costs. The annual water quality monitoring cost was set as a fixed cost of $1,385 (Kennedy, 2013). This cost is based upon the annual cost of an existing truck wash water quality monitoring program, approved by the Ohio EPA, at the Henry County Garage in District 2.

The disposal and hauling costs are a function of the wash water volume generated. Each ODOT maintenance facility will generate different volumes based on the site-specific conditions, such as the number of winter events that occur in a year. The calculation of the annual volume, in gallons, is shown in Equations 3.5 and 3.6.

\[
\text{Annual volume (gallons)} = \text{Number of trucks} \times \text{hose flow rate (gpm)} \times \\
\text{wash time per event (min)} \times \text{number of wash cycles}
\]

\[
\text{Number of wash cycles} = \text{number of winter events} \times 1.1
\]

Each truck goes through one wash cycle during a typical winter event. ODOT personnel estimated approximately 10% of winter events will require an additional wash cycle. To incorporate this variable, the number of winter events will be multiplied by a factor of 1.1 to generate the number of wash cycles.

The number of trucks and the number of winter events are defined as distributions. The distributions are discrete histograms based on the data provided by ODOT. The number of winter events were determined by historical data provided by
ODOT based on the number of winter events from 2008 to 2011. Refer to Figures 3.2 and 3.3 at the end of this chapter for a graphical representation of the histograms. The data that quantifies the number of trucks per ODOT facility includes both county and outpost garages. County garages are larger, with a mode of 12 trucks per facility. Outpost garages are significantly smaller, with a mode of 3 trucks per facility.

Correspondence with ODOT personnel reported the hoses used to wash the trucks have flow rates ranging from 4 gallons per minute to 6 gallons per minutes. The model input utilizes a uniform distribution of 4 through 6 gallons per minute for hose flow rate to account for the potential variation in the flow.

ODOT personnel reported times ranging from as little as 30 minutes and up to 90 minutes of wash time per truck. A typical wash time of 60 minutes was reported. To incorporate the range of values, a uniform distribution with a standard deviation of 12 minutes and a mean of 60 minutes was applied to the variable for wash time.

The cost of disposal was based on the volume of water multiplied by the disposal rate. The distribution for the cost per gallon of disposing wash water is based on data from the Ohio EPA 2011 Sewer and Water Rate Survey. A histogram was created for the price per gallon from the 461 municipalities and sewer districts in Ohio. The histogram provided the full range of values and the likelihood of occurrence for the sewer rate throughout the state. In order to incorporate the uncertainty of future costs of disposal, @Risk was utilized to calculate a distribution of expected disposal rates over the next 12 years using the historical increase of yearly rates data. The distribution was calculated by combining a histogram of sanitary sewer rates for the entire state of Ohio multiplied by the rate increase factor shown in Equation 4. For the disposal rate calculations, the
midpoint of the planning horizon is fifteen (15) years. and the rate increase factor is based on a histogram of rate increases obtained from historical data (Ohio EPA 2013).

\[ r = (1 + i)^n \]  

(3.7)

where \( r \) = rate increase factor, \( i \) = rate increase, and \( n \) = midpoint of the planning horizon.

The hauling costs were calculated on a per trip basis. The cost is based on the labor and operational expenses of the vehicle for each trip. Labor cost is based on the truck driver’s compensation. The labor cost per hour was calculated by multiplying the hourly rate of the truck driver by a factor of 1.55 to account for salary and benefits (Bureau of Labor Statistics 2012). ODOT District 2 personnel indicated an hourly wage of $17.50 hour per driver. The distribution for labor cost per hour was fit by @RISK based on the hourly wage supplied by ODOT ($17.50/hour), multiplied by a factor of 1.55, and multiplied by the rate increase factor in Equation 3.7. The rate increase is a distribution of the Average Wage Increase from 1951 to 2013 (Social Security Administration 2014). The total labor cost per trip is based on Equation 3.8.

\[ \text{Labor Cost} = \frac{\text{Distance}}{\text{Speed}} + \text{Time to load and unload truck} \times \text{Labor Rate} \]  

(3.8)

The distance of each round trip was defined as a distribution based on street addresses supplied by ODOT. The distribution is based on the distances between outpost garages and country garages, and the distance between county garages and district garages. The average roundtrip hauling distance is 49.2 miles. The speed was assumed at 45 mph. The time to load and unload the truck is approximately 1 hour.

The cost of operating a truck to haul the wash water to a location for disposal includes fuel, depreciation, purchase, insurance, maintenance, and permits. The diesel fuel cost was defined as a distribution. The distribution was derived using low, likely, and
high predictions for the cost of a gallon of diesel fuel in the year 2020 (U.S. Energy Information Administration, 2013). The average fuel efficiency used in the calculations was 7 miles per gallon (Barnes & Langworthy, 2013). An additional $0.53/mile was added to the fuel cost to account for depreciation, purchase, insurance, maintenance, and permits as shown in Table 3.3.

Table 3.3 Costs of operating a truck used to haul wash water to disposal at an off-site ODOT facility

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cost ($/mile)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of vehicle</td>
<td>0.235</td>
<td>American Transportation Research Institute (2011)</td>
</tr>
<tr>
<td>Insurance</td>
<td>0.06</td>
<td>Trego and Murray (2009)</td>
</tr>
<tr>
<td>Repair/maintenance</td>
<td>0.105</td>
<td>Barnes and Langworthy (2003)</td>
</tr>
<tr>
<td>Tires</td>
<td>0.03</td>
<td>Trego and Murray (2009)</td>
</tr>
<tr>
<td>Depreciation</td>
<td>0.08</td>
<td>Barnes and Langworthy (2003)</td>
</tr>
<tr>
<td>Permits/licenses</td>
<td>0.023</td>
<td>Barnes and Langworthy (2003), American Transportation Research Institute (2011)</td>
</tr>
<tr>
<td>Total Cost</td>
<td>0.53</td>
<td></td>
</tr>
</tbody>
</table>

In order to determine the total annual hauling cost, the number of trips for disposal must be calculated. This number is calculated by dividing the volume of wash water at a facility by the capacity of truck, assuming the capacity of the truck is less than the capacity of the storage tank. The calculations are based on a 2,000 gallon tanker truck.
Figure 3.2. The distribution defined for number of trucks used in the Collect and Dispose annualized cost calculations. The distribution is a discrete histogram based on all ODOT county and outpost garages. The data was provided by ODOT.
Figure 3.3  The distribution defined for the number of winter events used in the Collect and Dispose annualized cost calculation. The distribution is a discrete histogram based on the number of winter events recorded at all ODOT county garages from 2008 to 2011. The data was provided by ODOT.
Figure 3.4 The distribution defined for the roundtrip distance of hauling the stored wash water used in the Collect and Dispose annualized cost calculation. The distribution is based on the distances of outpost garages to country garages and county garages to district garages based on addressed supplied by ODOT. The average roundtrip hauling distance is 49.2 miles.
The distribution defined for labor rate used in the Collect and Dispose annualized cost calculation. The distribution is a lognormal distribution with $\alpha=5.7701$, $\beta=6.9332$, and shift = 16.3638. The distribution was fit by @RISK based on the hourly wage supplied by ODOT ($17.50/hour), multiplied by a factor of 1.55 to account for salary and benefits (Bureau of Labor Statistics, 2012), and multiplied by $(1+i)^n$, where $i$ is a distribution of yearly wage increase based on the Average Wage Increase from 1951 to 2013 (Social Security Administration, 2014), and $n$ is 12 years based on the planning period used in the Collect and Dispose annualized cost calculations. The mean labor rate is $56.37/hour.

Figure 3.5
Figure 3.6  The distribution defined for the cost of fuel per gallon used in the Collect and Dispose annualized cost calculation. The distribution is a normal distribution with a mean of 4.315 standard deviation of 0.395. The distribution was fit based on low, likely, and high predictions for the cost of a gallon of diesel fuel in the year 2020 (U.S. Energy Information Administration, 2013).
Figure 3.7  The distribution defined for the cost of disposal per gallon of wash water via sanitary sewer in the Collect and Dispose and Sanitary Sewer annualized cost calculation. The distribution is a Lognormal distribution with $\mu = 0.016936$, $\sigma = 0.0043147$, and shift = -0.0048511. The distribution was fit by @Risk based on a histogram of sanitary sewer rates for the entire state of Ohio multiplied by $(1+i)^n$, where $i$ is a histogram distribution of rate increases based on historical data (Ohio EPA, 2013), and $n$ is 15 years based on the midpoint of planning period used in the Collect and Dispose annualized cost calculations. The average disposal rate is $0.012$/gallon.

3.2.4. Sanitary Sewer Option

The capital cost for the Sanitary Sewer Option is the cost of constructing the sanitary sewer connection. This cost is site specific. Factors influencing this cost include the distance from an existing sanitary sewer system and site topography, both which will
impact if a gravity sewer can be utilized to meet the existing sewer system. Calculations were performed with capital costs ranging from $100,000 to $1,000,000. To provide a point of reference, ODOT District 4 constructed a connection to a sanitary sewer system that required 3,000 linear feet of 8" sanitary sewer in Conneaut, Ohio in 2011 that cost $330,000. Construction in Greensburg, Ohio utilized 600 linear feet of 6" sanitary sewer that cost $100,000.

Disposal of the wash water is the only operational cost for the Sanitary Sewer Option. The disposal rate of the Collect and Dispose option will also be used for the Sanitary Sewer Option. Refer to Section 3.1 for a discussion on the disposal rate.

3.3 Definition of Input Variables for Facilities without Sanitary Sewer Access

Approximately 40% of the ODOT maintenance facilities currently lack access to a sanitary sewer system. Many of these facilities will be requiring a revised approach to managing wash water in order to meet regulations. Separate analyses of cost for the facilities lacking sanitary access will be performed to provide insight for the selection of a new management strategy. These facilities tend to be outpost garages and in rural areas. Therefore, input variables must be revised to match the site-specific characteristics of these garages.

New probability distributions were defined for the number of trucks and the roundtrip hauling distance. The data provided by ODOT indicated which facilities lack access to sanitary sewer. Using this information, the histograms were revised to include only data from facilities lacking the sewer access.

The remaining input variables will maintain either the distributions or point values as describe in the previous section. The values for discount rate, water quality
monitoring, and labor cost are uniform throughout the entire state. The facilities lacking sanitary sewer connections are apportioned throughout the entire state so the distribution for winter events will still apply.

Figure 3.8. The distribution defined for number of trucks at ODOT facilities currently without sanitary sewer access. The distribution is a discrete histogram based data provided by ODOT. The average garage without sanitary sewer access has five (5) trucks.
Figure 3.9. The distribution defined for the roundtrip distance of hauling the stored wash water for facilities currently without sanitary sewer access. The distribution is based on the distances of outpost garages without sanitary sewer access to country garages and county garages without sanitary sewer access to district garages based on street addresses supplied by ODOT. The average roundtrip hauling distance is 39.9 miles.
CHAPTER IV
RESULTS AND ANALYSIS

Once the cost equation was set and input variables defined, a detailed cost analysis was performed for the Collect and Dispose and Sanitary Sewer options. The objective of the analysis was to determine which management strategy is less costly on an annualized basis. The calculations were performed on both the statewide and non-sanitary sewer access data sets. Both data sets provide useful data. The statewide analysis can be used when making statewide decisions, replacements or when deciding new locations of outpost or county garages. The analysis of the non-sanitary sewer locations provides insight to determine the best management option for garages with current substandard management strategies currently in place.

For discussion purposes, the collection and off-site disposal of wash water at an ODOT facility will be referred to as the “Collect and Dispose” option. The strategy of tying into an existing sanitary sewer system will be referred to as the “Sanitary Sewer” option. The probability output will also be in the context that assumes the probability of the Collect and Dispose method is less costly than the Sanitary Sewer option.

4.1 Advanced Sensitivity Analysis

As discussed in previous sections, the cost equations for the management strategies under further review are composed of multiple input variables defined by probability distributions. Based on the probability distribution and its associated weight
in the cost equation, these parameters will have a varying impact on the output results and annualized cost. Understanding the influence of each input parameter is important when evaluating the annualized costs of the management strategies. Insight about each input parameter will also determine which have the greatest impact to the annual cost. This insight will also clarify which input parameters require a more detailed analysis in order to further the understanding of the annualized costs. The technique to provide the initial analysis is referred to as a sensitivity analysis. A sensitivity analysis is the study of how the uncertainty of an output of mathematical system can vary based on the uncertainty or variability of the input parameters.

The Advanced Sensitivity Analysis in @Risk performs sensitivity analyses and calculations to determine how the inputs affect the outputs. The advanced analysis calculates the sensitivity by performing the annualized cost calculations a defined number of iterations at each input parameter. The calculations are performed over a specified variable range while varying the other parameters based on defined probability distributions. For example, the cost calculations will be performed a set number of iterations at 1 truck while all other variables are defined by their distributions, 2 trucks, then 3 trucks, and so on.

For the advanced sensitivity analysis, the input parameters were varied from 5% to 95% of the defined distribution. This range was selected to provide a comprehensive range of values without including statistical outliers. All feasible values will occur within 5% to 95% of its probability distribution.

Advanced sensitivity analyses were performed for the annual cost equation for both the Collect and Dispose and Sanitary Sewer options. This analysis provided a
detailed look at the influence of every variable defined by a probability distribution. The results from this analysis will provide information as to which input variable requires further investigation.

4.1.1 Collect and Dispose Option

The Advanced Sensitivity Analysis for the Collect and Dispose option selected the following input variables to calculate output results: number of trucks, number of winter events, roundtrip hauling distance, wash time per event per truck, hose flow rate, discount rate, wage rate, cost of fuel, and disposal rate. The annualized cost was calculated for each variable over a range of 5% through 95% of its probability distribution. At both 5% and 95% of the probability distribution, 10,000 iterations of the cost equation calculation were performed. All cost factors were varied based on their defined probability distributions. Results of these calculations are summarized in Table 4.1 and Figure 4.1.
Table 4.1  The range of values calculated for the annualized cost of collecting and disposing of wash water at a nearby ODOT maintenance facility based on an advanced sensitivity analysis calculated using @Risk. The cost factors were varied between 5% and 95% of their defined distributions. The annualized cost is most sensitive to the number of trucks, number of winter events, and the roundtrip hauling distance.

<table>
<thead>
<tr>
<th>Cost factors</th>
<th>Min. Value</th>
<th>Max Value</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Number of trucks</td>
<td>$5,798</td>
<td>$18,931</td>
<td>$13,133</td>
</tr>
<tr>
<td>(2) Number of winter events</td>
<td>$6,658</td>
<td>$18,100</td>
<td>$11,442</td>
</tr>
<tr>
<td>(3) Roundtrip hauling distance</td>
<td>$8,626</td>
<td>$17,447</td>
<td>$8,820</td>
</tr>
<tr>
<td>(4) Wash time per event per truck</td>
<td>$9,159</td>
<td>$14,295</td>
<td>$5,136</td>
</tr>
<tr>
<td>(5) Wage rate</td>
<td>$9,847</td>
<td>$14,274</td>
<td>$4,427</td>
</tr>
<tr>
<td>(6) Hose flow rate</td>
<td>$10,342</td>
<td>$13,160</td>
<td>$2,819</td>
</tr>
<tr>
<td>(7) Discount rate</td>
<td>$11,031</td>
<td>$12,428</td>
<td>$1,397</td>
</tr>
<tr>
<td>(8) Wash water disposal rate</td>
<td>$11,268</td>
<td>$12,364</td>
<td>$1,097</td>
</tr>
<tr>
<td>(9) Cost of fuel</td>
<td>$11,562</td>
<td>$11,922</td>
<td>$360</td>
</tr>
</tbody>
</table>
Figure 4.1  The range of annualized costs calculated for the Collect and Dispose option based on an advanced sensitivity analysis performed using @Risk. The model input values were varied between 5% and 95% of the input variable probability distribution.

The Advanced Sensitivity Analysis identified the number of trucks, number of winter events and the roundtrip hauling distance as having the greatest impact on the annualized cost of the Collect and Dispose option.

The number of trucks and number of winter events influences the volume of wash water. Greater wash water volume increases both the annual costs for disposal and hauling. Based on the above results, the number of trucks and winter events must be further analyzed when determining which management strategy is most cost effective.
These input parameters are location-specific and the values may vary depending on the site characteristics of each facility. The roundtrip hauling distance is also a sensitive parameter for annualized cost of the Collect and Dispose option. This variable will also require further analyses when determining which management strategy is most cost effective.

The following input parameters were determined to have minimal impact on the annualized cost of the Collect and Dispose option: wash time per event per truck, hose flow rate, discount rate, wage rate, cost of fuel, and disposal rate. The variability and uncertainty of the parameters has minimal impact on the annualized cost. Therefore these variables will not require further analyses.

4.1.2. Sanitary Sewer Option

The Advanced Sensitivity Analysis was performed in a revised form for the Sanitary Sewer option. The only operational cost of the Sanitary Sewer option is the disposal rate of the wash water. As shown in the Collect and Dispose sensitivity analysis, disposal rate has very little impact on the annualized cost. Therefore, the impacts of the disposal rate will not be further analyzed. After removing the disposal rate, the capital cost of the sanitary sewer and the discount rate are the only input parameters to be considered for the sensitivity analysis. Since a distribution cannot be defined for the capital cost of the sanitary sewer, a sensitivity analysis for the discount rate was performed for the capital cost of the sanitary sewer at $100,000 increments, as shown in Table 4.2.
Table 4.2  The range of values for the annualized cost of the connection to an existing sanitary sewer system based on the capital cost of the sewer construction. The minimum and maximum values were calculated by an advanced sensitivity analysis in @Risk, where the discount rate was varied between 5% and 95% of its defined distribution.

<table>
<thead>
<tr>
<th>Capital cost of sanitary sewer</th>
<th>Annual Cost</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min. Value</td>
<td>Max Value</td>
<td>Delta</td>
<td></td>
</tr>
<tr>
<td>$100,000</td>
<td>$5,949</td>
<td>$12,428</td>
<td>$6,479</td>
<td></td>
</tr>
<tr>
<td>$200,000</td>
<td>$10,971</td>
<td>$23,929</td>
<td>$12,958</td>
<td></td>
</tr>
<tr>
<td>$300,000</td>
<td>$15,967</td>
<td>$35,404</td>
<td>$19,437</td>
<td></td>
</tr>
<tr>
<td>$400,000</td>
<td>$20,975</td>
<td>$46,892</td>
<td>$25,916</td>
<td></td>
</tr>
<tr>
<td>$500,000</td>
<td>$25,982</td>
<td>$58,377</td>
<td>$32,395</td>
<td></td>
</tr>
<tr>
<td>$600,000</td>
<td>$30,984</td>
<td>$69,859</td>
<td>$38,875</td>
<td></td>
</tr>
<tr>
<td>$700,000</td>
<td>$35,991</td>
<td>$81,345</td>
<td>$45,354</td>
<td></td>
</tr>
<tr>
<td>$800,000</td>
<td>$40,999</td>
<td>$92,832</td>
<td>$51,833</td>
<td></td>
</tr>
<tr>
<td>$900,000</td>
<td>$46,002</td>
<td>$104,314</td>
<td>$58,312</td>
<td></td>
</tr>
<tr>
<td>$1,000,000</td>
<td>$51,008</td>
<td>$115,798</td>
<td>$64,791</td>
<td></td>
</tr>
</tbody>
</table>

The results of these calculations demonstrated the importance of the discount rate on the annualized cost of the Sanitary Sewer option. For capital costs of $300,000 and greater, the delta between the annualized cost at 5% and 95% is greater than any delta between minimum and maximum values in the Collect and Dispose calculations. The discount rate merits further investigations.

4.2  Cost Effectiveness based on Input Variable

The Advanced Sensitivity Analysis determined that the number of trucks, number of winter events, and roundtrip hauling distance have the greatest influence on the annualized cost of the wash water management strategies. A detailed cost analysis was performed to show how changes in the input variable affects the calculated probabilities of which management strategy is least costly.
4.2.1. Number of Trucks

The Advanced Sensitivity Analysis determined the number of trucks to be the most sensitive variable in the calculation of the annualized cost. Further analysis was performed to provide additional insight as to how the number of trucks affects the annualized cost. The calculations were performed by determining the probability that the cost of the Collect and Dispose option is less costly than the Sanitary Sewer option. This was determined by performing 10,000 calculations at 1 to 24 trucks with a defined capital cost for the sanitary sewer of $100,000, $300,000 or $500,000. All other variables were defined as point values, or as probability distributions as previously discussed. The probability was determined by calculating the percentage of time that the Collect and Dispose option was less costly than the Sanitary Sewer option. For example, if 10,000 iterations were performed, the cost of the Collect and Dispose option was less expensive 5,000 times and the probability for those parameters would be 0.50.

The results of the calculations can be found in Figure 4.2. The probability that the Collect and Dispose option is most cost effective at the state-wide average number of trucks, eight (8), for a sanitary sewer at a capital cost of $100,000, $300,000, and $500,000 is 37.0%, 95.9%, and 99.5% respectively.

As shown in Figure 4.2, a significant observation is the difference in the slopes of the output at capital costs $100,000, $300,000, and $500,000. The slope of the $100,000 line vastly differs from the slopes of the other two lines. At a capital cost of $100,000, the probability that Collect and Dispose strategy is most cost effective drops significantly as the number of trucks increases. The probability does not even begin to flatten until over fifteen (15) trucks. The probability is less than 50% at five (5) trucks. This indicates that
for a location of five (5) or more trucks, tying into the sanitary sewer is a cost effective management strategy if the capital cost is around $100,000.

Contrarily, when sanitary sewer capital costs are $300,000 or greater, the Collect and Dispose strategy is the most cost effective. Regardless of the number of trucks at a facility, the probability of the Collect and Dispose strategy being the most cost effective is 60% or greater. For capital costs of $300,000, minimal change is observed in the probability until the number of trucks exceeds ten (10). Likewise, minimal change is observed for any of number of trucks for capital costs of $500,000. The probability remains approximately 90% at the upper limit of this variable. This demonstrates the importance of the capital cost of the sanitary sewer. As this cost increases, it leaves the parameters of the Collect and Dispose option with marginal significance when determining which option is the most cost effective.

The type of garage often dictates the expected number of trucks. A typical outpost garage will have only 3 trucks while a typical county garage has 12 trucks. For an outpost garage, Collect and Dispose is nearly 100% probable to be most cost effective when capital cost of the sanitary sewer is $300,000 or greater. At capital costs of $100,000, the probability is nearly 80%. These results point to the Collect and Dispose option as the most cost effective strategy for nearly all outpost garages.

County garages have much lower probabilities for the Collect and Dispose option as most cost effective. The typical county garage of 12 trucks has probabilities of 21%, 88%, and 98% that the Collect and Dispose option is most cost effective at sanitary sewer capital costs of $100,000, $300,000 and $500,000, respectively. If the cost is
approximately $100,000 for a county garage to connect to the sanitary sewer, the construction of the sewer is likely to be the most cost effective strategy.

As previously discussed, facilities without sanitary sewer access on average have fewer trucks. The facilities without sewer access average five (5) trucks per location. The Collect and Dispose option is the likely strategy to be least costly based on the results shown in Figure 4.3.

![Figure 4.2](image-url)  
Figure 4.2 The probability that the annualized cost of collecting and disposing wash water at a nearby ODOT facility is the least costly strategy based on the number of trucks at the facility. The probability that at average number of eight (8) trucks collecting and disposing is less costly than a sanitary sewer capital cost of $100,000, $300,000, and $500,000 is 37.0%, 95.9%, and 99.5% respectively.
4.2.2. Number of winter events

The number of trucks per facility was found to be the second most sensitive parameter when calculating the annual cost of the Collect and Dispose option. The probabilities shown in Figure 4.4 were calculated similarly to the method used in the calculations for the number of trucks. However in this case, the 10,000 iterations of the calculations were performed from 1 to 60 winter events.

The slopes of the lines look very similar to those calculated for the change in the number of trucks. This is to be expected, as both parameters impact the volume of wash water generated. Similar to Figure 4.3, the probability sharply decreases as winter events begin to increase when the capital cost is $100,000. For capital costs $300,000 or greater, the probability remains high with gently sloping lines.

A key observation for this figure is that the Collect and Dispose strategy has probability greater than a 70% being the most cost effective strategy when sanitary sewer capital costs are greater than $300,000. This observation is regardless of the number of winter events. The facility can be in the snowiest part of Ohio and the Collect and Dispose option would likely be the most cost effective. When capital costs are closer to $100,000, the number of winter events must be taken into consideration.

The number of winter events is a direct function of the location of the garage. Most areas served within a district or county will have similar snowfall totals. Subsequently, a facility cannot be strategically placed in a particular location to experience fewer winter events. Although this factor cannot be managed, it must be understood when making the decision between the Collect and Dispose or Sanitary Sewer
options. The greater the number of winter events, the less likely the Collect and Dispose option is the most cost effective strategy.

Figure 4.3  Snowfall gradient for the State of Ohio based on data from 2009.

Snowfall in the State of Ohio was summarized in Figure 4.3. Although this map does not provide the number of winter events, higher snowfall in inches indicates a greater number of winter events. The facilities located in the northeast corner of the State of Ohio will be in the upper limit of winter events. These facilities are primarily in Districts 4 and 12. In the opposite corner of the state, Districts 8 and 9, snowfall is much less and the number of winter events is greatly reduced.
4.2.3. Roundtrip distance

The roundtrip distance of hauling was determined to be the third most sensitive variable to the annualized cost of the Collect and Dispose option. Unlike the number of trucks and the number of winter events an increase in the roundtrip distance only increases the cost of the Collect and Dispose option. The number of trucks and number of winter events impacts the cost of disposal, which is a factor in both Collect and Dispose
and Sanitary Sewer options. The roundtrip distance affects the cost of hauling. Hauling is not a cost factor for the Sanitary Sewer Option.

The shape of the output results is similar to Figures 4.2 and 4.4, but the slopes of the output lines are flatter. This was expected since the annualized costs were not as sensitive to change with this variable as seen with the previous two factors analyzed.

Despite this variable not being as sensitive of a factor, the roundtrip distance is important because the distance can be managed. As per previous discussions, the location of a new facility controls the number of winter events and number of trucks. The roundtrip distance can be managed by controlling where new garage is located. Likewise, existing garages may already be connected to the sanitary sewer, giving other facility a point to haul. Figure 4.5 demonstrates that only a 10% change in probability is observed when the roundtrip distance is increased from 60 to 110 miles when the capital cost is $150,000. When the capital cost is $300,000 or above, the probability is over 70% that the Collect and Dispose option is more cost effective at travel distances up to 120. Therefore, at high capital costs the hauling distance can be long. At low capital costs, the probability is marginally sensitive to distance. This means fewer garages need to be connected to the sanitary sewer because the water can be hauled long distances without incurring high costs. Therefore, long distances should not hinder the decision in choosing a wash water management strategy. This indicates a need for district-wide facilities with sanitary access, for which all other county and outpost garages use for disposal.
Figure 4.5  The probability that the annualized cost collecting and disposing of wash water at a nearby ODOT facility is the least costly strategy based on the roundtrip distance of hauling the wash water for disposal. The probability that the average roundtrip distance, 49.2 miles, that Collect and Dispose is less costly based on a sanitary sewer capital cost of $100,000, $300,000, and $500,000 is 18.7%, 83.0%, and 96.0% respectively.

4.2.4. Discount rate

The discount rate is used in calculating the annualized cost for both management strategies. The importance in both equations varies greatly. The Collect and Dispose option has limited change based on the discount rate. This is due to the much smaller capital cost. As earlier discussed, the discount rate is used to put capital cost into the annualized cost form. For the Sanitary Sewer option, the discount rate plays a major role. This is attributed to the sanitary sewer capital cost the main factor in the cost equation.
Figure 4.6 for the Discount Rate has a much different shape than the previous figures. Similar to the other figures, the output line representing the $100,000 capital cost is much lower than the other two output lines. This continues to show that the probability of the Collect and Dispose option being the least costly strategy increases as the cost of the capital cost of the sanitary sewer increases.

As the discount rate increases the annual capital cost also increases, making the Collect and Dispose option a more cost effective strategy. The capital cost of the Collect and Dispose option is much smaller than the capital cost of the Sanitary Sewer option.

As discussed in Chapter III, the discount rate is a function of the interest rate of the 30-year treasury note. Current interest rates are at the lower limit of rates recorded 1979 to 2013, which correlates to the time frame used in the discount rate probability distribution. The rates have decreased for almost ten (10) consecutive years. The 2013 interest rate was 3.0%. If low interest rates remain common, the probability of the Collect and Dispose option being the most cost effective strategy decreases. At the 2013 interest rate of 3.0%, the probability that Collect and Dispose was the least costly option for a sanitary sewer at a capital cost of $100,000, $300,000, and $500,000 was 8.6%, 74.4%, and 91.8%, respectively.
Figure 4.6 The probability that the annualized cost collecting and disposing of wash water at a nearby ODOT facility is the least costly strategy based on the discount rate. The probability at a discount rate of 7% that Collect and Dispose is less costly based on a sanitary sewer capital cost of $100,000, $300,000, and $500,000 is 41.4%, 93.8%, and 98.7% respectively.

4.3 Overall probability

After analyzing the key input parameters individually, a clear trend developed. The trend shows that if capital cost are $300,000 or greater, the Collect and Dispose option is almost always the most probable management strategy to have a lower annualized cost. To further investigate this trend a cumulative distribution function of the probability versus the capital cost of the sanitary sewer was created. To create an overall cumulative distribution function, 10,000 calculations were run at capital costs of sanitary

46
sewer ranging from $0 to $800,000. All other identified parameters were set at the
defined probability distributions. Refer to Figure 4.7 for results.

The figure has a steep increase in probability from $75,000 to $300,000. At
$300,000 the Collect and Dispose option is approximately 90% probable to be the most
cost effective strategy. By the time the capital cost approaches $700,000, the probability
is almost 100%. This means that the Collect and Dispose option is an easy decision to
make when capital costs are above $300,000.

The probability of both management strategies being cost effective is
approximately 50% when the capital cost of the sanitary sewer approaches $120,000.
When the capital cost of the sanitary sewer is approximately $100,000, the probability of
both options being cost effective are nearly equal. This may further complicate the
strategy selection decision. However, focusing on the site characteristics and referencing
back to Figures 4.2, 4.3, 4.5, 4.6, and 4.7 provides the decision maker with more
considerations for the selection of the most cost effective management strategy.
4.4 Overall Probability for Locations Without Sanitary Sewer Access

The results in Section 4.3 examined probabilities when considering all ODOT maintenance facilities. Observations from this section is useful when building new facilities or evaluating the statewide network of facilities. An additional point of interest is facilities without access to sanitary sewer. These facilities, as discussed in Chapter III, may require attention in the near future so as to meet regulations.

A simulation, like that performed in Section 4.3, created a cumulative distribution function for the probability of the Collect and Dispose option as the least costly strategy.
versus the capital cost of the sanitary sewer. The distributions of the inputs for the number of trucks and roundtrip hauling distance varies from what was used in Section 4.3. The input parameters used in this simulation were defined by the distributions in Section 3.3.

As expected, the results from this simulation increases the probability that Collect and Dispose is the most cost effective strategy. This was expected, given the fact that garages without sanitary sewer access are defined by distributions with fewer trucks and shorter roundtrip hauling distances.

The results from this analysis indicate that in a state-wide approach, locations without sanitary sewer access should utilize the Collect and Dispose option.

Table 4.3  Comparison of the probability that Collect and Dispose is least costly management strategy for all ODOT maintenance facilities and facilities lacking access to a sanitary sewer system.

<table>
<thead>
<tr>
<th>Capital Cost of Sanitary Sewer</th>
<th>All Facilities</th>
<th>Facilities without Sanitary Sewer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$61,000</td>
<td>7%</td>
<td>10%</td>
</tr>
<tr>
<td>$65,000</td>
<td>10%</td>
<td>17%</td>
</tr>
<tr>
<td>$100,000</td>
<td>40%</td>
<td>60%</td>
</tr>
<tr>
<td>$172,000</td>
<td>73%</td>
<td>90%</td>
</tr>
<tr>
<td>$280,000</td>
<td>90%</td>
<td>98%</td>
</tr>
<tr>
<td>$300,000</td>
<td>92%</td>
<td>98%</td>
</tr>
<tr>
<td>$500,000</td>
<td>98%</td>
<td>99%</td>
</tr>
</tbody>
</table>
Figure 4.8  The cumulative distribution function for collect and dispose as best management strategy based on the capital cost of the sanitary sewer connection for ODOT facilities without current sanitary sewer access.

4.5 Case Study

In Ashtabula County (District 4), two ODOT outpost garages were connected to existing sanitary sewer systems in 2011. The county’s decision to select the Sanitary Sewer option was analyzed to illustrate how the findings of this research can be used to assist in future decisions by other counties and districts. Table 4.4 provides a summary of the garages’ site characteristics. All data used in the table was provided by ODOT. The capital cost of the sanitary sewer connections are based on the approximate construction cost, including incidentals.
Table 4.4  Summary of the site characteristics of the two facilities that tied into existing sanitary sewer systems.

<table>
<thead>
<tr>
<th></th>
<th>Sanitary Sewer Capital Cost</th>
<th>Number of Trucks</th>
<th>Number of Winter Events</th>
<th>Roundtrip Distance (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conneaut Outpost</td>
<td>$330,000</td>
<td>5</td>
<td>64</td>
<td>70.8</td>
</tr>
<tr>
<td>Harpersfield Outpo</td>
<td>$100,000</td>
<td>3</td>
<td>64</td>
<td>24.2</td>
</tr>
</tbody>
</table>

The first step of the analysis was to refer to Figure 4.7 to determine the probability that the Collect and Dispose option was the most cost effective management strategy. Based on the $330,000 capital cost, the Conneaut Outpost garage has a 94% probability that the Collect and Dispose option is the most cost effective management strategy.

Next, other site characteristics were considered, particularly the number of winter events. Since this facility is located in Ashtabula County, it experiences the most winter events, on average, in the State of Ohio. Despite the 94% probability that the Collect and Dispose option is the least costly strategy, Figure 4.5 was referenced to evaluate how the extreme number of annual winter events would affect which strategy is ultimately the most cost effective. It was found that the high number of winter events decreases the probability to approximately 70% that the Collect and Dispose option is the most cost effective strategy. Although the level of confidence has decreased in a location with a high number of winter events, the Collect and Dispose method should still be selected as the wash water management strategy. The reduced confidence can be subsequently increased by referring considering the number of trucks and the roundtrip distance. Given the capital costs, the low number of trucks, and the roundtrip distance just above average, the probability that the Collect and Dispose option is the most cost effective strategy is
bolstered to 90%. Therefore, it was unlikely that Ashtabula County chose the least costly wash water management strategy by connecting to the sanitary sewer.

The second facility, Harpersfield Outpost, has a much lower sanitary sewer capital cost. Using the same method used to evaluate the Conneaut Outpost, it was initially determined that the Collect and Dispose option had a 40% probability of being the least costly strategy based on the $100,000 capital cost. Since the Harpersfield facility is also located in Ashtabula County, the number of annual winter events was considered. Figure 4.5 indicates a probability of less than 15% that the Collect and Dispose option was the most cost effective strategy. The facility was ultimately connected to the sanitary sewer and it is likely that the County made the right choice for the Harpersfield Outpost.
CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The overall objective of this research was to evaluate the management strategies of wash water generated during winter maintenance activities. From a review of previous research on wash water strategy, the following two strategies were evaluated: (1) connection to an existing sanitary sewer system and (2) collection and off-site disposal at a nearby ODOT facility using ODOT personnel. Although six feasible management strategies for use by ODOT were identified, the detailed cost evaluation was performed only for the above two options. The annualized cost for each management strategies was selected as the common basis for comparison.

The annualized cost equations for the two management strategies are comprised of yearly operational costs and capital costs. An annualized cost factor was employed to put capital costs in terms of annualized costs. The input parameters in the cost equation were either defined as point values or probability distributions. The probability distributions incorporated the uncertainty and variability of the parameter. Calculations were performed in Microsoft Excel using Palisade's @Risk add-in. The Monte Carlo Simulation ability of @Risk enable thousands of iterations of the calculations to be performed.
An Advanced Sensitivity Analysis determined that four parameters impact cost more significantly than others: number of trucks, number of winter events, roundtrip distance of hauling, and discount rate. The four input parameters were further analyzed to see how an increase in those parameters would affect the probability that the Collect and Dispose option is the most cost effective strategy, depending on the capital cost of the sanitary sewer connection.

The results of the Advanced Sensitivity Analysis exhibited that change in the input variable generally had a marginal effect on the probabilities when the capital cost of the sanitary sewer were $300,000 or greater. The probabilities were much more reactive to the changes in the key input variables when the sanitary sewer capital cost was set to $100,000. This statement is illustrated by the change in probability based on the number trucks of typical outpost garage, three (3) trucks, versus a typical county garage, twelve (12) trucks. When the capital cost of the sanitary sewer is $100,000, the outpost garage is nearly 80% probable that collect and dispose is the least costly management strategy, whereas the county garage is only 21% probable. The difference is probabilities means the county and outpost garage will likely have different methods as most cost effective. These results are common for the number of winter events, and to a lesser degree, the roundtrip hauling distance. Discount rate has an opposite effect than the other key variables, lower values increase probability that the sanitary sewer option is the best choice. The discount rate has the greatest impact of the variables when capital costs of the sanitary sewer are $300,000 or greater.

The number of trucks and winter events are a direct function of the location of the garage. Facilities located in counties that experience a high number of winter events will
require more trucks. While the number of winter events cannot be managed, it must be understood when making the decision selecting the management strategy. Conversely, the roundtrip distance of hauling wash water can be managed by locating a new garage near a disposal site connected to a sanitary sewer. The results of this research have shown that the impact of the hauling truck’s roundtrip distance is marginal when determining the least costly management strategy. Therefore, when considering the locations of new garages other factors besides distance from a facility with sanitary sewer, such as roadway plowing needs and the cost of land, should carry more weight in the decision.

Two cumulative distribution functions were created to analyze probability of collection and off-site disposal of wash water at an ODOT facility and the sanitary sewer connection being the most cost effective. One function was calculated using input data from all ODOT maintenance facilities. The other function was calculated using input data only from the ODOT facilities currently lacking access to the sanitary sewer. The results show that, when considering all ODOT facilities, collection and off-site disposal being the least costly strategy is 90% probable when the capital cost of the sanitary sewer connection is $280,000 and above. When considering only locations without sanitary sewer, collection and off-site disposal being the least costly strategy is 90% probable when the capital cost of the sanitary sewer connection is $172,000 and above.

The results of this research reveal that collection and off-site disposal is the generally the most cost effective management strategy for ODOT maintenance facilities currently lacking sanitary sewer access when the capital cost of connecting to the sanitary sewer exceeds $100,000. In the instances where the cost of the sanitary sewer connection is less than $100,000, the site specific conditions must be considered to decide the best
management strategy. Recent construction of sanitary sewer connections by ODOT have averaged at approximately $300,000, which further reinforces the idea that collection and off-site disposal is the optimal choice when deciding how to manage the waste wash water at facilities without sanitary sewer access.

5.2 Recommendations

Selecting the best management strategy is a function of many parameters. This research used many parameters which are unique to the State of Ohio and the ODOT. Future research could use the same methods but perform the calculations using input data from other states. For example, calculations for the State of Pennsylvania may differ from the results in this research due to differences in winter event and number of trucks distributions.

The capital cost of the sanitary sewer connection was key parameter through this research. Numbers were based on recent construction at a few facilities in District 4. The data does not provide comprehensive state-wide insight to expected sanitary sewer costs. Additional research into this cost would further understanding of the best management strategy. This research may find that sanitary sewer connection is not feasible or excessive in cost.

The volume of truck wash waster is a major driver in the cost of the annualized cost of all management strategies. Changes to the truck washing process will impact the costs. Further research could determine if the current practices are effective, or if more effective wash processes that would either increase or decrease the volume of water should be implemented.
REFERENCES


Transportation Road-Salt Storage Facilities (VTRC 08-R17)." Virginia Transportation Research Council: Charlottesville, Virginia


